Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 3052932, 8 pages
https://doi.org/10.1155/2019/3052932

Research Article

Effect of Axial Pressure on Lime-Treated Expansive Soil Subjected to Wetting and Drying Cycles

Chuxuan Tang,[1,2] Zheng Lu ,[1] and Hailin Yao[1]

[1]*State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China*
[2]*University of Chinese Academy of Sciences, Beijing 100049, China*

Correspondence should be addressed to Zheng Lu; lzwhrsm@163.com

Received 18 July 2019; Revised 19 September 2019; Accepted 7 November 2019; Published 2 December 2019

Academic Editor: Annan Zhou

The impact of seasonal moisture variation on subgrade soil, including lime-treated expansive soil, has been investigated in many studies. However, when performing wetting and drying cycles, the effect of stress, which decides the behavior and mechanical properties of soil, is usually ignored. In this paper, the effect of axial surcharge pressure on the deformation and resilient modulus of lime-treated expansive soil subjected to wetting and drying cycles was investigated. A self-made apparatus was chosen to apply axial surcharge pressure and precisely control the variation of moisture content. The lime-treated specimens were placed in the self-made apparatus and then subjected to wetting and drying cycles under three different surcharge pressures. The results show that the axial surcharge pressure has a significant influence on the development of axial strain and resilient modulus. In particular, larger surcharge pressure induces accumulate irreversible shrinkage, whereas lower surcharge pressure tends to lead to irreversible swelling. On the contrary, the larger surcharge pressure leads to higher resilient modulus of the tested specimen after wetting and drying cycles.

1. Introduction

The complexity and variety of natural environment are important factors that affect the long-term service performance of highway subgrade. The moisture content of subgrade soil changes seasonally because of the effects of environmental variations, including rainfall infiltration and evaporation [1, 2]. Untreated expansive soil exhibits obvious volume change due to the variation of moisture content, causing severe damage to the structure of pavement [3]. Lime is wildly used in treating expansive soil [4]. The treatment by lime decreases swelling potential, improves workability, and enhances strength of expansive soil [5, 6]. However, after subjected to wetting and drying cycles caused by environmental change, the positive effect of lime stabilization is weakened. To evaluate the negative effect, former researchers have performed experiments on the static mechanical properties, including volumetric strain [7], swelling potential and swelling pressure [8, 9], and strength [10]. For a pavement structure, the resilient modulus presents the stiffness of subgrade to withstand repeated traffic load. Bhuvaneshwari et al. [11] compared the resilient modulus of untreated and lime-treated expansive soil based on different lime dosages and curing periods. Drumm et al. [12] and Naji [13] discussed the relationship between moisture content and resilient modulus of lime-treated expansive soil. Elkady et al. [14] studied the resilient modulus of lime-treated expansive soil along the wetting and drying paths in forms of changes of suction, and a hysteresis phenomenon was found. To our knowledge, rare experiments have been made to understand the effect of wetting and drying cycles on the resilient modulus of lime-treated expansive soil.

Furthermore, when subjected to variations of natural environment, pressure induced by upper road structure and soil has a significant effect on the behavior of subgrade soil [15, 16]. However, in most of the research for wetting and drying cycles, the effect of axial pressure is ignored. It is important to consider the effect of axial pressure because axial pressure presents the spatial location. Even if the whole of subgrade goes through the same wetting and drying cycles, the different axial pressure will lead to diverse behavior. This means the different parts of the subgrade may be impact in different degrees when subjected to the same cycles. Estabragh et al. [17] studied the effect of wetting and drying cycles on the behavior of an expansive soil using a modified oedometer. It was found that the surcharge pressure has a great influence on the axial deformation during wetting and drying cycles. Though the apparatus used can apply different surcharge pressures, only one path of wetting and drying cycle can be applied, which is full swelling and shrinkage. Other devices and methods [8, 18, 19] are not able to simultaneously meet the demands of quantitative controlling of moisture content and applying surcharge pressures. Thus, we have designed an apparatus that can meet the two major demands and is also convenient to move and measure (details are shown in Section 2.2).

The main purpose of this study is to assess the impact of axial surcharge pressure on the deformation and resilient modulus of lime-treated expansive soil subjected to wetting and drying cycles. The expansive soil was treated by 5% lime and then placed in an airtight container for 7 days, during which the moisture content was adjusted at least 3 times. The material was compacted on the degree of 94% at optimum moisture content and then placed in the self-made apparatus subjected to wetting and drying cycles comprised between 14.5% and 18.5% under three different surcharge pressures. The maximum number of wetting and drying cycles was 4. This research may contribute to the understanding of the development of deformation and mechanical properties of soil in different spatial distributions when subjected to moisture variation and promote the search for methods to improve the long-term performance of subgrade.

2. Experimental Work

2.1. Materials and Specimen Preparation. The expansive soil used in this research was obtained from Guangxi, China. A summary of geotechnical characteristics of the expansive soil is presented in Table 1. According to the Chinese standard GB 50112-2013 [20], the free expansion rate is 60% corresponding to weak expansive soil. The lime used in this study contained 90% quicklime (CaO). Yang [21] performed a series of tests on the same kind of expansive soil, and it was found that the mixture reached a nonexpansive potential standard when lime content was more than 4%. Considering this, 5% lime content was chosen to stabilize expansive soil in this study. Prior to specimen preparation, bulk soil samples were subjected to air-drying, pulverizing, and processing through a 2.00 mm sieve to produce soil powder. The amount of lime corresponding to 5% lime content was added to the soil powder and hand mixed to reach a homogeneous mixture. Distilled water was then added to reach the target moisture content and thoroughly mixed. Because the hydration of lime consumes water, the moisture content of the mixture gradually decreases with time. To precisely control the moisture content, the mixture was stored in an airtight container for 7 days, during which the moisture content was checked more than three times and water was supplied to reach the aimed moisture content. Cation exchange and flocculation induced by lime brings about instantaneous changes in texture and clay plasticity [5], which reduces expansibility and increases water stability. These improvements are mainly completed in the first 24 h [22]. The strength of the specimen grows rapidly at first, generally during the first 7 d, and then the increasing rate becomes slow [5]. So, after 7 d, the specimen is suitable for subsequent experiments.

The degree of compaction of embankment in highway is required to be more than 94% [23]. Hence, the cylindrical specimens with 39 mm in diameter and 78 mm in height were compacted at optimum moisture content at the degree of 94%. The compaction was applied in a rigid split mold and in five layers of equal weight using a Proctor hammer. The specimens were then subjected to wetting and drying cycles within the self-made apparatus.

2.2. Wetting and Drying Cycling Method and Apparatus. A self-made apparatus was used to provide the specimen surcharge pressure and precisely control the moisture content of the specimen in the process of wetting and drying. Figure 1 shows the details of the apparatus. The apparatus consists of a rigid cylinder, which allows for the swelling and shrinkage of the specimen under controlled surcharge axial pressure. The cylinder consists of a pair of half cylinders which are bounded by two clasps. The axial-force conduction cap and cylinder are made of acrylic, making the weight of the whole device less than the specimen and convenient to move and weigh. Thus, the moisture content change of the specimen can be precisely presented by the quality change of the whole apparatus. The side of the specimen was wrapped with plastic film to prevent evaporation. The specimen was then placed in the cylinder between two pieces of the filter paper and porous stones. The axial surcharge pressure is provided by the tension of springs. The force of springs is converted to a uniform load on the specimen through axial-force conduction caps and porous stones.

After the full settlement was achieved under the aim surcharge pressure, water was added equally into the apparatus through the two vents on each side of the apparatus by using a dropper, when the apparatus was placed on an electronic scale. And the water seeped into the specimen gradually through porous stones as a simulation of water infiltration in the subgrade. The apparatus was then put in a closet at 20°C for two days to achieve relative homogenization of the moisture content within the soil, and the two vents were plugged with rubber plugs to avoid evaporation.

To simulate the evaporation condition of the subgrade, the drying stage was implemented by removing the rubber plugs and putting the apparatus into an oven where the temperature was controlled at 40°C. The mass of the apparatus was continuously measured. As soon as the apparatus reached the target mass, the vents of it were

Table 1: Main geotechnical properties of the tested soils.

Properties	Natural soil	Soil treated with 5% of CaO (7 d of curing)
Specific gravity	2.70	2.68
Liquid limit (%)	63.00	32.70
Plastic limit (%)	25.00	23.00
Sand (>0.075 mm, %)	3.80	2.80
Silt (0.005 mm to 0.075 mm, %)	23.60	27.20
Clay (<0.005 mm, %)	72.60	70.00
USCS classification	MH	CL
Maximum dry density (Mg/m^3)	1.83	1.77
Optimum moisture content (%)	14.30	15.40
Free expansion rate (%)	60	—

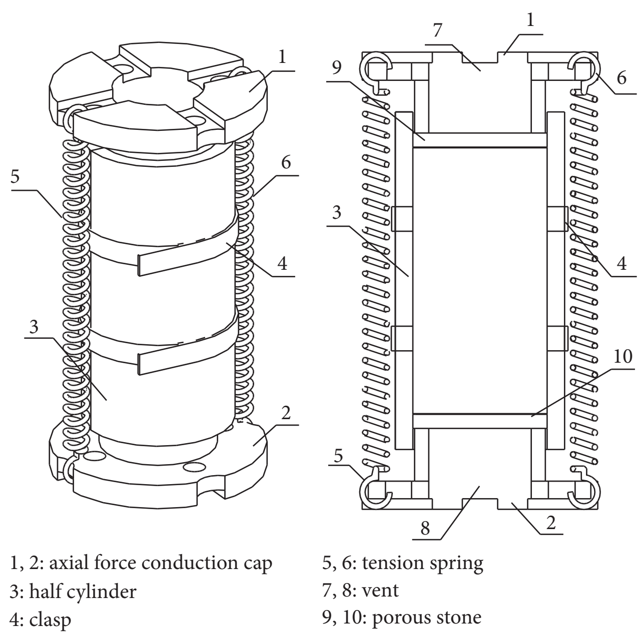

Figure 1: Layout of the apparatus.

plugged and placed in the closet for one day at 20°C to achieve uniform distribution of moisture in the specimen. Due to the porous stones, the evaporation rate was slow enough to allow the water in the specimen having sufficient time to immigrate. The duration of this drying stage was nearly 35 h.

To record the variation of axial strain, the height of specimen was measured by using a digital caliper at four specific locations. And then the mean of the measurements was considered. The height of specimens was measured every time before the next step began. In this study, two specifications of spring (Table 2) were chosen to provide 6 kPa, 27 kPa, and 54 kPa pressure on the specimen, respectively, corresponding to the combination of two A springs, two B springs, and four B springs. One of the possible sources of error in this method could be the instability of axial pressure since the tension of the spring was related to the height of the apparatus which was changing with the variation of moisture content. To evaluate the error, we define tension sensitivity (S_s) which presents the changing degree of spring tension when the height of the apparatus changes 1 mm. S_s is calculated as

$$S_s = \frac{1 \times (T_1 - T_0)}{(S_1 - S_0)T_1}, \tag{1}$$

where S_0 and T_0, respectively, present the length and tension of the spring at natural state and S_1 and T_1, respectively, present the length and tension of the spring at working state.

It can be seen from Table 2 that the tension sensitivities of both springs are no more than 1.8%, while the maximum variation of spring length during the wetting and drying cycles was less than 1 mm in this study. Therefore, the variation of tension is small enough, and the axial pressure applied on the specimen could be considered stable.

In the construction of highways, subgrade soils are generally compacted at or close to optimum moisture content. The moisture content of subgrade will firstly reach equilibrium moisture content (EMC) and then fluctuates near EMC due to external environment factors such as evaporation, rainfall infiltration, and groundwater table variation. To simulate the realistic variation of moisture content, we chose 16.5% as the EMC and conducted wetting and drying cycles in the range of moisture content comprised between 14.5% and 18.5%. The applying of wetting and dying cycles can be described as follows: (1) Use the wetting method to increase moisture content to 18.5% and wait for two days; (2) apply the drying method to decrease moisture content to 14.5% and wait for one day; and (3) use the wetting method to increase moisture content to 16.5% and wait for two days. Apply Steps 1, 2, and 3 for one wetting and drying cycle. For more than one cycle, repeat Steps 1 and 2, and then end by applying Step 3. Figure 2 shows the changing path of moisture content for two wetting and drying cycles.

2.3. Resilient Modulus Tests. The resilient modulus (M_R) represents the ability of subgrade soils to resist vertical deformation caused by cyclic axial load. M_R of the lime-treated specimen was tested by performing semisinusoidal repeated load of 1 Hz with no rest period using the GDS dynamic triaxial testing system. Water was used as the medium for applying confining pressure. During the test, the specimen in the triaxial cell was subjected to multistage loading with different combinations of dynamic deviator stress (σ_d) and static confining pressure (σ_c) as shown in Table 3. The loading list is chosen by considering the loading

Table 2: Parameters of the spring used in this study.

Spring type	Free length L_0 (mm)	Working length L_1 (mm)	Initial tension T_0 (N)	Working tension T_1 (N)	Tension sensitivity S_s (%)
A	85.00	124.00	5.00	15.25	1.72
B	110.00	124.00	2.75	3.50	1.53

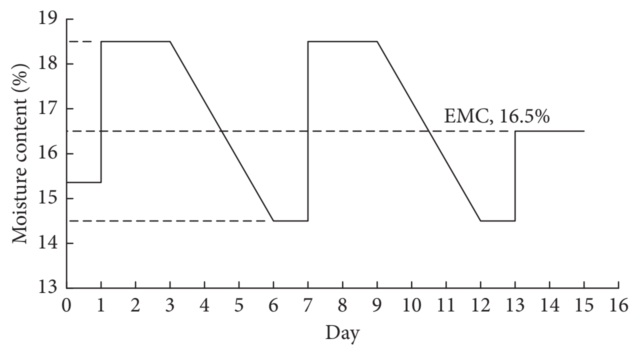

Figure 2: The changing path of moisture content for two wetting and drying cycles.

Table 3: Loading sequence of the M_R test.

Stage	Confining pressure (kPa)	Contact stress (kPa)	Dynamic deviator stress (kPa)	Maximum deviator stress (kPa)	Cycle
0	30	6	20	26	1000
1	60	12	10	22	100
2	45	9	10	19	100
3	30	6	10	16	100
4	15	3	10	13	100
5	60	12	20	32	100
6	45	9	20	29	100
7	30	6	20	26	100
8	15	3	20	23	100
9	60	12	30	42	100
10	45	9	30	39	100
11	30	6	30	36	100
12	15	3	30	33	100
13	60	12	40	52	100
14	45	9	40	49	100
15	30	6	40	46	100
16	15	3	40	43	100

stages suggested by Chen et al. [24] and AASHTO T-307-99 [25]. The test starts with a conditioning stage (sequence 0) by applying 1000 repetitions with haversine dynamic deviator stress (σ_d) of 20 kPa and confining pressure (σ_c) of 30 kPa. This stage aims to reduce the effect of the interval between compaction and loading and minimize the imperfect contact between the specimen cap and the specimen. The subsequent stages with 100 repetitions each were then applied on the specimen with different dynamic deviator stress and confining stress. And for each stage, the last five cycles were chosen to determine the resilient modulus.

3. Results and Discussion

3.1. Deformation during Wetting and Drying. The variations in height ($\Delta H/H_0$) of the lime-treated specimens with the number of wetting and drying cycles are presented in Figure 3. On the whole, it can be noticed that the higher the surcharge pressure is, the lower the axial strain will be during the process of wetting and drying cycles. To better understand the deformation of specimens, a part of important information is extracted from Figure 3 and presented in Figures 4 and 5.

Total axial strain of specimens after every step of wetting and drying process under different surcharge pressures is shown in Figure 4. The first wetting conducted to a significant swelling level, and then the total axial strain decreased in the second wetting for all surcharge pressures. The total axial strain of specimens under 27 and 55 kPa progressively deduced in the following wetting stages, resulting in irreversible shrinkage. However, in the following wetting stage, the total axial strain of specimens under 6 kPa increased, causing slight swelling. Similar to the wetting stages, in the process of drying stages, the value of total axial strain progressively decreased for the specimens under 27 and 55 kPa surcharge pressures, while the value of those under 6 kPa surcharge pressure

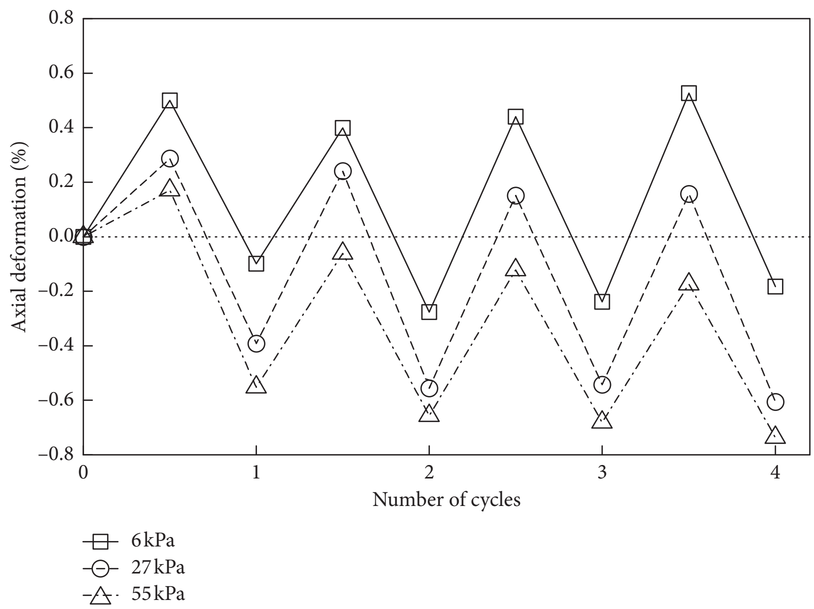

Figure 3: Axial strain of specimens with the number of wetting and drying cycles under different surcharge pressures.

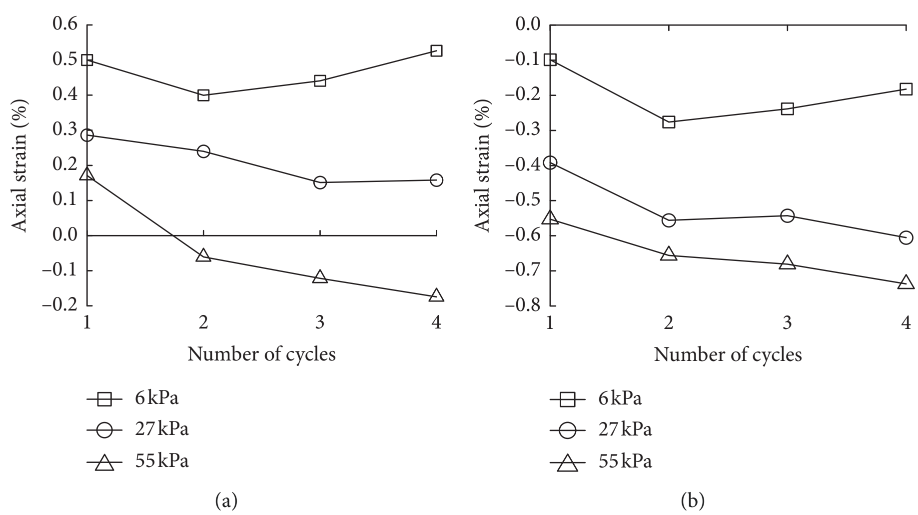

Figure 4: Total axial strain of specimens after every step of (a) wetting and (b) drying process under different surcharge pressures.

exhibited a decreasing trend at the first two stages and then increased in the subsequent cycles. This indicates that the specimens tend to attain irreversible swelling strain under low surcharge pressure, while they attain shrinkage strain under higher surcharge pressure. Estabragh et al. [17] found irreversible swelling and shrinkage of expansive soil over the wetting and drying cycles under different surcharge pressures. Stoltz et al. [10] found that controlled suction cycles lead to a progressive accumulation of irreversible shrinkage of a lime-treated soil, whereas severe cycles cause irreversible swelling. The different development trends of strain could be explained by the different spatial distributions of desorption rate, which is the main fact controlling the stretching rate of internal microcrack when the initial specimen is the same [26]. From this point of view, the effect of surcharge pressure on shrinkage/swelling behavior can be explained by resisting the development of microcracks.

The shrinkage and swelling amplitude of specimens according to the number of wetting and drying cycles under different surcharge pressure are displayed in Figure 5. The first wetting stage caused 0.5% expansion in the height of specimens under 6 kPa surcharge pressure, which is, respectively, 1.7 and 3.0 times as under 27 and 55 kPa surcharge pressure. The shrinkage strain of the sample under 55 kPa in the first drying stage is 0.72%, which is, respectively, 1.05 and 1.20 times as under 27 and 6 kPa surcharge pressure. This indicates that higher surcharge pressure leads to lower swelling and larger shrinkage in the

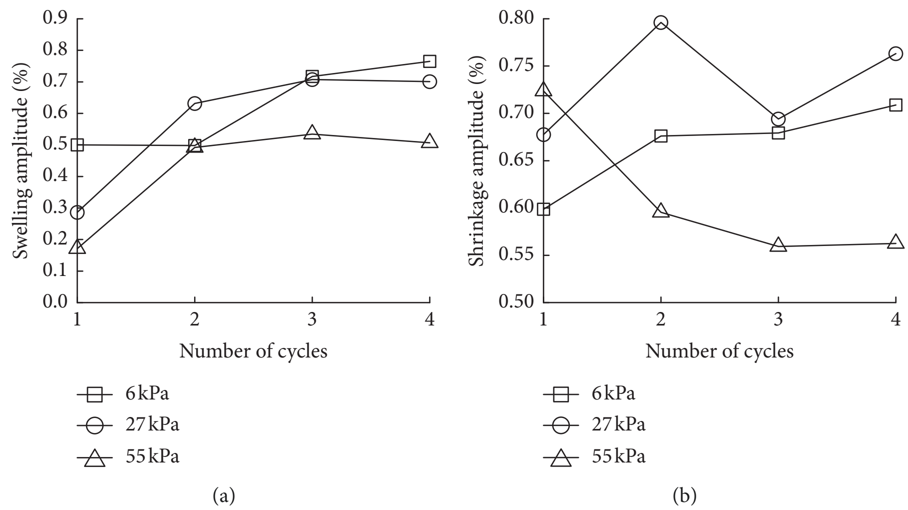

Figure 5: Shrinkage/swelling amplitude of specimens according to the number of (a) wetting and (b) drying cycles under different surcharge pressures.

first cycle. In the following stages, the amplitude of swelling and shrinkage gradually reached a constant state, where the value of 55 kPa surcharge pressure is much lower than that under 27 and 6 kPa surcharge pressure. This illustrates that the higher the surcharge pressure, the lower the magnitude of shrinkage and swelling. The trend is more obvious when the number of wetting and drying cycles increase. This finding is consistent with the result reported by Estabragh et al. [17].

3.2. Variation of Resilient Modulus during Wetting and Drying. The average values of the resilient modulus of specimens according to the number of wetting and drying cycles under three different surcharge pressures are shown in Figure 6. It can be found that under different surcharge pressures, the resilient modulus after every cycle varies significantly. On the whole, the larger pressure leads to the higher resilient modulus after a specific number of cycles. The value of the resilient modulus is the mean of values in 16 stages, which are calculated by the mean of the value of the modulus in last five load cycles at each stage. Thus, the value presents the overall ability to withstand repeated traffic loads. In this study, the resilient modulus presents the stiffness of the specimen, which mainly depends on the stabilization of lime treatment, surcharge pressure, and the effect of wetting and drying cycles. The stabilization effect of lime on expansive soil mainly contains cation exchange, flocculation, and pozzolanic reactions. In the short term, cation exchange and flocculation play the dominant role, and with these effects, expansive soil looses plasticity immediately [5]. Pozzolanic reaction then gradually increases strength and stiffness, resulting in continuous increase in the resilient modulus. As discussed in Section 3.1, ignoring radial strain, the axial length of the specimen under low surcharge pressure (i.e., 6 kPa) tends to increase with wetting and drying cycles, which means the decrease in dry density and the development of internal microcracks. These changes result in the reduction of the resilient modulus. On the opposite, larger surcharge pressure (i.e., 27.5 kPa) induces positive effect on the resilient modulus for the shrinkage behavior is observed. This means the increase of surcharge pressure has a positive effect on the resilient modulus by controlling the swelling/shrinkage behavior. As discussed in the study of Stoltz et al. [10], the effect of wetting and drying cycle induced a strong decrease of the strength and stiffness of lime-treated expansive soil, and the effect may contain physicochemical effects besides changes in pore radius. The effect of wetting and drying cycles is relatively complicate. Since we focus on the effect of axial surcharge pressure, the effect of wetting and drying cycle can be regarded as a negative effect on stiffness and resilient modulus. Overall, irreversible swelling related to low surcharge pressure and the effect of wetting and drying cycle have negative effect on the resilient modulus, while pozzolanic reaction and irreversible shrinkage related to large surcharge pressure promote the growth of the resilient modulus.

It can be observed from Figure 6 that the values of the resilient modulus progressively increased in the first two cycles and then exhibited a decreasing trend in the following wetting and drying cycles. This trend could be explained as a competition among the effect of wetting and drying cycle, pozzolanic reaction, and irreversible strain. It is obvious that the positive effect outweighs the negative effect during the first two cycles and an opposite phenomenon exhibits in the subsequent cycles. To explain the shift of trends of the resilient modulus, the key question is to understand the variation tendency of positive and negative effects. Under the specific surcharge pressure, pozzolanic reaction is the only effect which depends on time. As described by Bell [5], the most notable increase of strength of lime-treated clay occurs within the first 7 d. In other words, the extent of the positive effect by pozzolanic reaction decreases with time. Thus, although positive effect outweighs more at first, it will ultimately be backward to negative effect after a certain number of wetting and drying cycles. Therefore, the shift in trends of developing of resilient modulus after 2 cycles occurs.

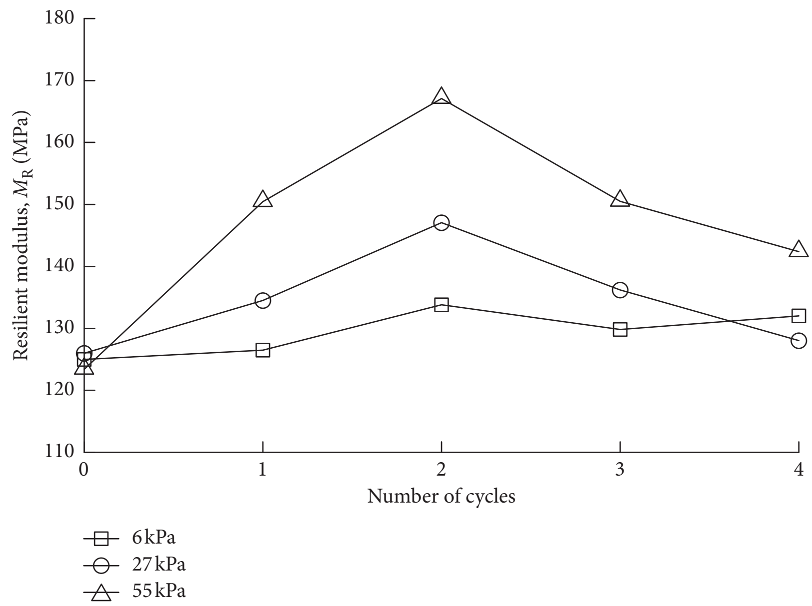

Figure 6: Resilient modulus of specimens according to the number of wetting and drying cycles under three different surcharge pressures.

As shown in Figure 6, the increase of the resilient modulus under 55 kPa surcharge pressure after the second wetting and drying cycle is 1.25 times as that under 6 kPa surcharge pressure. According to Figure 2, after the second drying process, the axial strain under 55 kPa is 0.38% lower than that under 6 kPa, and the difference is 0.62% after the third wetting process. Thus, when two wetting and drying cycles complete, the difference of axial strain under 6 kPa and 55 kPa at equilibrium moisture content (16.5%) is between 0.38% and 0.62%. In other words, after the second cycle, the increment of the resilient modulus of specimens under surcharge pressure between 6 kPa and 55 kPa is 25%, and the corresponding rise of dry density is less than 0.62%. Yue [27] made a series of experiments on the same lime-treated expansive soil. It was found that the resilient modulus increased by 5% for every 1% increase of the dry density when the dry density of the specimen with 15.4% moisture content changed around 94%. As described by Yue, 0.62% increase of dry density induces 3.1% rise in the resilient modulus, which is far less than the observed increase of 25%. This means, besides increasing the dry density, surcharge pressure can make more contribution in the development of the resilient modulus when subjected to wetting and drying cycles.

It is worth noting that there exhibits a similar shift of trends of axial strain and resilient modulus under low surcharge pressure (i.e., 6 kPa). In other words, after the second wetting and drying cycle, the specimen under 6 kPa surcharge pressure tends to swell and the resilient modulus of specimens under all surcharge pressure displays a decreasing trend (Figures 4 and 6). This indicates that under low surcharge pressure (i.e., 6 kPa), the reduction trend of the resilient modulus is reflected on the shift trends of axial strain.

4. Conclusions

A self-made device was applied to determine the effect of axial surcharge pressure on deformation and resilient modulus of lime-treated expansive soil, subjected to wetting and drying cycles. The following conclusions can be extracted from the results of this study:

(1) Specimens accumulate irreversible shrinkage under large surcharge pressure over wetting and drying cycles, whereas irreversible swelling is observed under low surcharge pressure in the overall condition.

(2) The surcharge pressure can reduce the amplitude of variation of axial strain.

(3) The larger surcharge pressure leads to higher resilient modulus of the tested specimen after wetting and drying cycles.

(4) The resilient modulus of the specimen increases in the first two cycles and decreases in the following cycles under all surcharge pressure. This shift of trends can be explained as the competition among pozzolanic reactions, irreversible strain, and effect of wetting and drying cycles.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the Youth Innovation Promotion Association CAS (2015270), Outstanding Youth Fund of Hubei Province (2017CFA056), and Science and Technology Service Network Initiative of CAS (KFJ-STS-ZDTP-037).

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