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Effect of suction change on water content and total volume of an expansive clay*

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Abstract: A laboratory study was carried out on both natural and compacted specimens to investigate the complex soil-water interaction in an unsaturated expansive clay. The laboratory study includes the measurement of soil-water characteristic curves, 1D free swelling tests, measurement of swelling pressure and shrinkage tests. The test results revealed that the air-entry value of the natural specimen was quite low due to cracks and fissures present. The hydraulic hysteresis of the natural specimen was relatively insignificant as compared with the compacted specimen. Within a suction range 0 to 500 kPa, a bilinear relationship between free swelling strain (or swelling pressure) and initial soil suction was observed for both the natural and compacted specimens. As a result of over-consolidation and secondary structures such as cementation and cracks, the natural specimens exhibited significant lower swelling (or swelling pressure) than the compacted specimen. The change of matric suction exerts a more significant effect on the water phase than on the soil skeleton for this expansive clay.

Key words: Expansive soil, Water content, Suction, Swelling, Shrinkage
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INTRODUCTION

Expansive clay is widely distributed in the world, and often causes damages to light buildings, pavements, and slopes, which has been reported in many countries around the world (Nelson and Miller, 1992; Liu, 1997). The damage of expansive soils is closely related to the strong soil-water interaction in the shallow soil layers subject to seasonal wetting-drying cycles. During dry seasons, evapotranspiration causes loss of water content in the shallow soil layer, and hence the expansive soil shrinks and cracks. During wet seasons, rainfall infiltration results in an increase in water content and a decrease in soil suction in the shallow soil layer, which leads to a reduction of shear strength and soil swelling (or a development of swelling pressure under a confined condition). Field studies show that the soil-water interaction induced by wetting-drying cycles is very complex, and involves the coupled effects among the changes in water content, suction, stress, deformation and shear strength (Ng *et al.*, 2003; Zhan, 2003). For example, the wetting-induced swelling of an expansive clay is a function of initial suction (or initial water content), initial dry density and confining stress, with the associated swelling pressure also depending on the stress-path employed in the tests (Brackley, 1975).

A laboratory study was carried out on both natural and compacted specimens to improve our understanding of the complex soil-water interaction in an unsaturated expansive soil. The laboratory study includes the measurement of soil-water characteristic curves, free swelling tests, measurement of swelling pressure, and shrinkage tests. On the basis of the test

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results, the relationships among matric suction, water content and void ratio for the expansive soil were obtained, and the difference in the soil-water characteristic between natural and compacted specimens was identified.

MATERIALS AND SPECIMEN PREPARATION METHOD

The soil used in this laboratory study was a brownish-yellow expansive clay taken from the research slope in Zaoyang, Hubei of China (Ng *et al.*, 2003). The basic physical properties of the soil are presented in Table 1. In accordance with the USCS classification system, the soil is classified as a silty clay. With respect to expansion potential, the soil can be classified as a medium expansive soil in accordance with the criterion proposed by Sridharan and Prakash (2000).

The procedure for preparing natural specimens includes cutting appropriate size of soil blocks from the block samples and then trimming them into dimensions fitting an oedometer ring (i.e., 70 mm in diameter and 19 mm in height). The compacted specimens were prepared with static compaction method. The compaction water content was adopted as 18.5%, with the maximum compaction pressure being 800 kPa. The dry density of the obtained specimens was equal to the average value of the natural specimens (i.e., 1.56 Mg/m^3). The compaction water content (i.e., 18.5%) was on the dry side of the optimum water content. The optimum water content as determined by the proctor compaction test was 20.5%, corresponding to a maximum dry density of 1.66 Mg/m^3. After completion of preparation, the initial suction of the natural specimens was measured by a tensiometer, with the values ranging from 20 to 30 kPa. The initial suction of the compacted specimen was measured by a high suction probe, with the measured value being about 540 kPa (Zhan, 2003). It was obvious that the difference in the initial suction between the natural and compacted specimens is attributable to the difference in their initial water content.

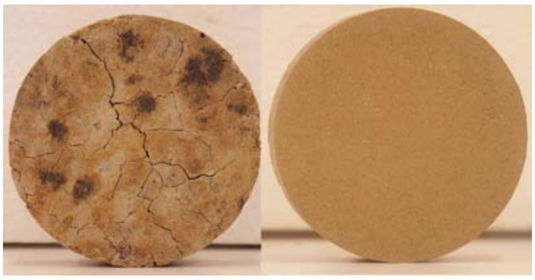
Fig.1 shows a comparison of the appearance of natural and compacted specimens. The two specimens were both in an air-drying state. Open cracks and fissures were well developed in the natural specimen, whereas no obvious cracks appeared on the compacted specimen. In addition, there appeared some black mottles on the natural specimen, which were identified as iron and manganese oxides (approximately 2.5%). It is generally believed that the black

Table 1 Soil properties obtained from the soil samples

Soil properties		Values	Remarks
Clay mineral	Percentage of illite, montmorillonite, kaolinite	16%, 21%, 4%	
Classification	Percentage of sand, silt, clay	3%, 58%, 39%	
	USCS classification	Silty clay	
Consistency limit	Liquid limit (LL)	50.5	
	Plasticity index (PI)	31	
	Linear shrinkage limit w_s	12%	
Density	Specific gravity G_s	2.67	
	Dry density (Mg/m^3)	1.56	
Flow properties*	Saturated permeability k_s (m/s)	2.7×10^{-10}	Oedometer test
	Air-entry value (kPa)	25	
Compressibility*	Compressibility index C_c	0.18	
	Swelling index C_s	0.038	
	Coefficient of consolidation c_v (m^2/s)	1.6×10^{-7}	From 100 to 200 kPa
Swelling and shrinkage*	One-dimension free swelling	16%	From air-dry to saturated
	Swelling pressure (kPa)	800~860	From air-dry to saturated
	Volumetric strain due to shrinkage	15%	From saturated to oven-dry
Shear strength parameters*	Effective cohesion c' (kPa)	11.7	
	Effective angle of friction ϕ'	24°	

* denotes measured from compacted specimens

oxides have a cementation effect between soil particles. However, the secondary structure was completely lost on the compacted specimen as a result of grinding and remoulding process.



(a) (b)

Fig.1 Comparison of appearance between (a) natural and (b) compacted specimens at air drying condition (Zhan and Ng, 2006)

TESTING PROGRAM, APPARATUS AND PROCEDURE

The laboratory investigation was carried out on both the natural and compacted specimens. The investigation on the compacted specimen was to provide a reference because it basically represents the particle-level properties of the soil material. The following testing procedures were conducted to investigate the soil-water characteristics of the expansive soil: Both the natural and compacted specimens were first saturated at constant volume condition. Then, all the specimens were moved into pressure plate extractors to measure soil-water characteristic curves (SWCCs). When each of the applied suction was equalized, one or two specimens were taken out from the extractor. The specimens with known values of suction were then used to conduct 1D free swelling tests, at the end of which each specimen was one-dimensionally compressed to its initial height (i.e., the height before free swelling tests), and hence the swelling pressures for different specimens corresponding to different suctions were measured. In addition, shrinkage tests were carried out on both the compacted and natural specimen to investigate the volume change behavior of the expansive clay upon drying.

Saturation process

During the saturation process, the soil specimens housed in steel rings were completely constrained on both ends to prevent soil swelling upon wetting so as to maintain the desired dry density. After saturation the constraint at both ends was removed and the specimens together with the steel rings were quickly moved to pressure plate apparatus for SWCC tests. After the removal of constraint, an obvious swelling was observed in the compacted specimen, but the swelling of the natural specimen was negligible. The significant swelling of the compacted specimen was mainly attributed to its larger initial suction as compared with the natural specimen. The increase in height due to the swelling was approximately 0.8 mm for the compacted specimen with a height of 19 mm, and it is equivalent to a volumetric strain of about 4%. Therefore, the dry density of the compacted specimen after saturation was less than that of the natural specimen.

Pressure plate tests

Two conventional apparatuses, i.e., 2-bar volumetric pressure plate extractor and 5-bar pressure plate extractor, were used to measure soil-water characteristic curves (SWCCs) for both natural and compacted specimens. The former apparatus was used to measure SWCC along both desorption and adsorption paths up to a suction of 200 kPa, and the latter one was used for measuring desorption curve up to a higher suction (i.e., 500 kPa). For the test conducted with 5-bar pressure plate extractor, 8 duplicate specimens were used to obtain a complete curve. The test procedures suggested by ASTM (2000) were followed.

Free swelling tests and measurement of swelling pressure

The specimens taken out of the pressure plate extractor after the SWCC tests and four air-drying specimens, which possessed different values of initial suction, were used for the free swelling tests. The test procedure included: (1) the unsaturated specimen housed in a steel ring was firstly wetted under a small vertical loading (e.g., 2 kPa), and the vertical swelling was monitored until it approached a steady value, which was recorded as the final swelling for the specimen; (2) the expanded specimen was then loaded by controlling a low displacement rate (i.e., 0.01 mm/min) until the initial height of the specimen prior to wetting was obtained. The pressure required to recover the initial height was recorded as swelling pressure for the specimen. It should be noted that the swelling pressure measured by the above method is usually larger than that from constant-volume method (Gens and Alonso, 1992).

Shrinkage upon drying

Shrinkage tests on both the compacted and natural specimen were also carried out to investigate the shrinkage characteristic of the expansive clay upon drying. The shape and dimension of the specimens are identical to the specimen for an oedometer test. The compacted and natural specimens were prepared in the same way as that for the measurement of SWCC. After saturation, each specimen was subjected to drying in a temperature and humidity controlled room. When the mass of each specimen kept unchanged in the temperature and humidity controlled room, further drying was made by placing the specimens at a dryer air condition and finally in an oven. The dimension (height and diameter) and mass of each specimen were measured periodically (e.g., every 1% change in water content). The height and diameter were measured by a caliper and a PI tape, respectively. The relationships between void ratio and water content can be deduced from the measurement.

EXPERIMENTAL RESULTS

Soil-water characteristic curves

Fig.2 shows the SWCCs in term of gravimetric water content measured for the natural and compacted specimens. The dash lines show SWCCs for the natural specimen. With an increase in suction, the water content in the natural specimens starts to decrease at a quite low suction (less than 1 kPa). It seems that the air-entry value of the natural specimen is quite low due to cracks and fissures present. The hysteresis between the adsorption and desorption curves is relatively insignificant. It should be noted that the final water content at the end of the adsorption curve is unusually larger than the start point of the desorption curve (i.e., at saturated condition). This finding is consistent with the results obtained by Wang (2000) for a similar expansive soil. Wang (2000) demonstrated the abnormal result was due to the structure change that occurred in the specimens during drying/wetting cycle on the basis of microscopic analysis.

The solid lines in Fig.2 show the SWCCs measured for the compacted specimens. It is noticed from both the two desorption curves that water content does not decrease as usual but increases slightly at the beginning. It may be attributed to the gradual swelling of the compacted specimens as a result of the removal of constraint at both ends. The slight difference between the two desorption curves measured by the two apparatuses could be due to the slight difference in their initial dry density. The slope of the desorption curves starts to increase significantly at a suction in excess of 25 kPa, which can be regarded as the air-entry value for the compacted specimens. The hysteresis between the drying and wetting curves appears to be more significant as compared with the natural specimen. As before, the final water content at the end of adsorption is slightly larger than the initial water content.

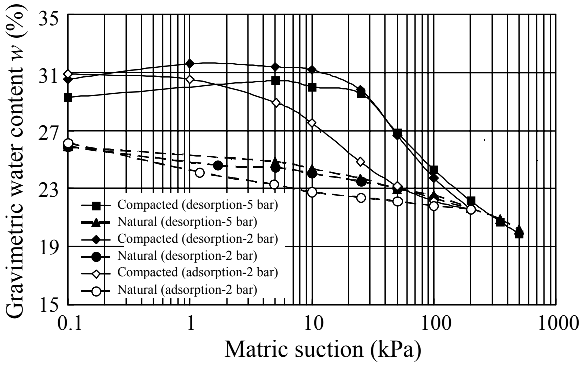


Fig.2 Comparison of SWCC between natural and compacted specimens

A comparison of SWCC between the natural and compacted specimens indicates that there is a distinct difference between the two types of specimen for suctions less than 200 kPa, whereas the two desorption curves tend to merge together when suction exceeds 200 kPa. Just prior to the desorption tests, the initial saturated water content of the compacted specimens is significantly larger than that of natural specimens, which implies the initial dry density of the compacted specimens is less than that of natural specimens. This is consistent with the significant swelling of the compacted specimens after the removal of constraint. The difference in the initial dry density inevitably causes a difference in water retention characteristic between the two types of specimens, particularly at low suction range (Vanapalli *et* *al.*, 1999; Ng and Pang, 2000). The compacted specimens retain more water at a given suction but exhibits a significantly greater desorption rate once matric suction exceeds its air-entry value. Therefore, it is postulated that the loose compacted specimens posses a relatively uniform fabric and much more pores of intermediate sizes (corresponding to the suction range from 10 to 200 kPa) than the natural specimens. The postulation can also help to explain why the compacted specimens exhibit a more significant hysteresis than the natural specimens. The cracks and fissures present in the natural specimens are likely to explain why the desorption rate of the natural specimen at suctions less than 10 kPa is slightly larger than that of the compacted specimen.

Fig.3 shows two SWCCs in terms of degree of saturation for the compacted and natural specimens, which correspond to the two desorption curves measured by 5-bar pressure plate extractor shown in Fig.2. The degree of saturation was deduced from the volume measurement for each specimen taken out from the 5-bar pressure plate extractor after equilibrium at each suction. It should be noted here that 8 duplicated specimens were used for the measurement of each of the SWCCs. It can be seen that the compacted specimens kept saturated until the air-entry value (25 kPa) was reached, and then de-saturated at a rapid rate. The natural specimens started to de-saturate at quite low suction, but the de-saturation rate was significantly lower than the compacted specimens. Therefore, the two SWCCs in terms of degree of saturation intersect at a suction of about 60 kPa, and the difference between the two types of specimen becomes significant even at a suction in excess of 200 kPa.

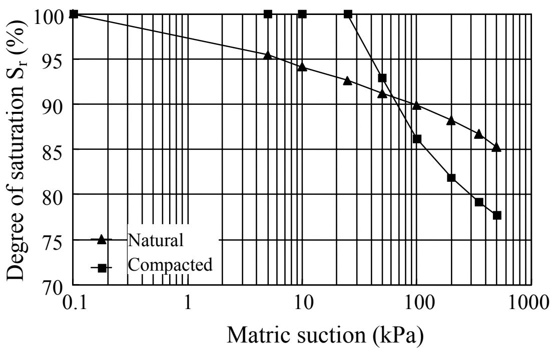


Fig.3 SWCCs in terms of degree of saturation for natural and compacted specimens

Relationship between free swelling strain and initial suction

Fig.4 shows the variations of 1D free swelling with the initial suction obtained for the natural and compacted specimens. In Fig.4a, the data points corresponding to a suction of 100000 kPa were obtained from air-drying specimens. The suction value was estimated from the water content of the air-drying specimens and the extended SWCC (Zhan, 2003). As expected, the measured swelling strain increases with the value of initial suction for both natural and compacted specimens. For a given initial suction, the swelling of the natural specimen is always less than that of the compacted specimen, regardless of larger initial dry density of the natural specimen. The maximum values of 1D free swelling measured for the natural and compacted specimens are approximately 8% and 16%, respectively, corresponding to an air-drying initial state. The less swelling of the natural specimens is likely attributable to its higher over-consolidation ratio (OCR) than the compacted specimens. Oedometer tests indicated that the pre-consolidation pressure of the natural specimens (230 kPa) was significantly greater than that of the compacted specimens (140 kPa). Another reason may be the cementation effect of the iron and manganese oxides present in the natural specimens. The cementation tends to bond clay particles, reduce particles surface for accessing water, and hence reduce the swelling tendency (Hillel, 1998). It should be noted that the cementation may contribute to the over-consolidation nature of the natural specimens.

To enlarge the left-lower part of Fig.4a, the data points corresponding to initial suctions not more than 500 kPa were re-plotted in Fig.4b together with the value of initial void ratio for each specimen. It can be seen that the inconsistency between the two specimens with the same initial suction is likely attributable to the difference in the initial void ratio. Within the suction range considered, the relationship between swelling strain and initial suction appears to be bilinear on a linear scale. The inflection points for the compacted and natural specimens correspond to an initial suction of 200 and 100 kPa, respectively. Prior to the inflection points (i.e., at low suction range), the variation of swelling strain with the initial suction is more significant than that at relatively high suction range. The observed behavior is consistent with the Suction-Decrease yielding locus in the elasto-plastic model proposed by Gens and Alonso (1992) for unsaturated expansive soils.

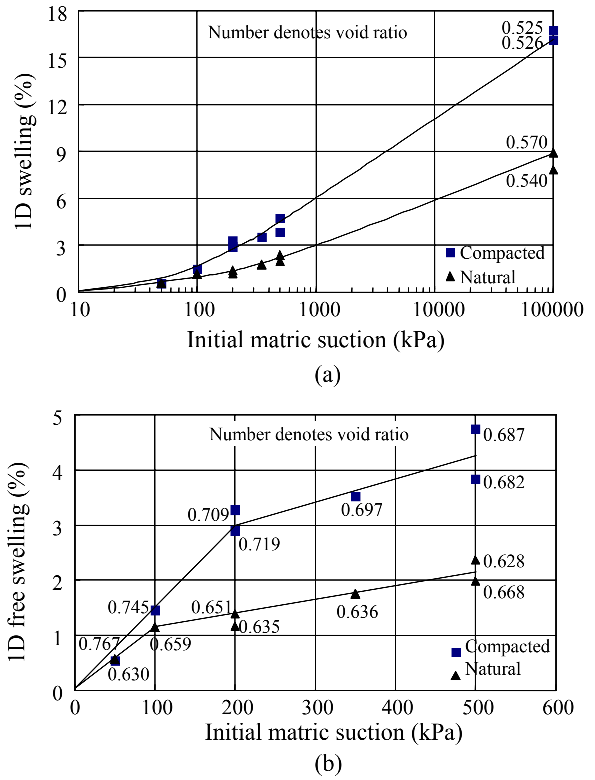


Fig.4 Variation of 1D free swelling with initial suction for natural and compacted specimens. (a) Logarithmic scale; (b) Linear scale

Relationship between swelling pressure and initial suction

After full swelling, swelling pressure for each specimen was measured by loading the specimen to its initial height. Fig.5a shows the variations of swelling pressure with the initial suction for both the natural and compacted specimens. The swelling characteristic reflected by the relationships between swelling pressure and initial suction in Fig.5a is basically consistent with that reflected by the relationships between swelling strain and initial suction shown in Fig.4a. The maximum values of swelling pressure measured for the compacted and natural specimens are about 800 kPa and 400 kPa respectively, corresponding to an air-dry initial state. Apart from the two reasons previously explained for the less swelling of the natural specimens, the less swelling pressure observed for the natural specimen was also likely related to its secondary structure (i.e., cracks and fissures). The open cracks and fissures provided a certain space allowing for the expansion of the soil matrix, resulting in a less inherent constraint. As before, the data points for initial suctions not more than 500 kPa were re-plotted in Fig.5b. It can be seen that the bilinear characteristic discussed above is kept for the relationship between swelling pressure and initial suction. It is noticed that the values of swelling pressure for the two natural specimens with an initial suction less than 200 kPa appear to be larger than the corresponding values for the compacted specimens.

The larger swelling pressure of natural specimen may be attributed to their significantly lower initial void ratios as compared with the corresponding compacted specimens.

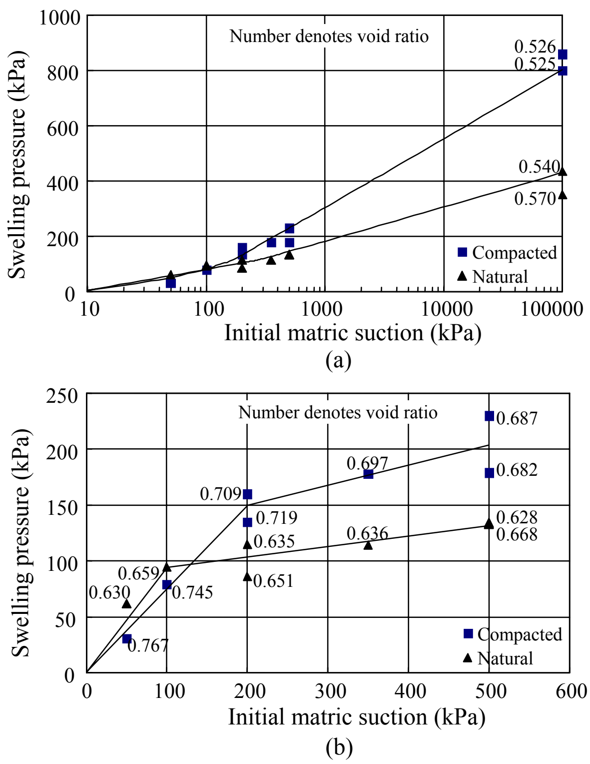


Fig.5 Variation of swelling pressure with initial suction for natural and compacted specimens. (a) Logarithmic scale; (b) Linear scale

Shrinkage upon drying

Fig.6 shows the shrinkage curves for the compacted and natural specimens (each two). The two shrinkage curves for the duplicated compacted specimens (A and B) are reasonably consistent with each other. However, an obvious divergency was observed for the other two curves for the natural specimens (C and D) at water content less than 20%. The observed divergency is attributed to the difference in the quantity and opening of cracks developing in the two natural specimens during drying. It should be noted here that the void ratio was deduced from the measurement of external dimension (height and diameter), which included the spaces of the cracks. It was found that there are more and wider open cracks developed in specimen C as compared with specimen D. Thus, the more cracks developed in the specimen, the larger the deduced void ratio even if the shrinkage of intact soil mass is identical. Shrinkage limit (w_s) can be identified from the shrinkage curves according to its definition (i.e., the water content at which drying-shrinkage ceases). The values of shrinkage limit identified for the compacted and natural specimens are 10.8% and 13.0%, respectively.

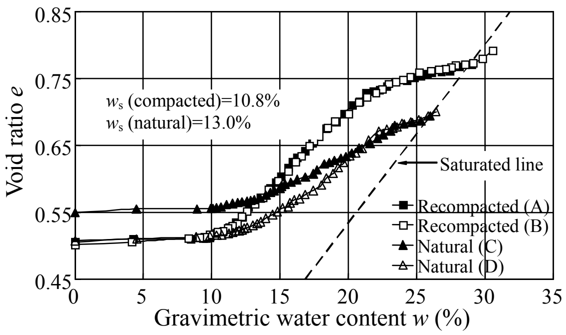


Fig.6 Shrinkage curves for natural and compacted specimens

As compared with the natural specimen, the compacted specimens possess a lower initial dry density and hence a low resistance to the dryness-induced shrinkage. Hence, the gradient of the shrinkage curve for the compacted specimen is generally larger than that for the natural specimen. It should be noted that the fabric of compacted specimens is relatively uniform so no obvious cracking was observed throughout the drying process (see Fig.1). The final void ratio of natural specimen D unexpectedly coincides with that of the compacted specimens. The total volumetric strain due to the shrinkage from an initial saturated state to a completely dry state can be calculated from the shrinkage curves, with the values for the compacted and natural specimens are 14.8%~15.1% and 8.6%~11.4%, respectively. As discussed before, the values of the 1D free swelling strain measured from air-drying specimens are 16.1%~16.7% and 7.8%~8.9% for the compacted and natural specimens, respectively. The data indicate that the magnitude of shrinkage upon the drying from a saturated state to an air-dry state is close to the magnitude of 1D free swelling upon the reverse wetting path for both the compacted and natural specimens. However, it should be noted that the stress state during the wetting path (K_0 condition) is different from that during the drying path (no stress applied).

Roles of suction on the soil skeleton and the water phase

The relationship between void ratio and suction can be approximately deduced from the combination of the shrinkage curve and SWCC measured. The obtained relationships for the compacted and natural specimens are shown in Fig.7, together with SWCC in term of "water ratio" (volume of water to volume of solids, wG_s) (Romero and Vaunat, 2000). It should be noted here that a change in void ratio (e) represents the change in soil skeleton, and that a change in "water ratio" (wG_s) reflects the change in water phase. A comparison between the e~s and wG_s~s curves indicates the water phase is more susceptible to a

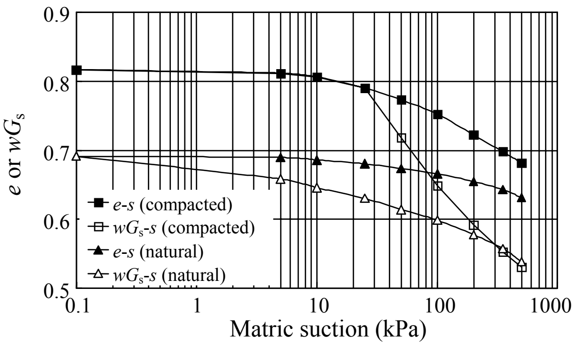


Fig.7 Comparison between the effects of suction change on soil skeleton and water phase

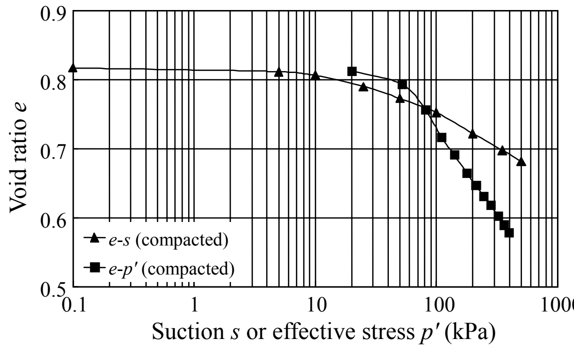


Fig.8 Comparison between the relationships of void ratio to changes in suction and effective stress

change of matric suction than the soil skeleton for both the compacted and natural specimens. In other words, the change of matric suction exerts a more significant effect on the water phase than on the soil skeleton for this expansive soil. In order to assess the effect of suction change on the soil skeleton, the relationship between void ratio (e) and suction for the compacted specimen was plotted in Fig.8 together with the isotropic compression curve for the saturated compacted specimen. It can be seen that the response of soil skeleton to a change in suction tends to be similar to the pre-yield response of soil to a change in compression stress (i.e., elastic response). However, once yielding is reached, the soil skeleton is much more susceptible to an increase in external stress than an increase in matric suction. In other words, the stiffness of soil skeleton with respect to a change in external stress is generally lower than that with respect to change in matric suction.

CONCLUSION

On the base of the laboratory test results, the following conclusions can be drawn. These experimental findings will helpful to interpret the complex soil-water interaction observed in unsaturated expansive soil foundation and slope, and improve our understanding on the associated deformation and failure mechanism.

(1) The air-entry value of natural expansive clay is quite low due to cracks and fissures present, as compared with that of the compacted specimens (i.e., 25 kPa). The hydraulic hysteresis of the natural expansive clay is relatively insignificant.

(2) The 1D free swelling strain (or swelling pressure) increased with the value of initial suction for both natural and compacted specimens. For a given initial suction, the swelling of the natural specimen was always less than that of the compacted specimen. The less swelling potential of the natural specimens may be attributable to both its over-consolidation nature and secondary structures (cementation and cracks).

(3) Within a suction range from 0 to 500 kPa, a bilinear relationship between free swelling strain (or swelling pressure) and initial soil suction was observed for both the natural and compacted specimens.

(4) The change of matric suction exerts a more significant effect on the water phase than on the soil skeleton for this expansive soil. The soil skeleton is more susceptible to an increase in external stresses than an increase in matric suctions.

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