Swelling Research of Expansive Soil Under Drying-Wetting Cycles: A NMR Method

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Abstract. The main purpose of this study is to examine the influence of drying-wetting cycles on the swelling of disturbed expansive soil at the micro-scale. Swelling curve - the relationship between swelling displacement and water-absorbing time - is measured based on specimens that experienced 0-4 drying-wetting cycles. Assisted by Nuclear Magnetic Resonance (NMR), the stage characteristic and mechanism influencing swelling curve are analyzed from a pore-change perspective. Specimens that experienced 1-4 cycles show a higher swelling rate when compared with the specimens without drying-wetting cycles; the swelling rates of each swelling curve are found to decrease with an increasing water-absorbing time. These swelling curves are divided into rapid-swelling stage, slow-swelling stage, and slow-stable stage, where three straight lines are used to fit these stages to each curve. The swelling displacement of the specimen increases after the first cycle, whereas it decreases gradually during the following cycles. Changes of pore structure at each stage are considered to be the main factor affecting the swelling rate during the saturating process. Some fine particles and water-soluble cements are lost after multiple cycles, and some smaller pores are converted into larger pores, resulting in an increase in volume and a decrease of swelling displacement. Moreover, the increase of larger pores and the suction difference after various cycles are important factors leading to the difference of the swelling curve and the swelling displacement.

Keywords: drying-wetting cycles, expansive soil, NMR test, pore change, suction.

1. Introduction

Expansive soil, a special clay with high expansibility, fissures, and overconsolidation, is found in more than 40 countries such as China, the United States, and Canada (Laureano & John, 2017). Because of its constitutive hydrophilic minerals, for example, montmorillonite, illite, and kaolinite, expansive soil undergoes volumetric swelling or shrinkage with adsorption or desorption of water; moreover, these displacement changes based on water content have a certain repeatability (Osman, 2018). Swelling displacement is considered to be a main expansive soil disaster causing the most serious damage (Khazaei & Moayeddi, 2019). The swelling ratio is approximately predicted by the initial water content, the plastic index, and the initial dry density, as these factors are considered to be important factors affecting the swelling characteristics in previous studies (Villar & Lloret, 2008; Signes *et al.*, 2016; Elbadry, 2017). Furthermore, factors such as mineral composition (Lin & Cerato, 2012), matric suction (Fredlund, 1983), and pH value have also been proved to have a good linear relationship with the swelling ratio; however, the displacement of expansive soil cannot be accurately calculated by the general unsaturated soil model due to its change of stress state and softening characteristics (Qi & Vanapalli, 2016). In addition, different stages of the swelling curve

have their own particularity rather than a linear relationship between swelling displacement and water-absorbing time (Xiao *et al.*, 2005), whose mechanism is not clear yet.

On the other hand, expansive soil in shallow layers inevitably experiences drying-wetting cycles because of rainfall and evaporation. After repeated drying-wetting, the attenuation of modulus (Li *et al.*, 2013), penetration resistance (Wang *et al.*, 2016), and shear strength (Raja & Thyagaraj, 2019) are observed, which seriously threatens the buildings founded on it (Jablonowski *et al.*, 2012). Jablonowski *et al.* (2012) suggested that the drying-wetting cycle promotes the enrichment of inorganic materials in the soil, forming cementation with certain cohesion whose dilatancy is one of the factors affecting the expansive potential of soil (Mehta & Sachan, 2017). After the repeated action of “in and out” of rainwater, how the swelling characteristic of expansive soil changes is also a problem to be considered in preventing engineering disasters. Similar to the drying-wetting cycle, the change of pore structure is another important factor related to the difference of swelling characteristics (Tahasildar & Rao, 2016). Mercury intrusion porosimetry, a traditional method for pore structure testing, causes error when operated at a high pressure (Al-daoood *et al.*, 2014). By being non-destructive, convenient, and keeping the pore intact, NMR is becoming more and

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Submitted on July 20, 2018; Final Acceptance on February 13, 2020; Discussion open until August 31, 2020.

DOI: 10.28927/SR.431021

more important in the study of geotechnical works (Kleinberg *et al.*, 2003).

This study focuses on exploring the intrinsic relationship between swelling displacement and changes of pore structure. Based on the previous researches, the swelling characteristics of disturbed expansive soil under various drying-wetting cycles are investigated in this study; NMR technology is then used to discuss the changes of pore structure of expansive soil with the variation of water content and the accumulating cycles. The swelling rate of each stage and the total swelling displacement are tested. Moreover, the soil-water characteristic curve (SWCC) after various drying-wetting cycles is also discussed because of its influence on the swelling characteristics.

2. Material and Methods

2.1. Basic properties of the soil used

Expansive soil used in this study is from depths between 2.0 m and 4.0 m under the subsurface of Nanning City, China. The soil was typical gray expansive soil with fissures, plasticity, strong stickiness, high water content, a small quantity of unweathered rock, and iron-manganese concretions. This soil, whose basic parameters and minerals are listed in Table 1, was classified as weak expansive soil according to relevant standards (GB 50112, 2013; ISO 17892-4, 2016; ISO 17892-12, 2018).

2.2. Specimen preparation

Compared with undisturbed soil, disturbed soil is without natural composition and cementation, which causes greater swelling displacement that threatens the buildings when meeting water (Frías-Guzmán & Hernández-Marín, 2019). Therefore, disturbed soil was used in this study. To achieve an equalized water content, wet soil with a water content of 12.0 % was firstly prepared and maintained in a sealed bag for more than 48 h before performing the tests. To eliminate the impact of iron on the magnetic field, a polytetrafluoroethylene-cutting sample ring (Φ 40 mm $\times$ 60 mm) was used instead of a conventional steel one. Subsequently, using the static pressure method, specimens with a diameter of 40.0 mm and a height of 40.0 mm were compacted at optimum moisture content (OMC), as the soil of subgrade and foundation engineering is usually compacted at OMC. Finally, three specimens

with a density difference less than 0.02 g/cm³ were divided into one group for the swelling test.

2.3. Swelling test

The swelling test was performed by a lever-consolidometer, where the swelling displacement was recorded by a dial indicator (range: 10.0 mm, accuracy: 0.01 mm). To avoid the specimen going beyond the top of the cutting sample ring during the swelling process, the selected specimen was removed into a cutting sample ring specially designed with a diameter of 40.0 mm and a height of 60.0 mm. The specimen together with the polytetrafluoroethylene cutting sample ring were placed into the consolidometer by using the testing method recommended by standards (JTG E40, 2007; ISO 17892-7, 2017), and the reading of the dial indicator was then recorded. Subsequently, distilled water was added to cover the bottom surface of the specimen to provide a free water-absorbing process. During the first 20 min, the reading of the dial indicator was recorded every 5 min while it was recorded every 10 min in the rest of the first 2 h, and then the recording time was changed according to the swelling rate of the specimen. When the value difference between the two readings in 2 h was less than 0.01 mm, the swelling displacement was considered to be stable. If the reading difference of them was less than 0.1 mm, the average value of three specimens was recorded as the vertical swelling displacement; otherwise, additional parallel tests were needed. Following the swelling process, the saturated specimen was dehydrated to a scheduled weight in a humidity-controlled chamber (range: from -20 to +120 °C, accuracy: $\pm$ 0.05 °C) at a temperature of 40 °C (here, the water content was approximately 5 %). At this point, a drying-wetting cycle was completed. The follow-up process of swelling and drying-wetting cycle is similar, where the repetition is unwanted.

2.4. NMR testing instrument and procedure

The testing instrument used in this work is a MiniMR-60 made in China. The magnetic field intensity of the instrument is 0.52 T, the temperature of the magnet is maintained at 32 ± 0.01 °C, and the effective testing area of the testing tube is Φ 60 mm $\times$ 60 mm. The testing procedure of this study is as follows: (1) Preparing soil specimens (Φ 40 mm $\times$ 40 mm); (2) Different drying-wetting cycles were completed in the polytetrafluoroethylene cutting sam-

Table 1 - Selected geotechnical properties of the soil obtained by testing.

w_L (%)	w_p (%)	I_p (%)	δ_{ef} (%)	G_s	P_e (kPa)	Mineral composition (%)			
						Gibbsite	Kaolinite	Illite	Quartz
45.30	22.10	23.20	57.00	2.72	169.00	6.44	23.1	25.46	45.00

Note: w_L is liquid limit; w_p is plastic limit; I_p is plastic index; δ_{ef} is free swelling ratio; G_s is specific gravity of soil particle; P_e is swelling force.

ple rings, except for the specimen of cycle 0; (3) All specimens were saturated with distilled water for 48 h; (4) Performing NMR relaxation measurement on saturated specimens experienced various cycles; (5) Collection and analysis of testing data.

3 Result Analysis and Discussion

3.1. Swelling curves under different cycles

To better discuss the influence of drying-wetting cycles on swelling characteristics, swelling curves of samples subjected to between 0 to 4 drying-wetting cycles are listed in Fig. 1, where the X axis is water absorbing time and the Y axis is vertical-swelling displacement. As the focus of this study is the swelling characteristic of soil affected by various drying-wetting cycles, the values observed within the N^{th} cycle disregarded the displacements of the previous cycle. Vertical displacements of the N^{th} cycle start from the same initial condition, since these displacements are net displacements based on a dried specimen that experienced $(N - 1)^{\text{th}}$ cycles.

3.2. Trend analysis of swelling curves

Cumulative vertical displacement, in this study, is equal to the volume swelling of the specimen since the lateral swelling is restricted by the cutting sample ring. Having similar trend, swelling curves under various cycles rapidly grow with the increase of water-absorbing time, and then slow down and achieve a stable state (Fig. 1). Before cycling, a lowest swelling rate is observed, in which 230 min are consumed to finish ninety percent of the swelling displacement. From the 1st to the 4th cycle, however, only 100 min are consumed to achieve the same quantity of swelling displacement, cutting off about 130 min. This phenomenon can be explained by the changes of pore structure. During the absorbing process of cycle 0, the specimen is compacted with a low water content, the diameter and distribution of pores are approximately uniform, where water

is forced to rise evenly and slowly by capillarity. After the larger pores are filled with water and are swelled, water is allowed to enter smaller pores to complete the remaining 10 % of the swelling displacement. A dehydration process is experienced during the drying-wetting cycle, causing a smaller contact angle between water and particles than that caused in the wetting process (Kholodov *et al.*, 2015). These changes reduce the distance between particles and shrink the pores. Moreover, some fine particles are moved by the water to a smaller pore and stopped to form a pore throat. Therefore, when the specimen encounters water again, the water rises rapidly along the finer holes, completing more than 90 % of the expansion in two hours because of the larger suction caused by smaller capillary cross section.

As shown in Fig. 1, the relationship between the swelling displacement and water-absorbing time cannot be accurately fitted by one curve alone because of its differences between stages, where the hyperbola (Xiao *et al.*, 2005), a combination of curve, and straight line are used to fit these relationships. Considering the water absorbing characteristics of each swelling stage, the example data of cycle 3 are divided into 3 stages, namely, 0-30 min, 30-90 min, and beyond 90 min, and then three straight lines are used to approximate each stage. Figure 2 shows the fitting curve with a good conformance and high correlation coefficients (all above 0.9); the maximum error between observed displacement and the fitted displacement is about 0.1 mm; the swelling rate, the angular coefficient in the equation of the fitted lines, decreases in turn along the three stages.

3.3. Swelling rate analysis of each stage

Noticed from Fig. 2, a significant difference in the swelling rate is observed among the three stages, namely the rapid-swelling stage (0-30 min), slow-swelling stage (30-90 min), and slow-stable stage (beyond 90 min). For a clearer understanding of the influence of drying-wetting

Figure 1 - Relationship between vertical displacement and time under different cycles.

Figure 2 - Comparison between the fitted and observed data.

cycles on swelling rate, these swelling rates experienced in different cycles are listed in Fig. 3, where the X axis represents the swelling stage and the Y axis is the gradient of the fitting line (Fig. 2) at each swelling stage.

Figure 3 shows that the swelling rates of the second and the third stage are close to each other, while a large gap (about 300 %) among first stages is observed. For the specimens that experienced no drying-wetting cycles, the difference of swelling rate at each stage is not so eye-catching (about 60 %). For the specimens that experienced 1-4 cycles, a significant difference (about 290 %-370 %) of swelling rate at each stage is revealed, where the largest swelling rate at stage one is about 4 times that of stage two. The relationship between swelling rate and water absorbing stage under 1-4 cycles can be approximated by a logarithm curve (Eq. 1), where k is the swelling rate, x represents the water absorbing stage (value 1, 2, 3).

$$k = -0.05581 \ln(x) + 0.0584 \quad (1)$$

The authors believe that the water absorption and swelling is a process where pores are gradually filled with water, which is also a process of gradual transition from the unsaturated state to saturated state. Therefore, an unsaturated part always remains before the entire saturation is reached because of the gradual spreading of water from the bottom to the top of the specimen. Based on the difference of saturating process, the unsaturated soil is acceptably divided into three stages, *i.e.*, the water sealing stage, the both opening stage, and the gas sealing stage (Yu & Chen, 1965). In the first swelling stage with a low degree of saturation, the gas in pores is connected only, and the water is separated by gas and soil particles. At this point, a water film is formed due to the migration of capillary water, swelling rapidly the particles (Gonen *et al.*, 2015). The gas in pores is compressed and driven out of the specimen as the pore is contracted, so that water rapidly flows into the inner part of the specimen and the outside water quickly enters the pores. At this stage, the specimen has a higher

swelling rate corresponding to the first stage of the swelling curve (Fig. 2). With the gradual increase of the saturation degree, the both opening stage it reached, in which both water and gas are connected and with their own channels to soil particles. Here, the swelling displacement of the soil particles contacting with water is basically completed, reducing the gas in pores, blocking some local pores, and causing a need of larger pressure to expel gas out. Accordingly, the reduced swelling rate at this stage shows a similar characteristic to the second stage in Fig. 2. After the swelling curve grows to the third stage, the gas sealing stage is reached via increasing the water in the specimen, gas in pores are surrounded and divided into bubbles. The water in the pores, in this case, is connected although few remaining bubbles are not, and the stability of swelling is coming.

3.4. Swelling under different drying-wetting cycles

After different cycles of drying and wetting, the total swelling displacement (vertical displacement) shown in Fig. 4 is obviously different. The swelling displacement of the specimen increases by about 20 % after the first cycle, and it then decreases with the accumulating of cycle number. The radial shrinkage of the specimen is found to be greater than the vertical shrinkage during the drying process due to the larger radial size of the specimen, which causes vertical compression of the soil particles. Therefore, after a drying process, the height of the specimen is greater than 20.0 mm (initial height), and the radial size of the specimen is less than 61.8 mm. Based on previous studies, the authors think that during the process of drying, pores are contracted after the water is discharged, and contraction stress on the pore is applied because of the surface tension of water, which intensifies the shrinkage of the pore (Dadashev & Dzhambulatov, 2015). Moreover, since some non-recoverable displacement is destined to occur in the drying process, the vertical swelling capacity of the specimen is greater than that of the radial after the first cycle

Figure 3 - Swelling rate at each stage under different cycles.

Figure 4 - Swelling displacement under various drying-wetting cycles.

(Komine & Ogata, 1994; Steiner, 1993). After the 2-4 cycles, however, the swelling displacement decreases with the accumulating of drying-wetting cycles, because the cycles all carried out on a same basis of dehydration and contraction, and because of the gradual accumulation of non-recoverable displacement.

The fissure in the specimen is believed to also be a reason for the differential swelling displacement. The SEM image of the specimen after one cycle is shown in Fig. 5a, while a similar image after four cycles is displayed in Fig. 5b. Soil particles after cycle 1 are closely contacted as the specimen is in a shrinking state (Fig. 5a). After the 4th cycle, nevertheless, obvious fissures are observed, and most of them are developed along the vertical direction (Fig. 5b). The force hindering the lateral displacement is decreased because of the loss of strength between particles on the fissure surface. Consequently, the specimen is further broken with the increasing number of drying and wetting cycles, weakening the swelling ability gradually.

4. Nuclear Magnetic Resonance Test

The NMR refers to the resonant transition nucleus between energy levels under an external magnetic field. Under such a field, the number of protons and the duration (T_2) of the spin axis of protons restored to initial equilibrium after being deflected are obtained (Schaumann, 2011; Conte *et al.*, 2017). This quantity can be represented as an area distribution of the T_2 curve, from which the pore size and the ratios of different sizes in the soil can be calculated, allowing calculation of the water content. When a pore is spherical, the duration (T_2) is related to the pore radius by Eq. 2, where ρ_2 is the surface duration strength determined by the physical and chemical properties of the particle surface (Coates *et al.*, 1999), R represents the pore radius, and $(S/V)_{pore}$ is the ratio of the pore surface area to the volume of fluid inside. As a fast, nondestructive testing technique, the NMR technique is widely used in the fields of medicine, well water exploration, and oil exploration, for example (Malz & Jancke, 2005; Pauli *et al.*, 2012). In this study, the

proton was used to explore the effect of the water content and drying-wetting cycles on the pores.

$$\frac{1}{T_2} = \rho_2^2 \left(\frac{S}{V} \right)_{pore} = \rho_2^2 \frac{3}{R} \quad (2)$$

4.1. Analysis of T_2 curves with different water content

Specimens (Φ 40 mm $\times$ 40 mm) in this section were free to swell vertically. After a quantity of distilled water was dropped into, the specimens were maintained in a sealed bag for more than 48 h to obtain a uniform water content. Experiments on 7 specimens with water contents of 10 %-28 % were completed using the method in section 2.4, and the T_2 curves were compared and analyzed, as shown in Fig. 6.

The NMR relaxation time related to the pore distribution is proportional to the pore radius of the specimens. Figure 6a shows that only one peak is observed in the T_2 curves with different water contents (from 10 % to 28 %), and these peaks are concentrated between 0.75 ms-2.3 ms. A uniform pore size was obtained by the static pressure method because the pore size of the specimen is mainly distributed between 0.10 ms-11.02 ms, and micropores (0.01 ms-0.1 ms) and macropores ($\geq$ 11.02 ms) are seldom found. The movement of the T_2 peaks to the right proved that some smaller pores gradually transform into larger pores to increase the proportion of larger pores in the specimen.

The integral area of the T_2 curve represents the total quantity of pores in the specimen (Fig. 6a), and a non-negligible difference among these areas was observed for multiple water content values (Chukov *et al.*, 2015). When the water content increases from 19 % to 22 %, the volume of water in the pore increases greatly. However, only a small increase in the water volume is observed when the moisture content is within 10 %-19 % and within 22 %-28 %. This can be explained by the local expansion in the soil swelling process. After the entry of water, the crystal layer as well as the soil particle swells, the pores are

Figure 5 - SEM images after (a) cycle 1, (b) 4 cycles.

Figure 6 - T_2 curves affected by water content in saturating process: (a) T_2 curves with water content from 10 % to 28 %, (b) Areas of the T_2 curves under different water content.

squeezed, and larger suction and expansion rate are observed. For continuous water entry, the maximum water film on the particle surface is achieved, and the swelling of the soil tends to stability.

The integral area of the T_2 curve relative to the X axis is listed in Fig. 6b, which shows the variation in the integral area of the T_2 curve with varying water absorption. The integral area of the T_2 curve and the water content can be represented by a linear function ($y = 364.51x - 2921.3$), and the correlation coefficient is $R^2 = 0.9787$. The integral area of the T_2 curve is very sensitive to the change in the water content because it increases by approximately 11.6 times for a small change (18 %) in water content, and the water absorption is also directly related to the swelling characteristics of expansive soil. Therefore, the NMR can be used as an important method to study the displacement characteristics of expansive soil.

4.2. Analysis of T_2 curves under different cycles

The T_2 curves that experienced various cycles have two peaks (Fig. 7a). These former peaks are larger but indicate a shorter relaxation time, and the peak value of the latter peaks having a larger relaxation time is smaller. The

relaxation time is proportional to the pore radius of the specimen, and the quantity of voids of a size less than this radius is represented by the size of the peak (Conte *et al.*, 2017). The integral area of the T_2 curve represents the total quantity of pores in the specimen. The smaller pores are represented by the integral area of the first peak, whereas the larger pores are characterized by the integral area of the second peak.

Figure 7a shows that the peaks of the T_2 curves do not change significantly with accumulating drying-wetting cycles, but the T_2 curves tend to increase as the cycle number increases, particularly the later peaks. In conclusion, the larger pores (5 ms-100 ms) are significantly affected by drying-wetting cycles, whereas smaller pores (0.01 ms-5 ms) are insensitive to the change in cycles. This may be due to the difference in pore structure caused by specimen particle composition, which results in the distinction of “S/V” inside the specimen, and ultimately leads to diverse relaxation time. The relaxation is weakened with larger aperture, and the amplitude of the T_2 curve is smaller (Jaeger *et al.*, 2006). On the contrary, the smaller aperture enhanced the relaxation, and a larger amplitude of the T_2 curve is observed. Each integral area is shown in Fig. 7b, where A

Figure 7 - T_2 curves under different number of drying-wetting cycle: (a) T_2 curves under 0-4 cycles, (b) Integral areas of T_2 curves, where A represents the total quantity of pores, B is the integral area of larger pores, and C is the integral area of smaller pores.

represents the total quantity of pores, B is the integral area of larger pores (the later peaks), and C is the integral area of smaller pores (the former peaks). Both the total integral area and the integral area of larger pores are found to increase with the accumulation of drying-wetting cycles. A slight fluctuation (about 5.3 %) of the integral area of smaller pores is discovered after the 4th cycle; whereas, the integral area of the larger pores increased by about 35 %, which is close to the increase of the total integral area. In short, the total volume and the average radius of the pores are significantly increased with the growing of cycle numbers. These results can be explained by the structural effect caused by the drying-wetting cycles. Water quickly enters the specimens along the formed fissures, an expansive force is produced on the fissures. Therefore, some small pores swell into larger pores and new small pores are formed at the same time. As indicated by curve B in Fig. 7b, the increasing quantity of larger pores is associated with additional cycles. The change between the integral area of larger pores and the cycle number is expressed by Eq. 3, where S is the integral area of larger pores and N represents the number of cycles; the correlation coefficient is $R^2 = 0.9464$.

$$S = 245.41N + 2712.7 \quad (3)$$

Generally, there are two reasons for the change in pore structure of soil, one is the change of the position and the contact state between soil particles (Shein *et al.*, 2017), and the dissolving of the cementation formed by water-soluble salt is the other factor. During the drying-wetting cycles, the physical and chemical effects of the soil-water system accelerate the dissolving of cementation, smoothing or expanding the pores. Accordingly, the pore structure of the soil is changed. A specimen without drying-wetting cycles has smaller pore volume, and the proportion of smaller pores and larger pores is relatively close (Fig. 7b). At this point, the water holding capacity of unsaturated soil is limited with a uniform pore radius, and a relatively gentle swelling rate is observed (Fig. 1). After various cycles, however, the small pore that provides higher water holding capacity is almost unchanged while the larger pore increases, which increases the contact area between the specimen and water. Therefore, the swelling rate of the specimen obviously increases after experiencing drying-wetting cycles (Fig. 1). When it comes to the change law of swelling displacement, the authors think that a greater electrostatic force is found on the surface of the fractured soil divided by fissures in the cycling process, increasing the total swelling displacement of the specimen (Rojvoranun *et al.*, 2012). After some cementation and fine particles being taken away by the repeated streaming of water, the swelling capacity of the specimen is reduced.

4.3. Microstructure analysis in drying-wetting cycle

During the drying-wetting cycles, the pores of expansive soil can be divided into two types: the pores between agglomerates and the pores inside agglomerates (Pulat *et al.*, 2014). After the first cycle, smaller solid particles form a larger particle (agglomerate) because of flocculation. The pores between such agglomerates are larger than those inside the agglomerates, achieving a skeleton-gap structure as indicated in the right part of Fig. 8. Weaker polymers are observed between such agglomerates, where smaller particles are easier to be taken away by water. Figure 8 shows the process how water flows into and out during the drying-wetting cycle, gradually taking away smaller particles and water-soluble cementation in soil. Subsequently, pores between particles increase, the ratio of macropores increases, and the total swelling displacement decreases.

4.4. Suction effect on swelling

The matric suction, an important factor forcing the water migration, changes a lot after different drying-wetting cycles (Espitia *et al.*, 2019). To further explore the relationship between cycle number and the swelling characteristic, soil water characteristic curves (SWCC) under different cycles were tested via the saturated salt solution method where the specimens that experienced different cycles were dehydrated in a humidity-controlled chamber. These SWCCs at high pressure were then determined following the drying path. The saturated salt solution and the corresponding suction value used in this test are shown in Table 2. The water content of the specimen is changed because of the difference of pressure produced by various solutions. The Young-Laplace formula and Kelvin formula (Gane *et al.*, 2009) were used to deduce the measured data of water content vs. matric suction, as shown in Fig. 9.

The water content gradually decreases with an accumulating suction, and the influence of drying-wetting cycles on suction mainly occurs at the higher water content (above 3 %). A weak influence is observed when the water content is lower than 3 %; subsequently, the SWCCs tend to be stable and to be close to each other (Zhang *et al.*, 2014). A lower water content provides a larger suction causing a greater swelling rate of specimen. Then the suction attenuates with the increase of water content, and a lower swelling rate is observed (Fig. 2). In conclusion, as a result of the suction caused by the drying and wetting cycle.

Figure 8 - Microstructure of expansive soil in drying-wetting cycle.

Table 2 - Saturated salt solution and corresponding suction (25 °C).

Saturated salt solution	HR (%)	Matric suction (MPa)
LiBr	6.37	371.79
LiClH ₂ O	11.30	294.40
CH ₃ COOK	22.51	201.35
MgCl ₂ ·6H ₂ O	32.78	150.60
K ₂ CO ₃	43.16	113.45
NaBr	57.57	74.55
KI	68.86	50.38
NaCl	75.29	38.32
KCL	84.34	22.99
K ₂ SO ₄	97.60	3.28

Figure 9 - Soil water characteristic curves by saturated salt solution method.

cles, especially at the higher water content, the divergence of swelling rate and the swelling displacement is smaller at the first swelling stage, while it is larger at the second and the third stages (Fig. 2).

5. Conclusion

This study characterized the influence of drying and wetting cycles on the swelling characteristics and the swelling displacement of expansive soil. Drawing support from the T_2 curves measured by the NMR technique, changes of pore structure under different water content and under various drying-wetting cycles were analyzed. Moreover, affecting the swelling characteristic, the SWCCs after different cycles were also discussed. The following conclusions can be drawn.

- 1) A similar trend of swelling characteristics and swelling displacement are found among specimens that experienced different cycles. The studied expansive soil, completing 90 % of the total swelling displacement in

a short time, is sensitive to water, and the swelling rate (swelling speed) slows down with the increase of water-absorbing time.

- 2) The swelling rate of each stage is significantly different, which is roughly divided into the rapid-swelling stage, slow-swelling stage, and slow-stable stage. Fitted by three straight lines, the swelling curves under different cycles show a reasonable fitting error (less than 0.1 mm).
- 3) Based on NMR tests, a good linear relationship between pore volume and water content is observed. The change of pore structure during the drying-wetting process is believed to be the key inducer leading to the difference of the swelling rate. The drying-wetting cycle mainly increases the volume of larger pores, while showing a less influence on the smaller. Some smaller pores are converted into larger pores because of the loss of fine particles and water-soluble cement.
- 4) The three-stage difference of unsaturated soil, namely, the water sealing, both opening, and gas sealing is a key reason related to the difference of the swelling rate. In addition, fragmentation and the suction performance after experiencing multiple cycles are also associated with the swelling characteristic.

Acknowledgments

Financial support for this study was provided by the National Natural Science Foundation of China (Grant no. 51169005). The support is greatly appreciated. The authors also gratefully acknowledge the Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering for the help on tests.

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