Influence of soil structure on the soil water characteristic curve behavior of compacted loess

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ABSTRACT: Several studies have highlighted that fine-grained soils compacted at different water contents will have different soil structures and hence exhibit different hydro-mechanical properties. However, similar studies on compacted loess are rather limited. For this reason, soil water characteristic curves (SWCC) of loess compacted at dry of optimum, optimum and wet of optimum water contents were measured by the filter paper method. In addition, the microstructure information was obtained by the mercury intrusion pore size distribution method (MIP). Comparison analysis of the SWCC curves and PSD curves of different loess specimens shows that the compaction water content has a significant influence on the SWCC and PSD curves. The SWCC curves are significantly different in low suction but exhibit similar characteristics in the high suction range. The dry of optimum specimen has the steepest SWCC in low suction. The PSD curves highlight significant differences in their macro-pores for the three compacted specimens; however, micro-pores characteristics are approximately the same. The similarities and differences in the SWCC behavior can also be derived from the PSD curves.

1 INTRODUCTION

Fine-grained soils compacted at different initial water contents will have different soil structures (Acar & Oliveri 1989). For example, soil compacted at a dry of optimum condition has a flocculated or open structure with more connected pores whereas the soil compacted at wet of optimum condition has a dispersed structure with limited or restricted connected pores (Vanapalli et al. 1999). The hydro-mechanical properties of the unsaturated compacted fine-grained soils are significantly influenced by their soil structure. During the last two decades, several investigators focused on studies related to the prediction of the unsaturated strength using the soil water characteristic curve (SWCC) as a tool (for example, Vanapalli et al. 1996; Sheng et al. 2011; Han & Vanapalli 2016) These studies suggest that the SWCC provides valuable information about the soil structure to interpret and as well predict the shear strength behaviour of fine-grained soils. Related studies in the literature on compacted loess on the shear strength and other hydro-mechanical properties however are limited (Ng et al. 2016). Studies investigated to-date on intact and as well as compacted loess suggest the shear strength and the deformation characteristics are significantly influenced by their soil structure (Wen & Yan 2014; Ng et al. 2016; Haeri et al. 2016). In practice, loess soils are compacted at their natural water content which is typically dry of optimum condition (Wen & Yan 2014; Ng et al. 2016). There are limited studies to highlight a particular water content that would induce more favourable engineering behaviour for compacted loess. For this reason, in this paper, the influence of the soil structure on loess from *Heifangtai*, Lanzhou, Gansu province, China compacted at different initial water contents representing dry of optimum, optimum, and wet of optimum conditions are interpreted from their SWCC behaviour and mercury intrusion pore size distribution method (MIP) tests. The studies presented in this paper are useful to better understand the hydro-mechanical behaviour of compacted loess.

2 LABORATORY STUDY

2.1 *Soil type and sample preparation*

Soil sample collected from *Heifangtai* loess highland, Gansu Province, China is used in the present study. Fig.1 shows the particle size distribution curve determined by the Bettersize2000 laser particle analyser. The silt fraction (0.002-0.05mm) makes up 75% of total amount. The clay particle (< 0.002mm) accounts for 5.6%. The coefficient of uniformity is 8.5 and the coefficient of curvature is 1.4.

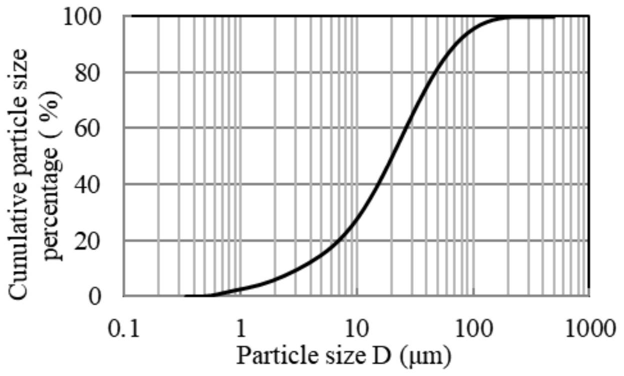

Fig. 1 Partical size distribution curve

Other parameters, including the bulk density, saturation condition and Atterberg limits are summarized in Table 1. The loess is classified as silty clay according to the Unified Soil Classification System (USCS: ASTM 2011).

Table 1. Summary of measured index properties of loess

Index property	
Bulk density	
Dry density (g/cm^3)	1.35
Natural density (g/cm^3)	1.47
Void ratio	0.99
Specific gravity	2.7
Different water contents	
Natural water content (%)	8.1
Saturated water content (%)	36.7
Air-dried water content (%)	3
Atterberg limits	
Plastic limit (%)	17
Liquid limit (%)	27
Plasticity index (%)	10
Unified soil classification system (ASTM)	Silty clay

Three steps were followed for preparing compacted specimens that were used for testing: (i) the soil was air-dried first and then passed through a 2mm aperture sieve; (ii) required amount of de-aired water was mixed with the prepared air-dried soil. Soil was mixed with water contents of 7%, 9%, 11%, 13%, 15%, 17%, 19% and 21%; (iii) the soil-water mixture was sealed inside plastic bags for 48 hours to ensure the moisture equalization and was again passed through a 2mm aperture sieve before use.

Standard compaction test was conducted using the prepared soil-water mixture following the ASTM protocols. It was observed that the measured water content of the compacted specimens were found to be a little lower than the targeted values because of the evaporation during the compaction process. Fig. 2 shows the compaction curve of the loess. The optimum water content and the maximum dry density of the soil were about 17.1% and 1.72g/cm^3, respectively. Three water contents were selected to study the influence of the compaction water content on the SWCC of compacted loess specimens; namely, 8%, 17% and 19%, which are respectively represent dry of optimum, optimum, and wet of optimum water contents. In the present study, 8% water content (i.e. dry of optimum) was chosen because the natural water content of the loess is 8.1%. Other properties of the three compacted specimens used in the following tests are summarized in Table 2.

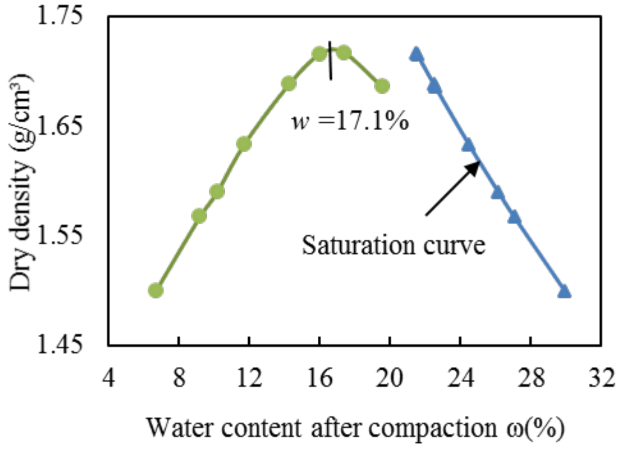

Fig. 2 Compaction curve for the loess

Table 2 Volumetric properties of compacted sanples

Soil specimens	
Dry of optimum (8%)	
Dry density(g/cm^3)	1.56～1.58
Void ratio	0.709～0.730
Saturated water content (%)	44.9～46.8
Optimum (17%)	
Dry density(g/cm^3)	1.70～1.72
Void ratio	0.588～0.578
Saturated water content (%)	33.8～34.6
Wet of optimum (19%)	
Dry density(g/cm^3)	1.67～1.68
Void ratio	0.607～0.616
Saturated water content (%)	36.1～36.9

2.2 *Filter paper measurements*

The cost-effective, simple, and reasonably accurate filter paper method that was developed by Gardner (1937) was used for measuring the SWCC (Houston et al.1994). Though the accuracy of the filter paper method was debated (Chandler et al. 1992), this technique was found to be suitable for measuring both high suction (Houston et al. 1994; Tsai & Petry 1995), and low suction measurements, for example, in the range of 20-300kPa (Power et al. 2008).

The Whatman No. 42 filter paper was employed to measure the wetting SWCC of compacted loess in the present study. Preliminary tests were first conducted to determine the time period for equilibration and to develop protocols following most of procedures of ASTM Standard D5298-03. The matric suctions measured in the preliminary test were compared with the values obtained by the pressure plate apparatus SWCC-150 manufactured by the GCTS Company. There is a good comparison between the suction values of compacted specimens using both the methods. The following test procedures were followed for determining soil suctions of compacted specimens:

(i) Compacted specimens of 20mm in height and 61.8mm in diameter were oven-dried for 8 hours.

(ii) These specimens were wetted by spraying water to achieve a series of targeted water content values, namely 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9%, 10%, 11%, 12%, 13%, 14%, 15%, 16%, 17%, 18%, 19%. The degree of saturation in the compacted specimens of dry of optimum, optimum and wet of optimum specimens for these water contents approximately varies from 7% to 90%. The specimens were wrapped with a thin plastic sheet and placed in a humidity controlled glass box for a period of 3 days to achieve moisture equilibration conditions.

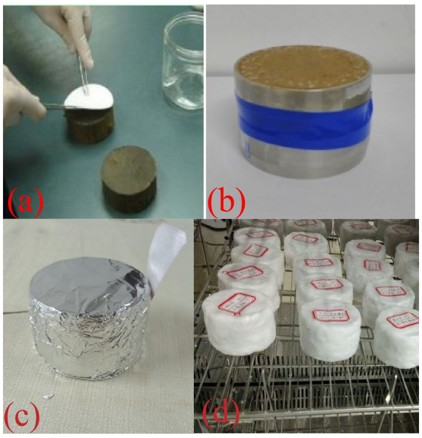

Fig. 3 Various steps followed in the filter paper method for measuring the SWCC

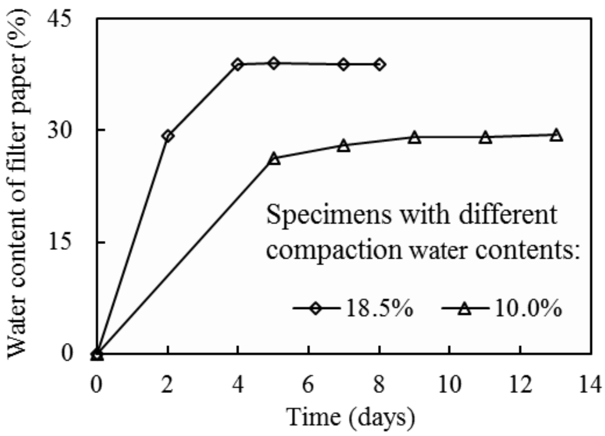

Fig. 4 Equilibrium time of the filter paper method from the preliminary tests.

(iii) The filter papers that were oven-dried for more than 12 hours after soaking in Formalin solution for 2 hours were used for measuring suction in the compacted soil specimens. Three circular pieces of filter paper 50mm in diameter were placed between the two identical soil specimens (see Fig. 3(a)). The diameter of central piece of filter paper is a little less than the other two such that it is free of contact from the sandwiched soil specimens. The two specimens were twined together by waterproof tape as shown in Fig. 3(b). The prepared specimen set-up was wrapped with a tin foil paper (see Fig. 3(c)) and then covered with a thin layer of wax coating such that a good seal can be achieved (see Fig. 3(d)). The sealed specimen was put into a thermal tank in which a constant temperature of 20°C was maintained for reducing the influence of evaporation and temperature. The technique used in the present study of wrapping the compacted specimens set with a tin foil paper is not an ASTM standards protocol. This is newly added in the present study based on the preliminary tests because wrapping of the specimens with tin foil paper reduces possible evaporation losses and ensures reproducible results.

(iv) The equilibrium time used in the present study was set for 12days based on preliminary tests results (see Fig. 4). The filter paper test assembly was opened carefully after 12 days equilibration period. The central piece of filter paper was carefully and quickly weighed with a high-precision balance (0.0001g) to obtain its water content. Finally, the suction was calculated using the calibration curve of the filter paper recommended by the ASTM. It needs to be mentioned that the filter paper method used herein is the contact filter paper method, for which the ASTM calibration curves can yield reliable matric suction values as suggested. However, for the non-contact filter paper method, the ASTM calibration equations should not be used as it will induce significant difference between the predicted values and actual values (Leong et al. 2002).

In total, 40 compacted soil specimens were used for measuring the wetting SWCC.

2.3 *Microstructure observations*

The microstructure of the compacted soil specimens was investigated by the mercury intrusion pore size distribution method (MIP).

The MIP method is based on the non-wetting property of mercury that has high surface tension. Mercury will not penetrate into pores due to capillary stresses. For this reason, mercury must be forced into the pores by the application of external pressure, which is inversely proportional to the size of the pores, see Eq. (1).

$$P = \frac{-4\gamma\cos\theta}{D} \tag{1}$$

where P is the external pressure, γ is the surface tension of mercury, θ is the contact angle between mercury and soil particle, D is the diameter of pores.

It can be seen that low pressure is needed to intrude mercury into large pores and a high pressure is required to force mercury into smaller size pores. The volume of mercury forced into soil under a certain pressure is the cumulative volume of pores with a diameter larger than the value defined by Eq. (1). Apparently, the more accurate is the pressure and volume measurements, the more accurate would be the resulting pore size data from MIP tests.

In the present study, soil specimens compacted at dry of optimum (8%), optimum (17%) and wet of optimum (19%) water contents were oven dried first before conducting the MIP tests. The PoreMaster-60 mercury injection apparatus manufactured by the American Quantachrome Company was used. The pore sizes that the apparatus can measure range from 3nm to 1000μm. The device is sensitive and can detect a change in mercury volume of 0.1μL

3 RESULTS

Fig. 5 summarizes the wetting SWCCs of loess compacted at dry of optimum (8%), optimum (17%) and wet of optimum (19%) water contents. Comparison of the three SWCC shows that (i) for the suction values higher than 1000kPa, the SWCCs of different initial compaction water contents tend to converge together; in other words, there is no influence of compaction water content on the SWCC behavior at high suctions; (ii) in the relatively low suction range (15-1000kPa), the shape of SWCC varies significantly from each other. The dry of optimum specimen has the steepest SWCC; (iii) SWCC curves tend to intersect at a suction value of 40kPa. The corresponding gravimetric water contents of the three specimens at the intersection point are respectively 15.3% (dry of optimum), 16.5% (optimum) and 16.3% (wet of optimum), which is close to the plastic limit of the loess (17.1%). These interesting results suggest that compacted soils with a water content equal to its plastic limit have a similar suction state regardless of its difference in the microstructure. More studies are required in this direction to better understand the significance of these results.

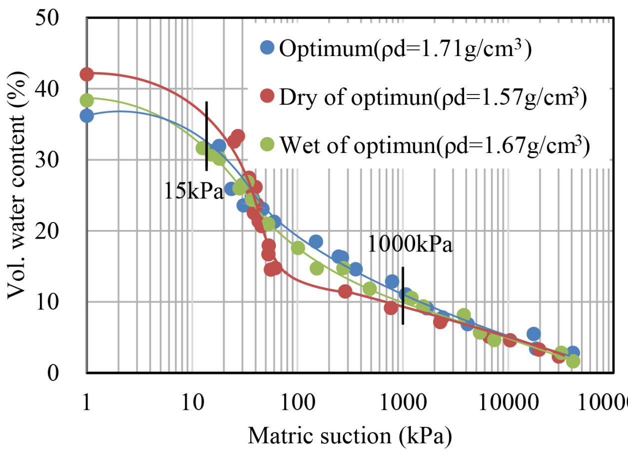

Fig. 5 SWCCs of loess specimens compacted at three different compaction water contents: optimum, dry of optimum and wet of optimum.

Fig. 6 illustrates the pore size distribution (PSD) curves of loess compacted at different water contents. The PSD curves vary significantly from each other, reflecting a significant difference in microstructure. For the soil compacted at the dry of optimum water content, the PSD displays a gentle bimodal characteristic with two main pore sizes, namely 3591nm and 90nm. For the soil compacted at the wet of optimum water content, the PSD only has one dominate pore size, which is1315nm after which the pore size density decreases with a decrease in the pore size. For the soil compacted at the optimum water content, the PSD is more uniform. As can be seen, the main pore size domain covers a large pore size range, which varies from 700nm to 6033nm.

It is of interest and also important to note that the PSD curves of the three specimens seem to converge together when the pore diameter is less than 180nm, meaning the micro-pores of loess specimens is not influenced by the compaction water content. Besides, the macro-pore in the soil compacted at dry of optimum is much larger in size compared to the soil specimens compacted at optimum and wet of optimum water contents.

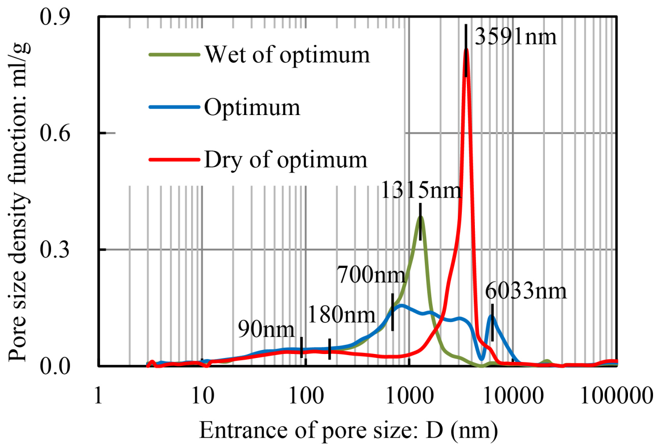

Fig. 6 Pore size distribution curves of loess specimens compacted at different water contents: optimum, dry of optimum and wet of optimum

4 DISCUSSION

It is well known that the SWCC behavior is closely linked to its PSD as the capillary stresses have a vital role in the soil-water interactions. The most widely used functions of SWCC, such as the van Genuchten (1980) function and Fredlund and Xing (1994) function, are derived based on this assumption. Recently, some studies were proposed for predicting the SWCC of a soil using the PSD curves (Simms & Yanful 2002; Munoz et al. 2012). To achieve this, the Laplace's equation is used to depict the relationship between the matric suction, the difference in air and water pressure at the interface of the fluid-solid system, and the diameter of the pore *D*, see Eq. (2).

$$u_a - u_w = \frac{4T\cos\theta}{D} \tag{2}$$

where u_a is the pore air pressure and u_w is the pore water pressure, T is the surface tension (at 20℃, T = 0.07525J/m^2), θ is the contact angle, which can be 0 for water-soil interface, D is the diameter of pores.

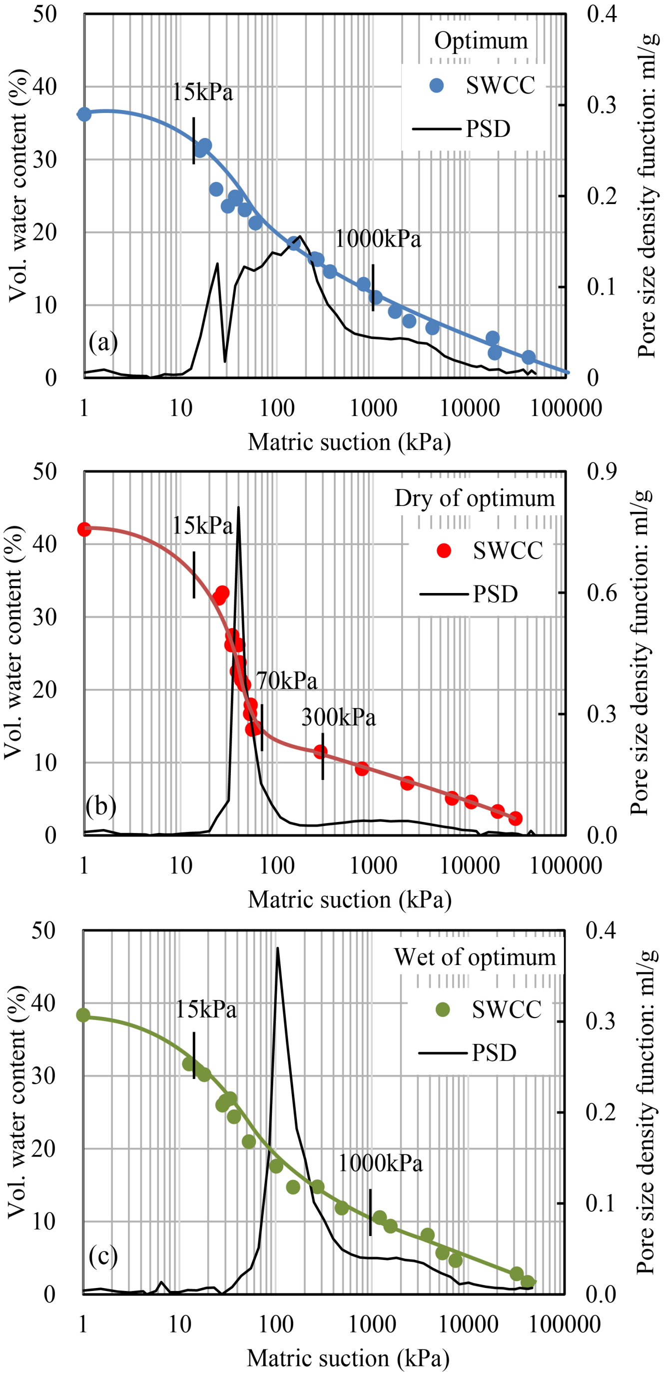

Fig. 7 Relationship between SWCC and PSD of loess compacter at different water contents: (a) at optimum water content (17%); (b) at dry of optimum water content (8%); (c) at wet of optimum water content (19%)

The relationship between SWCC and PSD can be expressed using Eq. (2) (see Fig. 7). The key information that can be derived from Fig.7 is the slope variation of the SWCC with the variation of pore size density. For the three different compacted loess specimens, when the pore size density increases, the slope of the SWCC at the corresponding matric suction range will also increase. For the soil compacted at optimum water content (Fig. 7(a)), the slope of the SWCC in the matric suction range 15-1000kPa is higher than that in 1000-10^{5}kPa. The corresponding pore size density is also higher. For the soil compacted at dry of optimum water content (Fig. 7(b)), the relationship between the SWCC and PSD is more obvious. In the suction range 15-75kPa, the slope of SWCC is significantly steeper than that in the suction range 300-10^{5}kPa, as the pore size density in this range is much higher. It is important to note that in the suction range 75-300kPa, there seems to exist a relatively flat stage in the SWCC curve as the pore size density is relatively low. Similar trends can also be derived from the measurements of the SWCC. For the loess compacted at the wet of optimum water content (Fig. 7(c)), the slope of SWCC curve in the suction range 15-1000kPa is higher than that in the range 1000-10^{5}kPa.

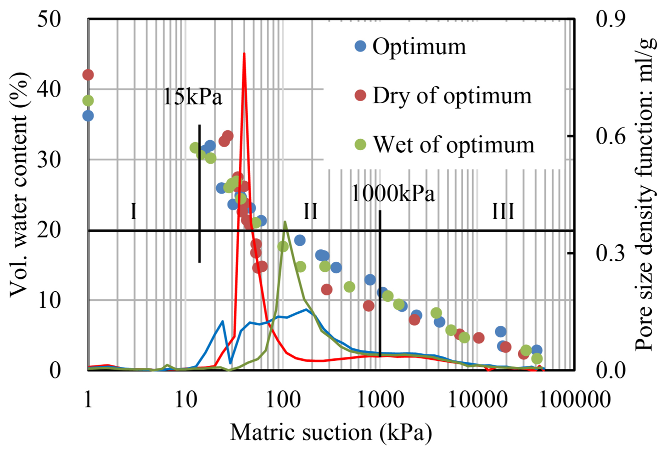

Fig. 8 Comparison of the SWCCs and PSDs of loess compacted at different water contents.

The similarity and differences in the SWCC curves for the three compacted specimens with different initial water contents can also be interpreted from the PSD curves. Fig. 8 compares the SWCC curves and the PSD curves. Based on the differences of the three specimens, the PSD and SWCC curves can be divided into three sections: namely, section I, section II and section III. The section I corresponds to a matric suction range 0-15kPa. The section II corresponds to the 15-1000kPa matric suction range. The section III corresponds to suction range from 1000kPa to 10^{5}kPa. There is limited data measured in section I because it is difficult to measure low suction values using the filter paper method. In section II, the PSD curves vary from each other greatly. The pore size density of dry of optimum specimens is more predominant than that of wet of optimum and optimum. Correspondingly, the slope of dry optimum is steepest. In section III, the PSD curves tends to converge together for all the specimens. Similar trends in behavior were also observed from the SWCC curves measurements.

The above analysis suggests that there is a high dependence of water retention properties of soil on their pore size distribution characteristics.

5 CONCLUSIONS

The initial compaction water content significantly influences the microstructure and water retention properties of loess soil. Three water contents; namely, dry of optimum, optimum, and wet of optimum, were chosen to study the effect of microstructure on the SWCC behavior. Filter paper method as well as the MIP test were conducted on the soil specimens compacted at these different water contents. The following conclusions were derived from the present study:

(1) The SWCC curves of loess compacted at three water contents are significantly different in low suction but exhibit similar characteristics in high suction range. In low suction range, the loess compacted at dry of optimum water content has the steepest SWCC.

(2) The PSD curves highlight significant differences in their macro-pores for the three compacted specimens; however, micro-pores characteristics are approximately the same. The PSD of loess compacted at dry of optimum shows a gentle bimodal characteristics with two main pore sizes. The soil compacted at optimum and wet of optimum water content only have one main pore size. The main pore size of the dry of optimum is significantly larger than that of wet of optimum. The PSD of optimum is most uniform with the main pore size covering a wide range than the other two compacted loess specimens.

(3) The similarities and differences in the SWCCs of the three compacted loess specimens can also be well interpreted from the PSD curves. It can be observed from the results, the larger the pore size density, the steeper the slope of SWCC.

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