Volume changes of an unsaturated low plasticity clay during a thermal cycle

Authors: C. W. W. Ng, Q. Cheng, C. Zhou* and E. E. Alonso

*Corresponding author

Information of the authors

Prof. C. W. W. Ng

Chair Professor, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

E-mail: cecwwng@ust.hk

Ms Q. Cheng

Research Student, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

E-mail: qcheng@ust.hk

Dr C. Zhou

Visiting Assistant Professor, Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

E-mail: czhou@connect.ust.hk

Prof. E. E. Alonso

Professor, Department of Geotechnical Engineering and Geosciences, Universitat Politècnica de Catalunya, Edificio D-2, Campus Nord, 08034 Barcelona, Spain.

E-mail: Eduardo.alonso@upc.edu

ABSTRACT

Thermally induced soil volume changes can have significant influence on many geotechnical structures such as energy pile. So far, researches on thermal volume changes of unsaturated soil are very limited, particularlyattemperatures lower than typical room temperature.The principal objective of this study is to investigate volumetric behaviour of normally consolidated intact and re-compacted low plasticity clay specimens (loess soil) over a wide thermal cycle ranging from 5^0C to 53^0Cusing a modified double cell triaxial apparatus. SEM measurements are also carried out. It is found that contractive volumetric strain increases as temperature increases. During the cooling process, soil volume keeps contracting until the temperature decreases to 5^0C. Different from previous studies in the literature on saturated remolded illite and natural silty clay, an irreversible contraction at a much higher rate is observed from 13^0C to 5^0C for both re-compacted and intact loess specimens. The irreversible volume changes during cooling are probably because cooling-induced contraction of soil particles leads to particle rearrangements in loess. Moreover, the irreversible volume change during cooling cannot be captured by existing thermo-mechanical models, which predictelastic contraction during cooling. A new yield surface (temperature decrease, TD) is proposed to simulate the observed elastoplastic behaviour during cooling. Furthermore, the cumulative thermal volume change of intact specimen during a thermal cycle is about 25% larger than that of re-compacted specimen, probably due to the existence of some larger pores in intact soil.

Keywords: unsaturated; heating and cooling; lower than room temperature

INTRODUCTION

Thermally induced volumetric behaviour of soils can have significant influence in many geotechnical engineering problems such as landfill cover system, pipeline engineering, geothermal energy development and pavement engineering (Gens, 2010).As far as the effect of temperature change on soil volume is concerned, many efforts have been made on saturated soils (Campanella and Mitchell, 1968; Delage et al., 2000; Sultan et al., 2002; Abuel-Naga et al., 2007; Donna and Laloui, 2015) and unsaturated soils (Romero et al., 2003; Tang et al., 2008; Uchaipichat and Khalili, 2009; Zhou et al., 2015; Coccia and McCartney, 2016). However, most of the researches have paid more attention to temperature higher than the typical room temperature. Moreover, in the previous studies, all the temperature cycles were applied on the drying path and the influence of wetting has been neglected. Few of the previous researches considered effects of soil structure (intact and re-compacted) on the thermally induced volumetric behaviour of unsaturated soils.

In this study, a new suction- and temperature-controlled double cell triaxial apparatus is developed. Four tests were carried out to study the volumetric behaviour of both intact and re-compacted soil specimens at 0 and 100kPa suction during a heating and cooling cycle using this modified system. The temperature ranges covered vary from 5^0C to 53^0C.

TEST PROGRAMME AND TEST APPARATUS

The principal objective of this research is to study volume changes of intact and re-compacted low plasticity clay specimens (loess soil) over a wide heating and cooling cycle ranging from 5^0C to 53^0C. Four suction- and temperature-controlled heating and cooling tests were carried out. Two of them (R0 and R100) were carried out on re-compacted specimens, but at different suctions (0 and 100kPa).The other two (I0 and I100) were carried out on intact specimens at suctions of 0 and 100kPa. Details of the test program are summarized in Table 1. In order to interpret effects of soil structure, scanning electron microscope (SEM) is used to investigate the microstructure of intact and re-compacted specimens, respectively.

In order to fulfil controlling suction and temperature independently in unsaturated soils, a double cell triaxial apparatus (Ng et al., 2012) was modified by adding a temperature control system. Fig. 1 shows a schematic diagram of the newly developed apparatus. The temperature control system includes a heating/ cooling bath (PolyscienceAD07R-20) connected with a spiral copper tube installed between the inner cell and outer cell. The heating/ cooling bath mainly consists of an advanced digital controller, a thermostat, a heating/ cooling unit, a water bath, an inbuilt pump and a thermocouple. In order to monitor the temperature, the thermocouple is put in the water in the inner cell to give feedback to the thermostat and the advanced digital controller automatically adjust the output of heating/cooling unit according to the set temperature. Furthermore, a thermal insulating material is used to wrap the whole triaxial apparatus to minimize the heat loss and exchange with the surroundings. After reaching the equilibrium, the temperature fluctuation is less than 0.2^0C.

The axis translation technique (Hilf, 1956) is used to control the matrix suction $(u_a - u_w)$ in the soil specimen, where u_a and u_w are pore-air pressure and pore-water pressure respectively. The total volume change of the specimen is measured by monitoring the change in the differential pressure between the water level inside the inner cell and that in the reference tube with a differential pressure transducer (DPT). After calibration, the accuracy of the DPT is 0.1mm. For the specimen size used in this research, 76mm in diameter and 20mm in height, this accuracy is corresponds to a volumetric strain of about 0.03%. The water flow in and out of the soil specimen is measured by a burette together with an air trap and a ballast tube. The equilibrium state can be considered to be attained when the water flow rate is less than 0.1ml/day, which is equivalent to a rate of 0.09%/day in gravimetric water content. More details of the measurement of total and water volume change were reported by Ng et al. (2012).

In each suction- and temperature controlled test, the thermally induced volumetric strain of soil specimen is calculated using the following equation:

$$\varepsilon_v(T) = (\Delta V_m(T) - \Delta V_a(T) - \mu t)/V$$

where $\Delta V_m(T)$ is the gross volume contraction measured by the DPT; $\Delta V_a(T)$ is tthermal contraction of inner cell, ceramic disk, top cap, membrane, water in the inner cell and connection tubes; μ/V is the water diffusion rate through the membrane and tube connections at a given pressure and temperature; t is the test duration; V is the volume of specimen.

SOIL TYPE AND SPECIMEN PREPARATION

The material tested in this paper is loess from Shanxi Province, China. It is aeolian sediment formed by the accumulation of wind-blown silt. The physical properties are summarized in Table 2 and some other properties such as water retention behaviour were reported by Sadeghi et al. (2016). According to the Unified Soil Classification System (ASTM, 2006), the test soil is classified as clay of low plasticity (CL) according to the Unified Soil Classification System (ASTM, 2006).

Intact block loess samples have been manually extracted using wooden cubic boxes, with 300mm length of the side, from the depth of 3.5m. And the cutter ring with 76mm diameter and 20mm height is used to obtain the intact specimens. The initial void ratio is 1.17 and the initial suction is 200±20kPa.For re-compacted specimens, static compaction is adopted. The compaction water content is about 10.9% and the initial void ratio is 1.17. These properties are set to be the same as the initial state of the intact specimens for later comparison.

TEST PROCEDURES

Fig. 2 shows the thermo-hydro-mechanical paths of the soil specimens. Each test consists of three stages: isotropic compression, wetting and thermal cycle. After set-up in the triaxial apparatus, the initial state of each specimen was controlled at point A. Each specimen was firstly isotropically compressed to a net confining stress of 50kPa (A→B). The next stage was to apply the target suction. In tests R100 and I100, soil specimens were wetted to 100kPa (B→C1). Similarly, soil specimens in tests R0 and I0 were wetted to 0kPa (B→C2). 7-10 days were required to reach the equilibrium condition. Then, the third stage was to change the temperature step by step (the change of soil temperature is about 10^0C in each step). The heating process was from the typical room temperature (about 23^0C) to 53^0C (C1→D1, C2→D2), followed by cooling to 5^0C (D1→E1, D2→E2) and re-heating to the room temperature (E1→F1, E2→F2).Each step lasted for 24 hours in order to achieve thermal equalisation.

INTERPRETATION OF EXPERIMENTAL RESULTS

Typical thermally induced volumetric behaviour

Fig. 3(a) shows the volumetric behaviour of re-compacted soil during heating and cooling at two different suctions of 0 and 100kPa. During the heating process, the contractive volumetric strain increases with increasing temperature, but at a decreasing rate. This is probably because the heating-induced expansion of soil particles triggered particle rearrangement and facilitated plastic contraction. These observations can be explained using elasto-plastic theory, as shown in Fig. 4. According to the previous research (Tang et al., 2008), the pre-consolidation pressure decreases when the temperature increases. When temperature increases until the yield curve being touched, the irreversible volumetric contractive strain from point 0 to point 1 could be observed and the yield curve would shift to the right.

When temperature decreases from 53^0C to 13^0C, the contractive volumetric strain keeps increasing, but at a much slower rate of around$2\times10^{-3}\%/^0$C. This process is within the yield surface, which means it is an elastic deformation due to thermal expansion of soil particles and the slope between point 1 and point 2, shown in Fig.4, is close to the thermal expansion coefficient of soil particles (for clay particles is $2.9\times10^{-5}/^0$C, Horseman & McEwen, 1996).When temperature keeps decreasing, from 13^0C to 5^0C, an irreversible contractive volumetric strain at a larger rate of$2.5\times10^{-2}\%/^0$C can be observed. It should be pointed out that this observation is different from previous studies on saturated soil. Campanella and Mitchell (1968) and Donna and Laloui (2015) measured volume changes of remolded illite and natural silty clay during cooling in the temperature ranging from 5^0C to 60^0C. For both soils, only reversible volume changes were observed during cooling. The discrepancy between the current study and the two previous studies may be because void ratio of the loess is larger by xx% than that of the other soils. With a much larger void ratio, cooling-induced contraction of soil particlesis more likely leads to irreversible particle rearrangements and plastic volumetric contraction. Furthermore, the observed contraction during cooling cannot be predicted by using existing elasto-plastic theory which predicts reversible contraction during cooling. Anew 'temperature decrease, TD' yield limit may be introduced in existing model to simulate the observed elasto-plastic behaviour during cooling, as shown in Fig. 4. When the new yield surface is reached, the soil volume would contract irreversibly at a larger rate from point 2 to point 3 and shift from point 3 to point 4during the reheating process.

For the thermally induced volume change of intact specimens, as shown in Fig. 3(b), the trend is qualitatively similar to that of re-compacted specimen. The differences between intact and re-compacted specimens are analyzed in the section of "effects of soil structures on volume changes during heating and cooling".

Suction effects on volume changes during heating and cooling

As shown in Fig. 3, for both intact and re-compacted specimens, thermally induced volume changes at suctions of 0 and 100kPa are different by about 5%.This value is much less significant compared with suction effects on Boom clay (Romero et al., 2003).In their study, the volume change at 60kPa is 30% larger than that at 200kPa with the same change of temperature. The observed differences are mainly due to different response during the wetting before heating. For the Boom clay in their study, the pre-consolidation was larger at a higher suction (suction hardening) and swelling was observed during wetting. For unsaturated loess in the current study, substantial volumetric contraction (about 17%, 25%, 13% and 19%for R100, R0, I100 and I0, respectively) was recorded during wetting. With a larger suction, the void ratio after wetting is larger. Effects of suction-induced hardening are compensated by effects of strain hardening induced by wetting collapse.

Effects of soil structures on volume changes during heating and cooling

Fig. 5(a) shows the volumetric behaviour of intact and re-compacted soils at the suction of 0kPa. It can be seen from this figure, the cumulative volumetric strain of intact specimen is about 25% larger than that of re-compacted one. Similar results are found at suction of 100kPa, as shown in Fig. 5(b). The differences between intact and re-compacted specimens may be attributed to their different soil structures. For intact specimen, there are a number of large pores (Bai et al., 2014) with diameter over 200μm, as shown in the SEM image in Fig. 6(a). The pores of re-compacted specimen are relatively uniform and no large inter-aggregate pore is observed (Fig. 6(b)). In addition, the wetting induced collapse has caused a larger void ratio of intact specimen before heating and cooling than that of re-compacted specimen. With more large pores and larger void ratio, the intact specimen shows larger volume change under heating and cooling cycle.

CONCLUSIONS

For both intact and re-compacted low plasticity clay specimens (i.e., loess soil), contractive volumetric strain increases when temperature increases from room temperature 23^{0}C to 53^{0}C incrementally. This is probably because the heating-induced expansion of soil particles triggered particle rearrangement and facilitated plastic contraction. During the cooling process from 53^{0}C to 13^{0}C, contractive volumetric strain keeps increasing at a rate of around 2×10^{-3}%/^{0}C. When soil temperature further decreases from 13^{0}C to 5^{0}C, different from previous studies on remolded illite and silty clay, an irreversible volume contraction at a much higher rate of 2.5×10^{-2}%/^{0}Cis observed. The change of contraction rate and irreversible volume changes during cooling are probably due to cooling-induced contraction of soil particles, leading to irreversible particle rearrangements in loess. More importantly, the observed irreversible response during coolingcannot be capturedby existing thermo-mechanical models, which predict reversible contraction during cooling. A new 'temperature decrease, TD' yield surface may be introduced in existing thermo-mechanical model to simulate the observed elasto-plastic behaviour during cooling.

The cumulative volumetric strain induced in an intact specimen by the applied thermal cycle is about 25% larger than that of re-compacted one, probably due to the existence of more large pores in intact specimen.

For the given thermal cycle applied, the difference between thermally induced volume changes at suctions of 0 and 100kPa is as low as 5%, which is much less significant than that reported on other soils such as Boom clay. This is likely because strain hardening induced by wetting collapse of the loess soil compensates the effects of suction-induced hardening on the soil behaviour.

Acknowledgements

The authors would like to acknowledge the financial supports provided by the Research Grants Council of the Hong Kong Special Administrative Region (HKSAR) through the research grants 647616812 and 16209415. In addition, the authors would like to thank the National Natural Science Foundation of China for their financial supports from Projects 51509041.

REFERENCES

Abuel-Naga, H., Bergado, D.T., Bouazza, A., and Ramana, G.V. (2007). Volume change behaviour of saturated clays under drained heating conditions: Experimental results and constitutive modelling. Canadian Geotechnical Journal **44**, No. 8, 942-956.

ASTM (2006). Standard practice for classification of soils for engineering purposes (unified soil classification system). West Conshohocken, PA, USA: American Society of Testing and Materials.

Bai, X.H., Ma, F.L., Wang, M., and Jia, J.G. (2014). Micro-structure and collapsibility of loess in China. Geomechanics from Micro to Macro, 1303-1308.

Campanella, R. G., and Mitchell, J. K. (1968). Influence of temperature variations on soil behaviour. Journal of Soil Mechanics and Foundations Division. ASCE**94**, No.3, 709–734.

Coccia, C. J. R., and McCartney, J. S. (2016). High-Pressure Thermal Isotropic Cell for Evaluation of Thermal Volume Change of Soils. Geotechnical Testing Journal. ASTM **39**, No.2, 217-234.

Delage, P., Sultan, N., and Cui, Y. (2000). On the thermal consolidation of boom clay. Canadian Geotechnical Journal **37**, No. 2, 343-354.

Di Donna, A. and Laloui, L. (2015). Response of soil subjected to thermal cyclic loading: Experimental and constitutive study. Engineering Geology **190**, 65-76.

Gens, A. (2010). Soil–environment interactions in geotechnical engineering. Géotechnique **60**, No. 1, 3-74.

Hilf, J. W. (1956). An investigation of pore water pressure in compacted cohesive soils. Technical Memorandum 654, U.S. Bureau of Reclamation, Washington, D.C.

Horseman, S. T. and McEwen, T. J. (1996). Thermal constraints on disposal of heat-emitting waste in argillaceous rocks. Engineering Geology **41**, 5–16.

Ng, C.W.W., Lai, C.H., and Chiu, C.F. (2012). A modified triaxial apparatus for measuring the stress path-dependent water retention curve. Geotechnical Testing Journal **35**, No. 3, 490-495

Ng, C. W. W., Shi, C., Gunawan, A., andLaloui, L. (2014). Centrifuge modelling of energy piles subjected to heating and cooling cycles in clay. Géotechnique Letters **4**, No. 4, 310-316.

Romero, E., Gens, A., and Lloret, A. (2001). Temperature effects on the hydraulic behaviour of an unsaturated clay. Geotechnical and Geological Engineering **19**, No. 3-4, 311-332.

Romero, E., Gens, A., and Lloret, A. (2003). Suction effects on a compacted clay under non-isothermal conditions. Géotechnique **53**, No. 1, 65-81.

Sadeghi, H., Hossen, S. B., Chiu, A. C., Cheng, Q., and Ng, C. W. W. (2016). Water retention curves of intact and re-compacted loess at different net stresses. Japanese Geotechnical Society Special Publication **2**, No. 4, 221-225.

Sultan, N., Delage, P., and Cui, Y.J. (2002). Temperature effects on the volume change behaviour of boom clay. Engineering Geology **64**, No. 2, 135-145.

Tang, A. M., Cui, Y. J., and Barnel, N. (2008). Thermo-mechanical behaviour of a compacted swelling clay. Géotechnique **58**, No. 1, 45-54.

Uchaipichat, A. and Khalili, N. (2009). Experimental investigation of thermo-hydro-mechanical behaviour of an unsaturated silt. Géotechnique **59**, No. 4, 339-353.

Zhou, C., Xu, J., and Ng, C. W. W. (2015). Effects of temperature and suction on secant shear modulus of unsaturated soil. Géotechnique Letters **5**, No. 3, 123-128.

List of tables

List of figures

Table 1 Details of experimental programme

Test ID	Specimen Type	Suction (kPa)	Temperature (^{0}C)	Void ratio	
				Initial	After wetting
R0	Re-compacted	0	23→33→43→53→ 43→33→23→13→5→ 13→23	1.17	0.86
R100	Re-compacted	100		1.17	0.97
I0	Intact	0		1.15	0.93
I100	Intact	100		1.17	1.01

Table 2 Index properties of loess

Property	Value
Specific gravity	2.69
Sand content (%)	0.1
Silt content (%)	71.9
Clay content (%)	28.0
Liquid limit (%)	36
Plastic limit (%)	19
Plasticity index (%)	17

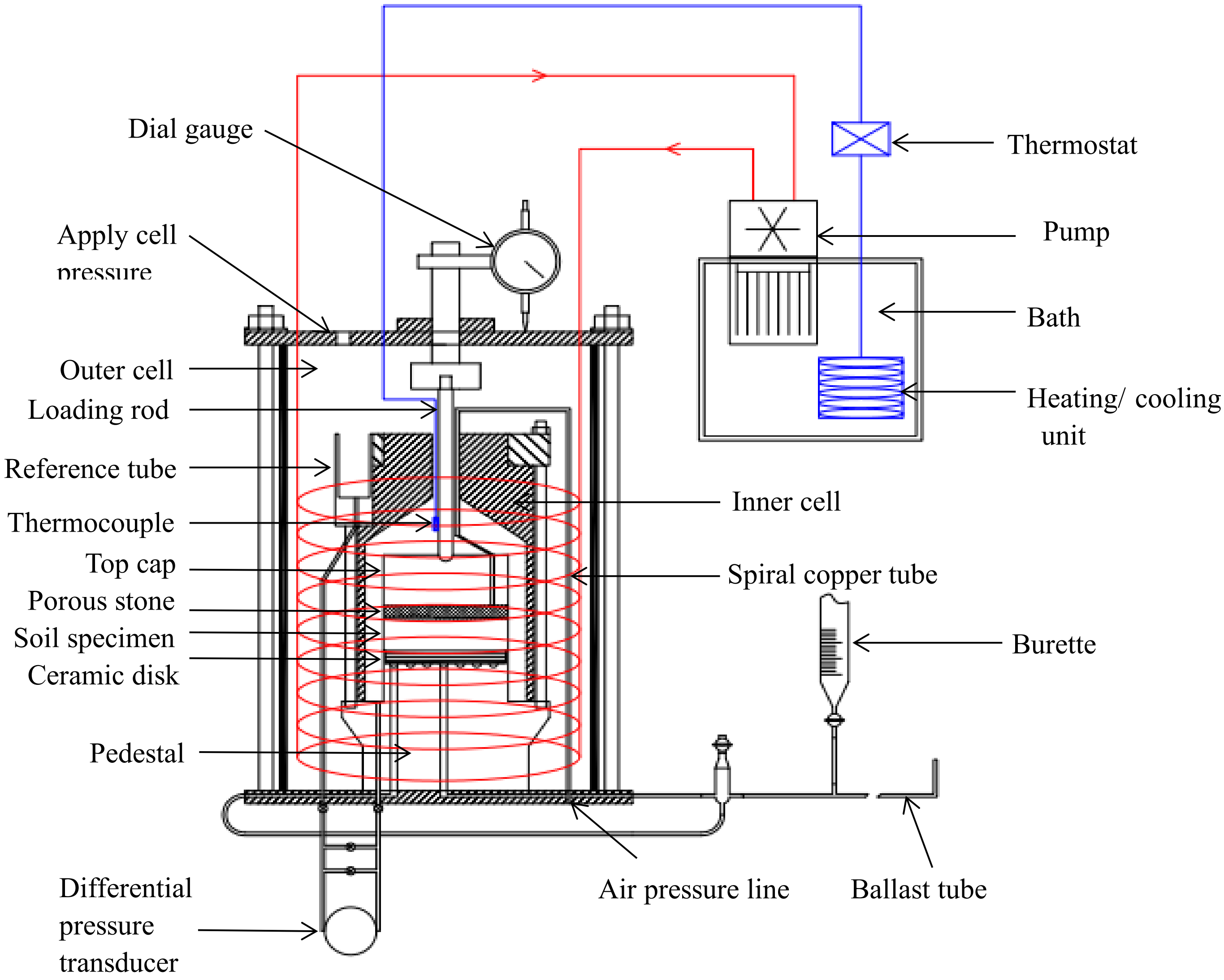


Fig.1 Schematic diagram of the suction- and temperature-controlled double cell triaxial apparatus

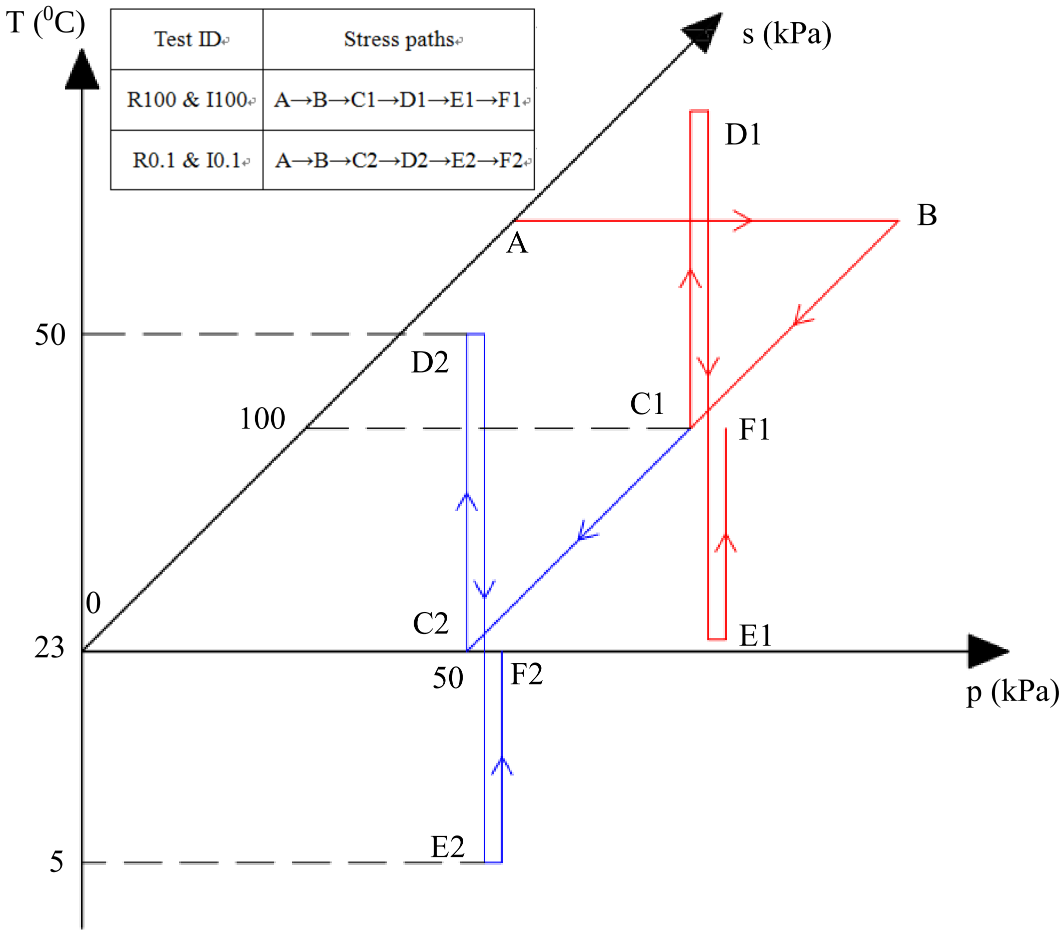
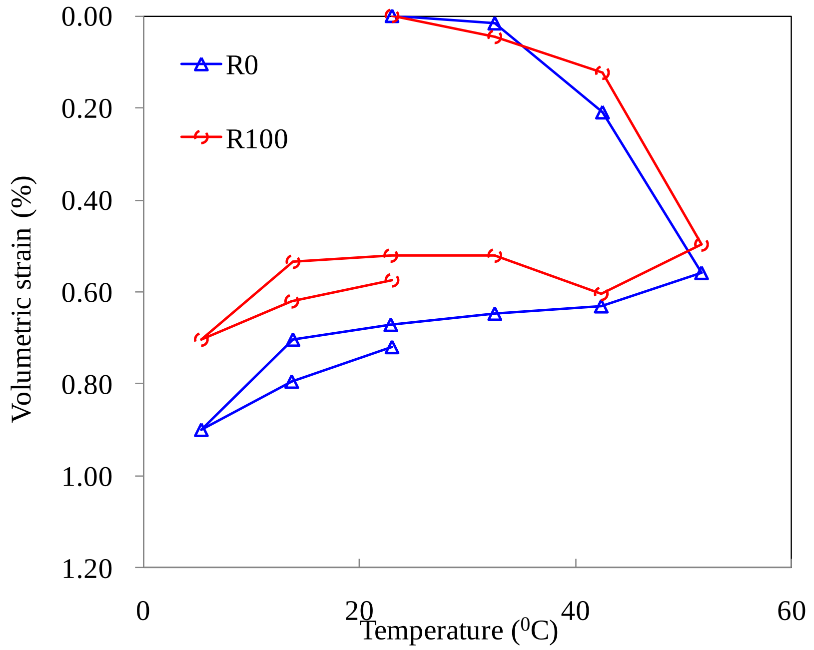


Fig.2 Thermo-hydro-mechanical path of each specimen

(a)



(b)

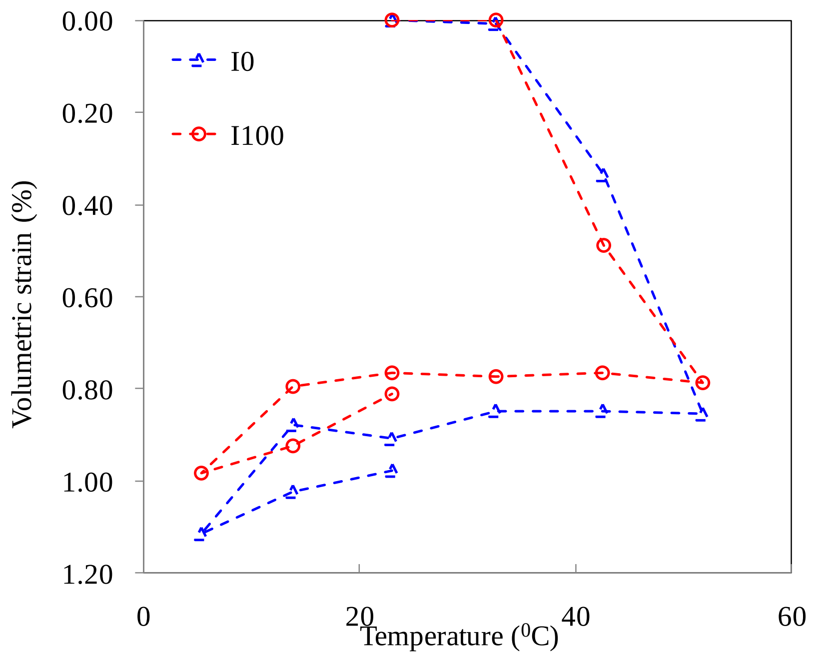


Fig.3 Suction effects on volume change of unsaturated soil during heating and cooling:

(a) re-compacted specimen, (b) intact specimen

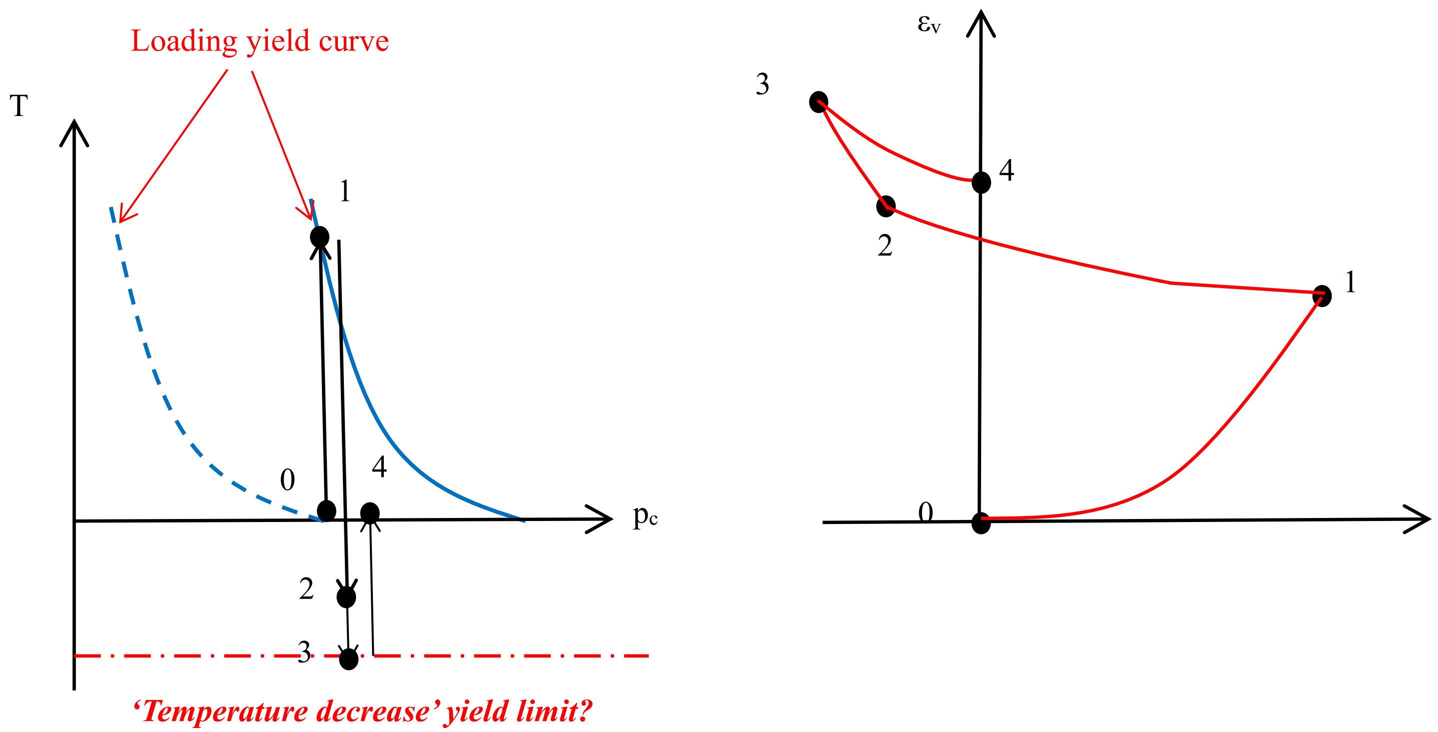
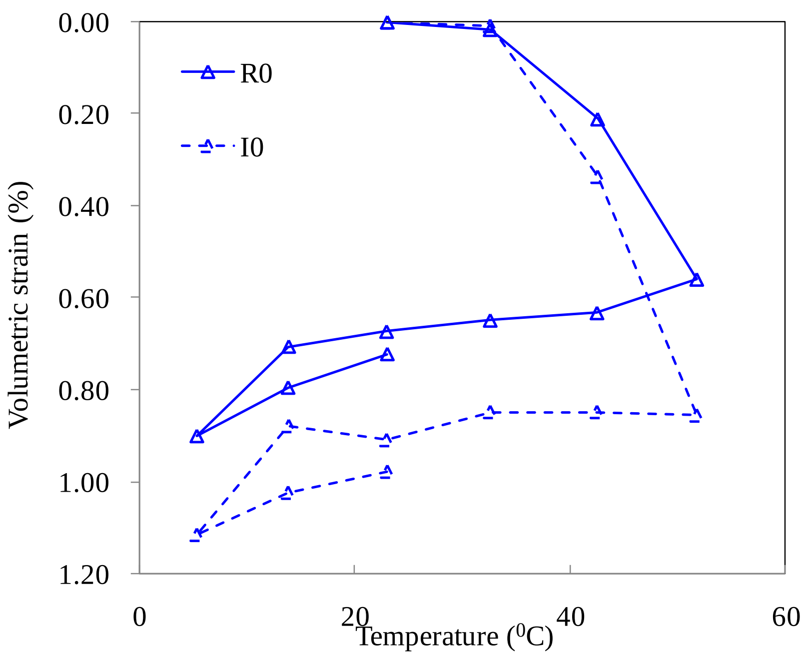


Fig.4 Postulation of the 'temperature decrease' yield limit

(a)



(b)

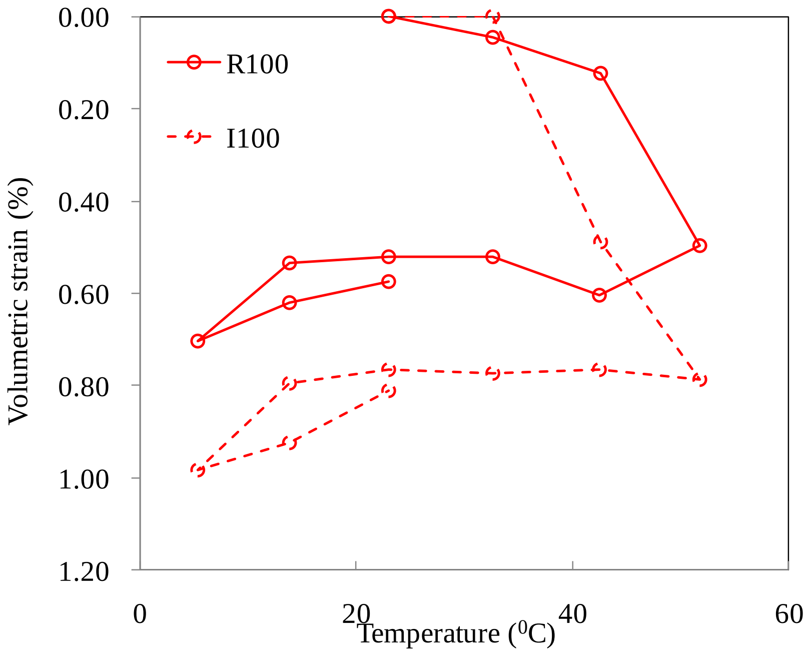
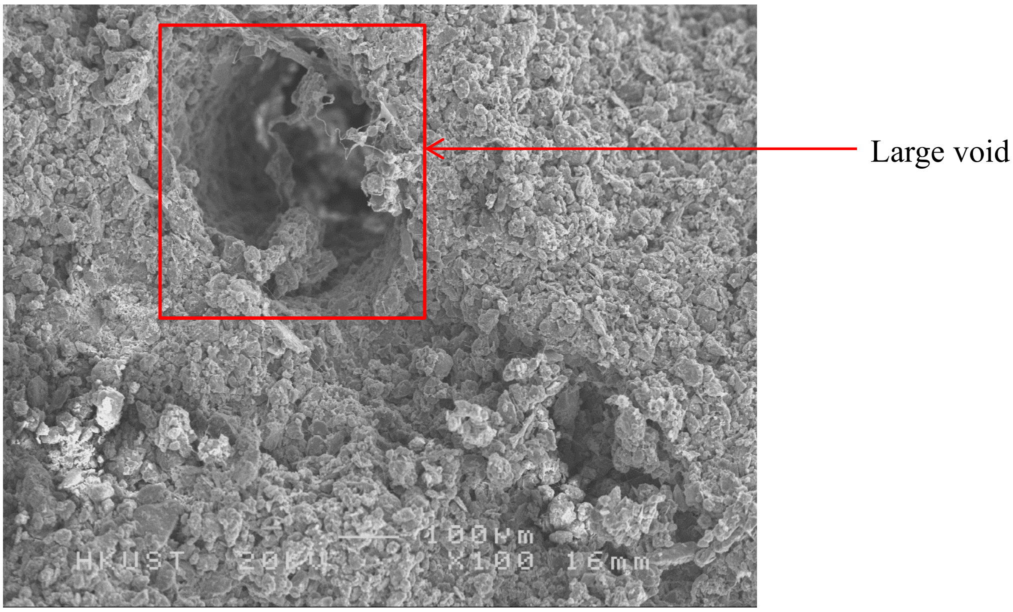


Fig.5 Effects of soil structure on volume change of unsaturated soil during heating and cooling: (a) s=0kPa, (b) s=100kPa

(a)



(b)

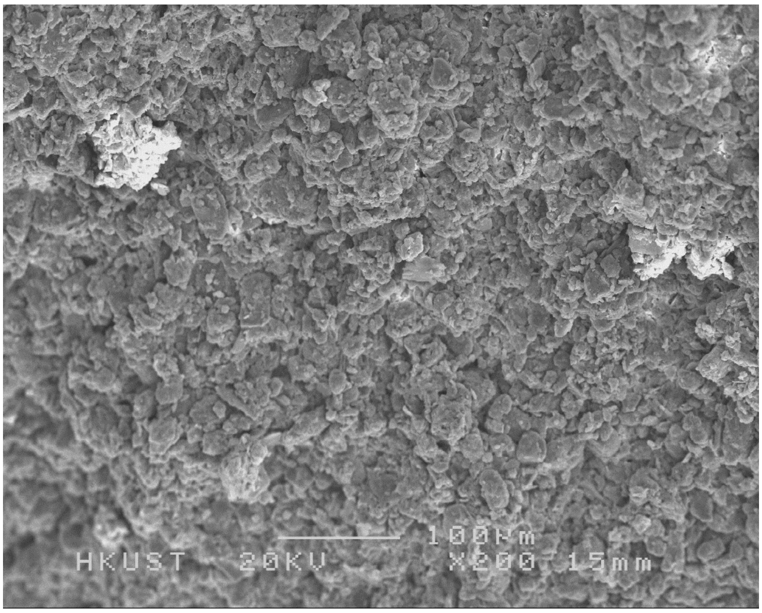


Fig.6 SEM images of (a) intact specimen, (b) re-compacted specimen

(Large void: diameter over 200μm which is the upper range of MIP test)