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ORIGINAL ARTICLE

An experimental study of vaporous water migration in unsaturated lime-treated expansive clay

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Abstract To ensure safety of lime treatment for expansive clay foundation, investigation of vaporous water migration features is of great significance since moisture migration leads to changes in engineering behaviors of the lime-treated expansive clay. Herein, a novel model was described to perform the vaporous water migration tests of unsaturated lime-treated expansive clays. And effects of initial water content, lime dosage, curing time, migration period, and transfer distance on vaporous moisture migration were discussed. The soil–water characteristic curves (SWCCs) and textures of expansive clay and the corresponding improved soil treated with 7 % lime were determined to further investigate changes in hydraulic characteristics by means of the geotechnical digital system (GDS) and scanning electron microscopy (SEM) tests. The results indicated vaporous water migration between two soil columns of different initial water contents increased as migration time went by, and moisture content variation mostly occurred in the first 30 days. For the cases of same 24 % initial water content in the left soil column, variation of moisture content in the case of 0 % initial water content in the right soil column after 90 days migration was about 3 times and 78 times, respectively, bigger than that for the cases of 6 and 12 % initial water content in the right soil column. Besides, as migration distance increased, it took longer time to reach the water migration balance. Moreover, the left and right soil columns behaved different migration characteristics, and transfer speeds of mixing water within the soil columns and vaporous water between columns were different.

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Introduction

Expansive clay, a special soil distributed widely all around the world, behaves distinct swelling and shrinking properties, causing the uplift or subsidence of structure foundations, and resulting in engineering disasters and great economic losses (Azam et al. 2013). Lime treatment has been widely applied in the stabilization of expansive clay foundation (Tonoz et al. 2003). At the same time, more and more engineering disasters, induced by moisture migration, occurred with the increase of engineering scale and quantity because water redistribution in unsaturated soils will alter soil suction and strength. There is yet no detailed description of vaporous moisture migration for lime-soil (Jackson, 1964; Jury and Letey 1979; Wang et al. 2014). Therefore, to provide useful information for foundation construction on unsaturated lime-treated expansive clays, the evolution mechanism of water migration has been a key subject and its study is of great significance.

The early study on water transfer in soil science began with the proposed concept of “capillary potential” (Hanks 1958). The researchers examined water migration in sand, unsaturated soils and expansive clays by means of simulations (Thomas 1987; Singh et al. 1989; Shoop and Bigl 1997; Liu et al. 1998; Romano et al. 1998; Kim et al. 1999; Choo and Yanful 2000; Salzmann et al. 2000; Li et al. 2012), experiments in the laboratory (Favre et al. 1997; Poulose et al. 2000; Zhang et al. 2002; Dobchuk et al. 2004) and field tests (Kean et al. 1987; Grifoll and Cohen 1996; Wuest 2002; Flerchinger et al. 2003) and gained beneficial results. These results demonstrated that water migration in soils associates not only with mineral composition, moisture content and temperature, but also with soil–water characteristic curve (SWCC) and micro level texture. At the same time, the effects of gravity and thermal gradient, wetting–drying cycles on water movement through unsaturated soils were also discussed by other studies (Mohamed et al. 2002; Krishnaiah and Singh 2003; Zhang et al. 2004; Mao et al. 2010; Wang et al. 2010; Akcanca and Aytek 2012). Obviously, while some studies have indicated that moisture migration results in changes of engineering behaviors, vaporous water migration in lime-treated expansive clay still remains in question.

As mentioned above, scientists attract many attentions on strength and liquid water migration of soil, but few investigations on vaporous water migration of lime-treated expansive clay. Unfortunately, it is difficult to fully understand hydraulic properties of unsaturated lime-treated expansive clay only by investigations of liquid water transfer. To further understand hydraulic property and moisture transfer of unsaturated lime-treated expansive clay, it is important to estimate properly hydraulic properties associated with vaporous water migration characteristics. This will help us to better characterize the moisture migration mechanism in unsaturated improved soils, and explore appropriate treatment methods.

The main objective of this paper is to examine the characteristics of vaporous water migration in unsaturated lime-treated expansive clay by a novel test model. And the effects of lime addition, curing time and distance, and initial water content on water content distribution were analyzed by comparing test results after three migration periods (30, 60 and 90 days).

Materials and methods

Tested materials

The sampled expansive clay, which is of weak-medium swelling potential, was taken from foundation treatment site of Hefei international airport. Physical and shrinkage-swelling properties of tested soils are listed in Table 1. Its maximum dry density is 1.84 g/cm^3, liquid limit is 48.0 %, plastic limit is 23.8 %, plasticity index is 24.2, optimum moisture content is 16.0 %, free swell ratio is 46.3 %, total swell-shrink ratio is 0.35 % and swelling pressure is 67.5 kPa. While corresponding basic characteristics of improved expansive soil with 7 % lime are as follow: maximum dry density is 1.61 g/cm^3, plastic limit is 28.2 %, liquid limit is 46.5 %, plasticity index is 18.3, free swell ratio is 6.2 %, total swell-shrink ratio is −0.32 %, dilatation coefficient is 0.28 and swelling pressure is 4.1 kPa. And their micro fabric and hydraulic features are discussed as follows.

Fabric features

By X-Ray diffraction (XRD) test, clay minerals of the tested expansive clay are most montmorillonite and illite (Wang et al. 2012). Their proportions are 13–22 % and 10–13 %, respectively. Other major mineral composition is quartz. Corresponding SEM images for untreated and lime-treated expansive clay are showed in Fig. 1.

It may be seen that SEM images of untreated and lime-treated expansive clay were different. The main fabric of expansive clay appeared “a double structure” (Al-Mukhtar et al. 2012; Stoltz et al. 2012) (Fig. 1a), while lime-treated expansive clay mainly exhibited aggregate structure of micro-pores and micro-particles (Fig. 1b). And spiculate hydrate, which linked clay and formed reticular texture, was observed among clay particles. The reason is that the lime stabilization changes the form of interparticle interaction and microstructures. For the improved soils, spherical micro-particles were dominant, while the proportion of sheet particles and flake particles was little. Besides, those micro-particles were similar in size but with bad directionality (Fig. 1b). The micro-pores filled in macro-pores and skeleton pores, and the radii were small. The lime added to the expansive clay results in an increase in the amount of micro-pores. It demonstrated that lime treatment strongly changed the expansive clay texture at the micrometer scale, and this texture of lime-treated expansive clay can improve the soil strength. These fabric features may be a reason that the maximum density of the lime-treated expansive clay was lower than that of expansive clay. These images also agreed with the decrease of the plasticity index of lime-treated expansive clay relative to that of expansive clay.

Soil–water characteristic curves (SWCCs)

Soil–water characteristic curve defined as the relationship between suction and moisture content is the most fundamental and important soil property in unsaturated soil mechanics. It is dependent on the soil microstructure and saturation degree of soil mass. Consequently, SWCC contains the fundamental information needed for understanding the water migration of unsaturated soil (Lin and Cerato 2013). To further investigate the hydraulic features of tested soils, SWCCs of undisturbed expansive clay and lime-treated expansive clay were obtained by a triaxial stress path testing device developed by Ng et al. (2002). Measured curves were shown in Fig. 2. It is obvious that the drying curves both appeared hysteretic characteristics compared to the wetting curves. Air-entry suctions were approximately 200 and 150 kPa for undisturbed expansive clay and lime-treated expansive clay, respectively, when specimens subjected to a confined pressure of 505 kPa.

Table 1 Physical and shrinkage-swelling properties of the soil samples used

Soil	Dry density (g cm^{-3})	Liquid limit (%)	Plastic limit (%)	Plasticity index	Optimum moisture content (%)	Free swell ratio (%)	Total swell-shrink ratio (%)	Swelling pressure (kPa)
Untreated clay	1.84	48.0	23.8	24.2	16.0	46.3	0.35	67.5
Lime-treated clay	1.61	46.5	28.2	18.3	17.0	6.2	−0.32	4.1

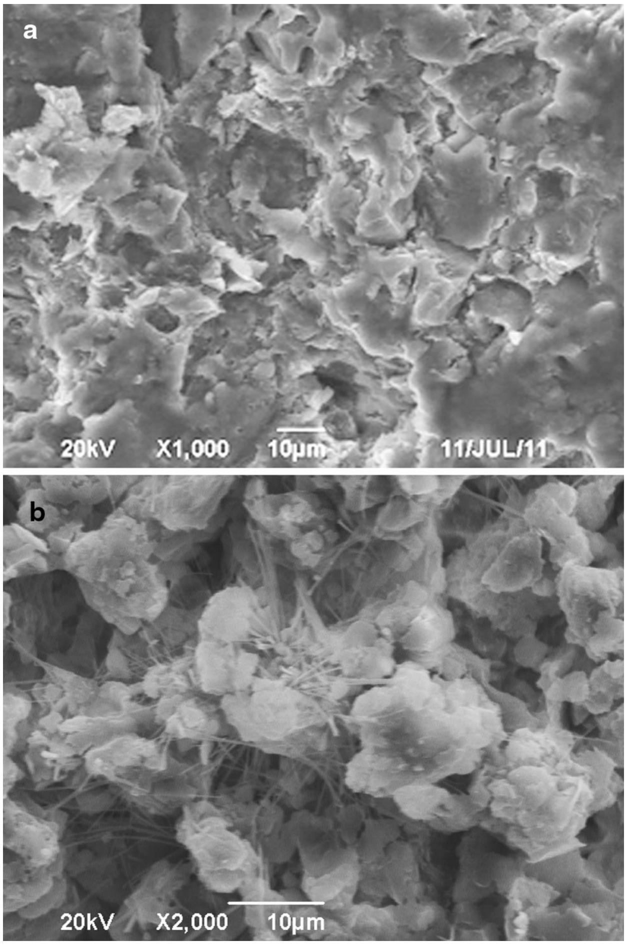

Fig. 1 Images of SEM tests: **a** expansive clay and **b** lime-treated expansive clay

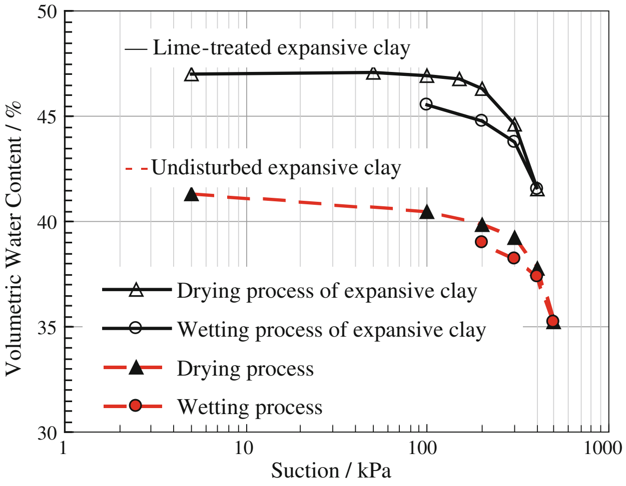

Fig. 2 SWCCs of undisturbed expansive clay and lime-treated expansive clay

This indicates that micro-pores in lime-treated expansive clay are different from undisturbed expansive clay. It may be seen from Fig. 2 that volume water content of lime-treated expansive clay is greater than that of undisturbed expansive clay in a same suction. The SWCC of lime-treated expansive clay was above that of the disturbed expansive clay. It can be accounted for that remolded sample was of smaller and uniform particles. And this was due to that expansive soils were ground to powder in preparing remolded specimens process. It once again showed that hydraulic properties of the expansive clay changed before and after lime treatment. Further study is necessary to investigate change in SWCCs for the remolded expansive clays.

Experimental design

The main types of water transport in unsaturated soil are vaporous water and liquid water. Water transfer is affected by many factors, and is of complexity and uncertainty, especially to the vaporous water migration, because the hydraulic characteristics of lime-treated expansive clay in unsaturated state involve mineral composition, water content, and lime dosage. Previous studies mostly focused on the mixed water migration, few pay attention to the vaporous water migration. It may be due to the inability to make a clear distinction between the vaporous water migration and the liquid water migration. Herein, a novel test model was presented to investigate the vaporous water migration in unsaturated lime-treated expansive clays. The proposed model was made up of polyvinyl chloride (PVC) pipe of good sealing and low cost. Concrete models are shown as Fig. 3. As shown in Fig. 3a there was a 10–20 mm atmospheric space in the middle of PVC pipe. During the tests, specimens are kept horizontally to avoid liquid water migration due to the gravitational potential.

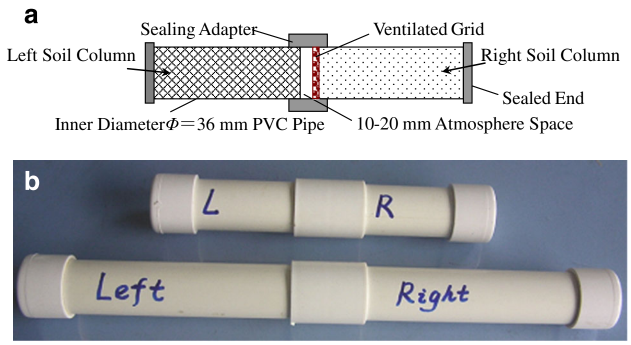

Fig. 3 The sketch of the migration model: **a** test model and **b** images of test model

Then water migration between the unsaturated soil columns is just in the vaporous water state.

A series of tests were conducted to study the impacts of lime contents by weight of dry expansive clay (% Cao dry weight), initial water content, migration time and distance on the vaporous water migration. Corresponding test cases are listed in Table 2.

Specimen preparation

The soil column preparation method should be rational and easy to operate, because it directly influences the accuracy and reliability of test results. The detailed procedures of the specimen preparation are depicted as below:

Step 1: Make test molds. The test model consists of two individual molds, an adapter and a ventilated grid. Each mold of the soil column is made up of PVC pipe of 36 mm inner diameter, 40 mm outer diameter, and 100 or 200 mm in length. And one end of each mold should be sealed (Fig. 3).

Step 2: Prepare test materials with required water content. Initial water content and curing time of prepared specimens play a role of the validity and reliability of vaporous migration test. The specified initial water contents (24 and 21 %) of the left soil column are determined for the tests based on moisture contents monitored in site. Other initial water contents tests will be discussed in the further work. Two types of curing process for test materials are adopted to prepare specimens. One is the lime-treated expansive clay with curing time of 100 days in curing room. In the preparation of the test specimens, the soil is taken out of the curing room and let to be drying. Then adding de-air water to attain the test materials of a certain water content. The other soil is that the same dry expansive clay mixed with lime of the same content, de-air and predetermined quantities of water but stabilized for 0 day. Prior to the soil column preparation, the both materials should be kept in a tightly closed plastic bag for 20 h in order to homogenize the moisture content.

Step 3: Prepare the soil column. This process will produce cylindrical specimens being 100 or 200 mm long. The right and left compaction specimens are prepared, respectively. The tool used to compact specimen is a hammer of 305 g. The specimen is prepared in three layers. And each layer is compacted by eight times from the same free-fall height of 315 mm with the hammer. According to the experimental program listed in Table 2, soils with the specified initial water content were packed into the left and the right test molds, and were compact to a specified compactness. For soil columns wherein initial water content was below 6 %, it should install a ventilated grid (Fig. 3a) on the soil surface to prevent soil column collapse when absorbing water. This is vital to ensure that the water migration was in the vaporous water state.

Step 4: Connect the left and the right test molds. The left and the right test molds are linked and sealed by an adapter. A 10–20 mm atmospheric space should be reserved between soil columns.

To avoid the influence of gravity and temperature, the test specimens were sealed and kept horizontally under homothermal condition in curing room. When water transfer period of the specimen reached its designed time, we first weight specimens to check the mold sealing condition. Then, the PVC pipe is cut in half from the middle, and extracts soil along the left and right column at every 30 mm to measure the water content. Herein, the length of the sample used was 100 mm and 200 mm to discuss the impact of migration distance.

Test results and discussion

Effect of initial water content and migration time

For Cases 1, 2, and 3, Fig. 4 exhibits the change of water contents in the left and right soil columns after moisture migration times of 30, 60, and 90 days. It can be seen that the water content of the left soil column decreased with increasing migration time, and the water migration amount in first 30 days was bigger than that in 30–90 days. However, water content of the right soil column showed the opposite trend, and it decreased with increments of initial water content. After 90 days of water migrations, the left soil column water content of Cases 1, 2, and 3 reduced to 17.5, 20.29, and 22.64 %, respectively. While in the right soil, column water content rose to 6.96, 8.77, and 12.68 %, respectively. Besides, an interesting phenomenon of hard soil shell formed was observed on the surface at the end of left soil column after 90 days of migration in Case 1. This may be due to quick water evaporation of left soil column near the atmospheric column of model relative to that of inner soil mass. Thus, the vaporous water migration

Table 2 Experimental program

Case	Lime added (%)	Curing time prior to moisture migration test (days)	Initial water content in left soil column (%)	Initial water content in right soil column (%)	Each column length (mm)	Migration time (days)
1	7	100	24	0	100	30, 60, 90
2	7	100	24	6	100	30, 60, 90
3	7	100	24	12	100	30, 60, 90
4	7	0	24	12	100	30, 60, 90
5	0	–	24	12	100	30, 60, 90
6	7	0	21	4	100	30, 60, 90
7	7	0	21	4	200	30, 60, 90
8	4	0	21	4	200	30, 60, 90

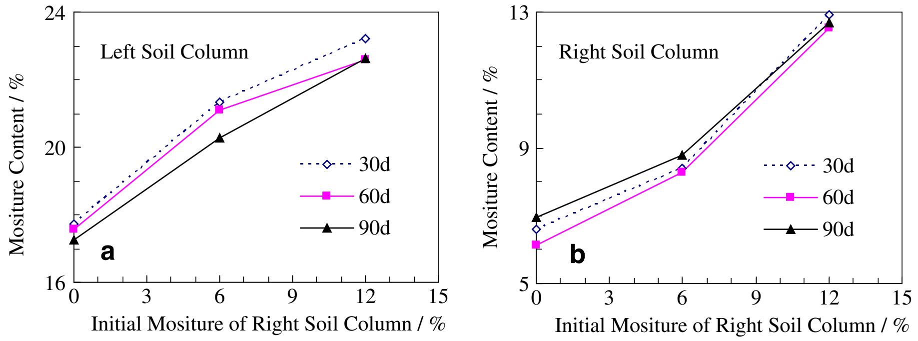

Fig. 4 Results from vaporous water migration tests

reduced as the initial water content of the right soil column increased, but their relationship was nonlinear. The biggest vaporous water migration quantity was witnessed in Case 1 of 0 % initial water content. In cases whose initial water content in the right soil column was higher than 6 %, the water migration speed was slow. Combining with the SWCC of lime-treated expansive clay in Fig. 2 it indicated that soil in dry condition corresponded to high suction, which meant the dry soil is of high water adsorption potential. High suction of the right soil column and the moisture gradient between columns play vital roles in the vaporous water migration. In addition, microstructure of soil mass will change with water migration. The quantification analysis of micromorphology is important in order to further understand evolution of engineering behaviors due to vaporous water migration.

Curing time alterations upon vaporous water migration

For Cases 3 and 4 with different curing times, corresponding measured results were presented in Fig. 5. Here, the curing time of testing soils denotes the maintained period after the expansive clay mixed with lime. Prior to the moisture migration test, the curing period of lime-treated expansive clay used in Cases 3 and 4 was 100 and 0 day, respectively. After 90 days migration time, the left soil column water content of Cases 3 and 4 reduction rates was 5.7 and 8.1 %, respectively (Case 3 from 24 to 22.64 %, and Case 4 from 24 to 22.05 %). While for the right soil column the water content growth rate was 5.7 % and 1.1 %, respectively (Case 3 from 12 to 12.68 %, and Case 4 from 12 to 12.14 %). And the final water content of Case 4 was lower than that of Case 3. It indicated that the interaction between expansive clay and lime may absorb water from the soil. Besides, the right soil column surface color was lighter than that of Case 3, which confirmed the low water content in Case 4. That did good agreement with the measured water content results.

Impacts of migration distance and lime percentage

Vaporous water migration test results from cases with different soil column lengths and lime dosages were illustrated in Figs. 6 and 7.

For Cases 7 and 8 with the same initial water content and migration distance, but different lime dosages, the left soil column water content decreased as migration time went by, and the right soil column exhibited the opposite trend. It was concluded that the lime dosage played a role in the migration process, Case 8 witnessed a decrease of 4.8 % water content for the left soil column, while 9.77 % for Case 7 (Fig. 6a). For 60 days migration tests with different lime percentages (Case 7 of 7 % lime and Case 8 of 4 % lime), water in the adjacent area of the left and right ends of the left soil column exhibited different migration speeds, and this situation in Case 8 was more prominent

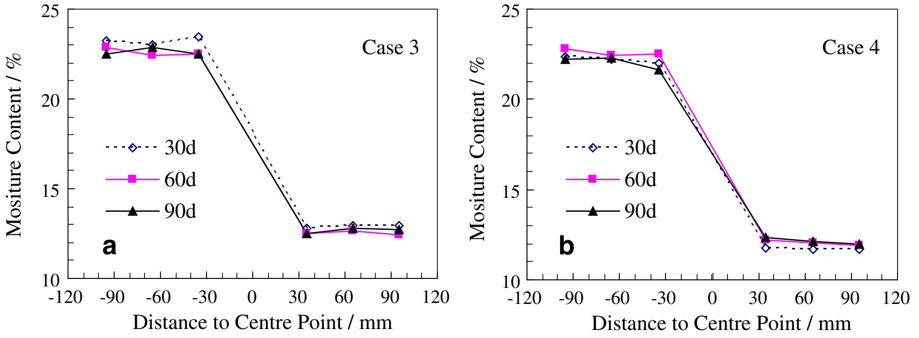

Fig. 5 Results from vaporous water migration tests with different curing times

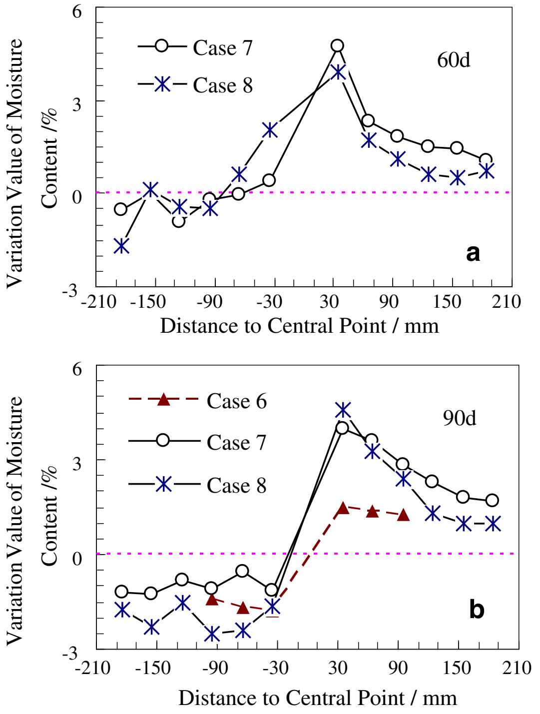

Fig. 6 Influences of lime dosage and soil column length on vaporous water migration: **a** 60 days of migration, **b** 90 days of migration

than that in Case 7. It revealed that water movement in the left soil column was quick during 60 days, while the vaporous moisture migration between the soil columns was slow. This resulted in water accumulation near the surface of the left soil column. But after 90 days of migration this phenomenon had not been observed in the left soil column, but remained in the right soil column. It indicated that water movement showed asynchrony features for the left and the right soil columns, and vaporous water migration and mixed water migration were of different speeds.

The migration distance may alter the moisture distributions in columns during the migration process, especially to the right soil column. For Case 7, the distribution of water content at different locations in the right soil column was not uniform after 90 days migration. However, for Case 6 of 100 mm length, the variation of water content was low (Fig. 6b). It indicated that the longer migration distance would extend the equilibrium time between soil columns.

Images of soil column surface after different migration times are illustrated in Fig. 7. The longer the migration time the lighter was the left soil column surface color. That meant vaporous water transfer quantities increased as time went by. For different lime content models, the shade degree of soil surface color was not identical. It demonstrated that the lime content also had an influence on vaporous water migration.

Effect of lime treatment

Comparison of moisture content variation in the right soil column between untreated and lime-treated expansive clays after 90 days vaporous water migration was described in Fig. 8. It's clearly seen that water content reductions in the left soil column were almost same. Water content rose significantly in the right column of expansive clays, while growth trend for lime-treated expansive clay was flat. It may relate with water consumption by reactions between lime and clay particles. In addition, network textures consisted of needle-like lime hydrate had cementation action and filling effect between clay particles.

As known to all, interaction mechanism between expansive clay and lime is complex, and moisture migration in unsaturated soils is influenced by many factors. Herein, vaporous water migration in the closed and thermostated system was discussed, but the temperature plays a role of moisture migration. Thus, it needs to carry out further investigation of the effects of temperature on moisture migration at micro and macro scales analysis.

Conclusions

Whilst the effects of lime treatment on the swelling of expansive clay are well characterized, and some beneficial realizations of water transfer were concluded in previous

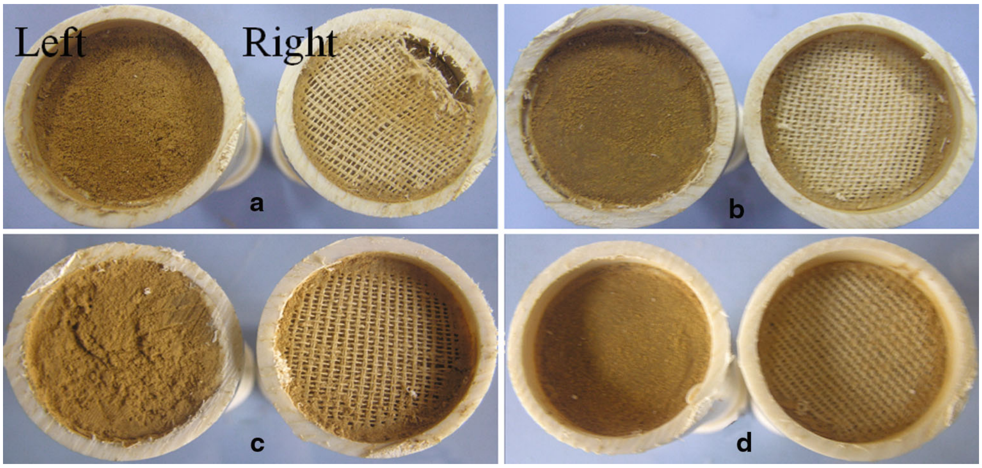

Fig. 7 Images of soil column surface in Cases 7 and 8 after 60 and 90 days of migration: **a** and **b** 60 days, **c** and **d** 90 days

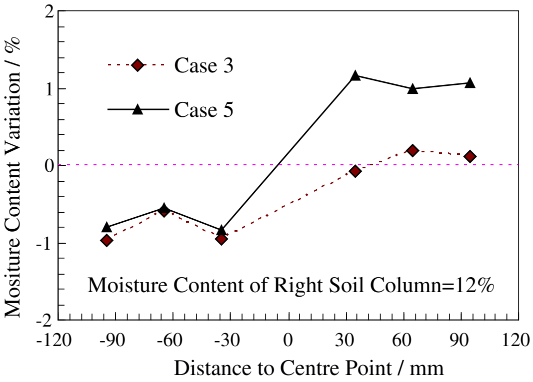

Fig. 8 Comparison of vaporous water migration in untreated and lime-treated expansive clays

researches, less is known about characteristics of vaporous water migration in unsaturated lime-treated expansive clays. Herein, a novel model and series of tests were presented to investigate the vaporous water migration in horizontal soil columns under constant temperature, and some conclusions were reached as follows:

1. Results of microstructure and SWCC show that lime treatment strongly changed features of micro-pores, geotechnical and hydraulic properties of improved soil relative to undisturbed expansive clay. The measured SWCC of lime-treated expansive clay appears hydraulic hysteresis between the drying and wetting cycles similar to that of undisturbed expansive clay. However, volume water content of lime-treated expansive clay is greater than that of undisturbed expansive clay with a same suction.
2. The proposed test model, which enables the moisture migration between soil columns in a vaporous water state, may be an effective alternative to investigate water transfer in unsaturated soils. Effects of water content gradient, lime content, migration time, and soil column length (migration distance) on the vaporous water migration were discussed using this model. It is concluded that vaporous water migration for the lime-treated expansive clay increased nonlinearly as migration time went by, and the moisture content variation quantity was dominant in first 30 days. Transfer speeds of mixing water within the soil columns and vaporous water between columns are different. Moreover, when the difference of initial water content between the two soil columns was less than 18 %, water content variation in soil columns due to vaporous water migration will slow down. A high gradient of the initial water content plays a vital role of velocity of vaporous water migration in relation to other factors.
3. Although our examination method has provided a useful tool for analyzing vaporous migration in unsaturated lime-treated expansive clay, further investigations will still involve a considerable amount of work both in the laboratory and in the field to quantify the effects of wetting and drying cycles and temperature on vaporous transfer mechanism of unsaturated soils.

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