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Effects of specimen preparation method on the volume change of clay under cyclic thermal loads

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Abstract:

Previous investigations of the volume change of soil with different fabric patterns were mostly carried out at a constant temperature. To investigate the influence of specimen preparation method on the volume change of saturated clay under cyclic thermal loads, reconstituted, intact and recompacted specimens were tested. Thermal axial strains of these specimens in a normally consolidated state were measured using a temperature-controlled invar oedometer apparatus. The soil fabric of each specimen was evaluated using a scanning electron microscope (SEM) and a mercury intrusion porosimeter (MIP). All specimens showed continuous contraction as the number of thermal cycles increased, albeit at a decreasing rate. After five heating and cooling cycles with temperatures ranging from 15 to 70^{o}C, the accumulated plastic axial strain of the reconstituted specimen was 38% and 68% larger than those of the intact and recompacted specimens, respectively. The SEM visualizations and MIP measurements demonstrate that these observed differences are likely attributed to different distributions of clay particles in the soil specimens (with a 28% clay content). In the intact and recompacted specimens, most of the clay particles formed silt-size aggregates. In the reconstituted specimen, the clay particles filled the spaces between silt particles and the soil fabric was homogeneous overall.

Key words: Temperature effects; Strain; Laboratory tests

Introduction

Soil fabric refers to the arrangement of soil particles (Mitchell & Soga, 2005) and significantly influences the volume change behaviour of soil. Most previous studies about the effects of soil fabric on the volume change behaviour of soil were limited to conditions of a constant temperature. To understand the volume change behaviour of soil under cyclic heating and cooling, Campanella & Mitchell (1968) tested remoulded illite clay in a normally consolidated state. They found that plastic contractions accumulated as the number of thermal cycles increased, but at a reducing rate. Recently, Vega & McCartney (2015) and Di Donna & Laloui (2015) studied the volume change of recompacted silt and intact silty clay under cyclic thermal loads respectively. Both studies confirmed that for soil with a low overconsolidation ratio, the subsequent heating-cooling cycles induce a volume change that is as much as 50% of that induced by the first thermal cycle. In all of these studies, the influence of soil fabric on the change in the soil thermal volume was not specifically studied.

The principal objective of this study is to investigate the effects of soil fabric on soil volume change under cyclic thermal loads. To meet this objective, a low-plasticity clay was tested in three different states (i.e., reconstituted, intact and recompacted). Through temperature-controlled oedometer tests, the thermal axial strains of these three types of specimens were measured and compared. To assist in the interpretation of test results, the fabric of each specimen was evaluated through scanning electron microscope (SEM) and mercury intrusion porosimeter (MIP) tests.

Test apparatus

The thermal axial strains of soil specimens were measured using a temperature-controlled invar oedometer apparatus. Invar (thermal expansion coefficient: 5×10^{-7} $^{o}C^{-1}$) was used to minimise the thermal strain of the oedometer ring. The vertical displacement was measured with a linearly variable differential transformer (LVDT). The accuracy of the LVDT was about 0.025% (linearity error (0.25%) × stroke length (2.5 mm) ÷ sample height (25 mm)). The test setup was described in detail by Ng *et al*. (2016a).

During cyclic thermal tests, the measurement of soil deformation is affected by the apparent deformation, which is attributed to the thermal response of different components of the oedometer. The apparent deformation of the test system was carefully calibrated by performing cyclic heating and cooling tests on an aluminium specimen with a thermal expansion coefficient of 2.3×10^{-5} $^{o}C^{-1}$. The results are shown in Figure 1. An irreversible deformation of 0.15% was observed at the end of the first thermal cycle. For the second thermal cycle, the deformation was almost reversible with negligible hysteresis.

Test soil

Loess block samples (0.25 m × 0.25 m × 0.25 m in size) were taken from Xi'an in China. The in-situ gravimetric water content and dry density of the intact specimen were 9.2% and 1.18 g/cm^3, respectively. According to the Unified Soil Classification System (ASTM, 2006), the soil is classified as clay of low plasticity. Other physical properties of the test soil were described by Ng *et al*. (2016b). Figure 2 shows the soil intrinsic compression curve and the compression curves of the saturated intact and recompacted specimens. The intrinsic compression curve, which is inherent to the soil

(Burland, 1990), was obtained following the consolidation of slurry with an incremental vertical effective stress ranging from 0.1 to 800 kPa. The slurry was prepared by mixing the air-dried soil and de-aired water with a gravimetric water content of 1.5 times the liquid limit. For the intrinsic compression curve, the relationship between void ratio (e) and effective vertical stress (σ_v') is linear in the e-$log\sigma_v'$ plane. The compression curves of the saturated intact and recompacted specimens are highly non-linear. The compressibility increases dramatically when the vertical stress exceeds the preconsolidation pressure, which is estimated to be 19 and 7 kPa for the intact and recompacted specimens respectively. Furthermore, the compression curves of the intact and recompacted specimens lie above the intrinsic compression curve at an effective vertical stress ranging from 1 to 800 kPa, mainly attributed to the more resistant soil fabric of the intact and recompacted specimens (Burland, 1990).

Test program

Axial strains of the reconstituted, intact and recompacted specimens under cyclic thermal loads were measured and compared. Loess block samples were taken from a trial pit at a depth of 3.5 m, which corresponds to a vertical stress of about 50 kPa. To achieve a similar stress state and soil structure to that of the in situ case, an effective vertical stress of 50 kPa was applied to the reconstituted, intact and recompacted specimens. The fabric of each soil specimen was evaluated through SEM and MIP tests. The test program is summarized in Table 1.

Specimen preparation

To prepare the reconstituted specimen, the air-dried soil was thoroughly mixed with de-aired water with a gravimetric water content of 1.5 times the liquid limit. The slurry was consolidated in a one-dimensional consolidometer to the effective vertical stress of 50 kPa. The reconstituted specimen was then obtained by pushing the oedometer ring into the sample. The top and bottom portions of the specimen were trimmed with a wire saw.

To prepare the intact specimen, a rectangular block with dimensions of 80 mm × 80 mm × 50 mm was cut from the large block sample. The small rectangular block was then further trimmed into a circular specimen measuring slightly over 70 mm in diameter. Then an oedometer ring (70 mm in diameter; 25 mm in height) was slowly pushed into the circular specimen by hand to yield the final specimen. According to Atkinson *et al.* (1992), sample disturbance is minimised when these methods of specimen preparation are used.

To prepare the recompacted specimen, the air-dried soil was mixed with de-aired water with the same gravimetric water content of 9.2% as the intact specimen. The mixtures were statically compacted into the oedometer ring. The target dry density of 1.18 g/cm^3 was similar to that of the intact specimen.

Test procedures

To saturate the soil specimens, each specimen was submerged in de-aired water inside the oedometer chamber and subjected to a vacuum of 80 kPa for about 24 hours. During this saturation process, the total stress, pore water pressure and effective stress of the specimen applied were -80, -80 and 0 kPa, respectively. Both the recompacted and intact specimens were saturated using the same method for cyclic heating and cooling tests and one-dimensional compression tests. In addition, the specimens tested in this study were all saturated with de-ionized water with a pH of 7.0. This saturation process altered the chemistry of the pore water, which was slightly alkaline with a pH of 8.4 in the block sample. As the mineral of the tested loess was dominated by quartz (>80%), the loess is classified as a non-active material. The influence of pore water chemistry on the experimental results is expected to be limited (Mitchell & Soga, 2005). After saturation, the effective vertical stress of each specimen was increased to 50 kPa for consolidation. The effective vertical stress applied exceeded the soil preconsolidation pressure (see Figure 2) and therefore, the tested specimens were in a normally consolidated state.

After consolidation, each specimen was subjected to cyclic thermal loads at a constant effective vertical stress. In the heating phase, the soil temperature was increased from 25°C to 70°C at 2°C per hour. In the cooling phase, the temperature was decreased from 70°C to 15°C at 5°C per hour. During heating and cooling at these rates, two thermocouples installed at the boundary and center of the soil specimen showed nearly identical temperature measurements (differing by less than 0.1°C). Furthermore, the measured excess pore water pressure at the bottom of the soil specimen was almost zero. These measurements suggest that the selected thermal loading rates were appropriate.

To quantify the effects of creep, a series of oedometer tests were carried out on the reconstituted, intact and recompacted specimens without thermal loads. In each test, an effective vertical stress of 50 kPa was maintained for 165 hours, which was exactly the duration of the cyclic thermal tests. At the end of the oedometer tests, the mechanical creep-induced axial strain rates of the reconstituted, intact and recompacted specimens were 8.7×10^{-3}, 5.8×10^{-3} and 6.5×10^{-3} %/day, respectively. The measured mechanical creep-induced axial strain was deducted from the measured overall axial strain in each cyclic thermal test to obtain the thermally induced strain.

Interpretation of experimental results

Soil fabric of the reconstituted, intact and recompacted specimens

Figure 3(a) shows an SEM photograph of the reconstituted specimen. It can be seen that the soil fabric is homogeneous overall. Silt particles with a diameter of a few tens of micrometres can be clearly identified. More importantly, the spaces between these silt particles are filled with clay particles. Figure 3(b) shows a SEM photograph of the intact specimen. The clay/silt aggregates with diameters of a few tens of micrometres are widely distributed in the specimen. Figure 3(c) shows the SEM photograph of the recompacted specimen. The distribution of clay/silt aggregates in the recompacted loess is similar to that in the intact loess. The recompacted specimen was compacted on the dry side of optimum and exhibited a soil fabric featuring a flocculated structure (Sides & Barden, 1971).

Figure 4 shows the pore size distributions of the reconstituted, intact and recompacted specimens. For the reconstituted specimen, a single pore size distribution was measured with an average pore diameter of 2 μm. The intact specimen showed a bimodal curve defining a population of large (i.e., 6 μm) and small (i.e., 0.04 μm) pores. For the recompacted specimen, a similar bimodal curve was obtained. The MIP results show that aggregates were formed in the intact and recompacted specimens while a homogeneous fabric was observed in the reconstituted specimen. The MIP results are consistent with the SEM visualizations, revealing that the clay particles form silt-size aggregates in the intact and recompacted specimens but not in the reconstituted one.

Effects of soil fabric on volume change under cyclic thermal loads

Figure 5(a) shows the axial strains of the reconstituted specimen under cyclic thermal loads. During the first heating process, a contractive axial strain of 0.41% was observed. During the subsequent cooling phase, a much smaller contractive axial strain was induced (less than 0.05%). Furthermore, the irreversible axial strain accumulated as the number of thermal cycles increased, albeit at a decreasing rate. After four thermal cycles, the soil response reached a stable state in which almost all thermal strains were reversible. Figures 5(b) and 5(c) show the axial strains of the intact and recompacted specimens, respectively. The measured behaviour such as the accumulation of plastic axial strain follows a similar trend to that of the reconstituted specimen. To quantitatively investigate the soil volume change under cyclic thermal loads, the accumulated plastic axial strain at a given number of thermal cycles was further examined.

Figure 6 shows the accumulated plastic axial strain as the number of thermal cycles increased. After the first thermal cycle, the plastic axial strain of the reconstituted specimen was 0.46%, which was 21% and 31% larger than those of the intact (0.38%) and recompacted specimens (0.35%), respectively. For the subsequent thermal cycles, the difference in accumulated plastic axial strain among the three specimens increased with the number of thermal cycles. After thermal stabilization, the accumulated plastic axial strain of the reconstituted specimen was 0.84%, which was 38% and 68% larger than those of the intact (0.61%) and recompacted (0.50%) specimens, respectively. This is likely because the skeleton of the reconstituted specimen was dominated by clay particles, whereas silt particles prevailed in the recompacted and intact specimens (see Figure 3). As reported by Brochard *et al.* (2007), thermal effects on water adsorption and thus thermal strains are more significant for clay-dominated soil skeletons than silt-dominated soil skeletons. On the other hand, a high axial strain of 13.5% was measured during the consolidation of the intact loess (see Figure 2). The structure of the intact specimen was likely partially lost. Hence, the thermally induced volume change behaviour of the intact specimen became more resembling that of recompacted specimen. In addition, the void ratio does not affect the magnitude of the thermal volume change much, as long as soil specimens are normally consolidated (Abuel-Naga *et al.*, 2007). However, soil specimens with the same void ratio but different particle arrangements are likely to exhibit different thermal behaviours.

The preparation of the recompacted specimen may have induced a larger lateral stress than the preparation of the intact and reconstituted specimens. The observed differences in the measured thermal volume change among the reconstituted, intact and recompacted specimens may be partially attributed to their different lateral stresses. Coccia & McCartney (2012) studied the effects of stress-induced anisotropy on the thermal volume change of saturated Bonny silt using a thermo-hydro-mechanical true triaxial cell. They found that the contractive strain in the axial stress direction increased slightly in magnitude when the ratio between lateral stress and axial stress decreased from 1 to 0.5. Therefore, the observed smaller thermal strain of the recompacted specimen may be partially attributed to the larger lateral stress.

Conclusions

In this study, the effects of specimen preparation method on the volume change of soil under cyclic thermal loads were investigated by testing normally consolidated reconstituted, intact and recompacted specimens. Under cyclic heating and cooling, the plastic axial strains of all specimens accumulated but at a reducing rate. The accumulated plastic axial strain of the reconstituted specimen was about 38% and 68% larger than those of the intact and recompacted specimens, respectively. As revealed by the SEM and MIP results, these observed differences are likely attributed to differences in the soil fabric among the three types of specimens. For the reconstituted specimen, clay particles filled the spaces between silt particles and the soil fabric was homogeneous in general. On the contrary, most of the clay particles in the intact and recompacted specimens were gathered in a small number of silt-size aggregates.

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References

Abuel-Naga, H. M., Bergado, D. T., Bouazza, A. & Ramana, G. V. (2007). Volume change behaviour of saturated clays under drained heating conditions: experimental results and constitutive modeling. *Can. Geotech. J.* **44**, No. 8, 942-956.

Atkinson, J. H., Allman, M. A. & Böese, R. J. (1992). Influence of laboratory sample preparation procedures on the strength and stiffness of intact Bothkennar soil recovered using the Laval sampler. *Géotechnique* **42** No.2, 349-354.

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

Brochard, L., Honório, T., Vandamme, M., Bornert, M., & Peigney, M. (2017). Nanoscale origin of the thermo-mechanical behavior of clays. *Acta Geotech.* **12**, 1261-1279.

Burland, J. B. (1990). On the compressibility and shear strength of natural clays. *Géotechnique* **40**, No. 3, 329-378.

Campanella, R. G. & Mitchell, J. K. (1968). Influence of temperature variations on soil behaviour. *J. Soil Mech. Fdn Engng Am. Soc. Civ. Engrs* **94**, SM3, 709-734.

Coccia, C. J. R. & McCartney, J. S. (2012). A thermo-hydro-mechanical true triaxial cell for evaluation of the impact of anisotropy on thermally induced volume changes in soils. *ASTM Geotech. Testing J.* **35**, No. 2, 227–237

Di Donna, A. & Laloui, L. (2015). Response of soil subjected to thermal cyclic loading: Experimental and constitutive study. *Engng Geol.* 1**90**, May, 65-76.

Mitchell, J. K. & Soga, K. (2005). Fundamentals of soil behavior, 3rd edn. New York, NY, USA: John Wiley & Sons.

Ng, C. W. W., Mu, Q. Y. & Zhou, C. (2016a). Effects of boundary conditions on cyclic thermal strains of clay and sand. *Géotechnique Lett.* **7**, No.1, 73-78.

Ng, C. W. W., Sadeghi, H., Hossen, S. B., Chiu, C. F., Alonso, E. E. & Baghbanrezvan, S. (2016b). Water retention and volumetric characteristics of intact and recompacted loess. *Can. Geotech. J.* **53**, No.8, 1258-1269.

Sides, G., & Barden, L. (1971). The microstructure of dispersed and flocculated samples of kaolinite, illite, and montmorillonite. *Can. Geotech. J.* ***8***(3), 391-399.

Vega, A. & McCartney, J. S. (2015). Cyclic heating effects on thermal volume change of silt. *Environ Geotech* **2**, No.5, 257-268.

Table Lists

Table 1. Details of the test program

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Test ID	Specimen preparation method	e_0 (void ratio, initial state)	e_1 (void ratio, after mechanical consolidation)	e_f (void ratio, after heating-cooling cycles)
R	Reconstituted	1.442	0.812	0.797
I	Intact	1.278	1.095	1.082
RC	Recompacted	1.271	0.907	0.898

Note: All specimens were tested under a constant effective vertical stress of 50 kPa

Figure Lists

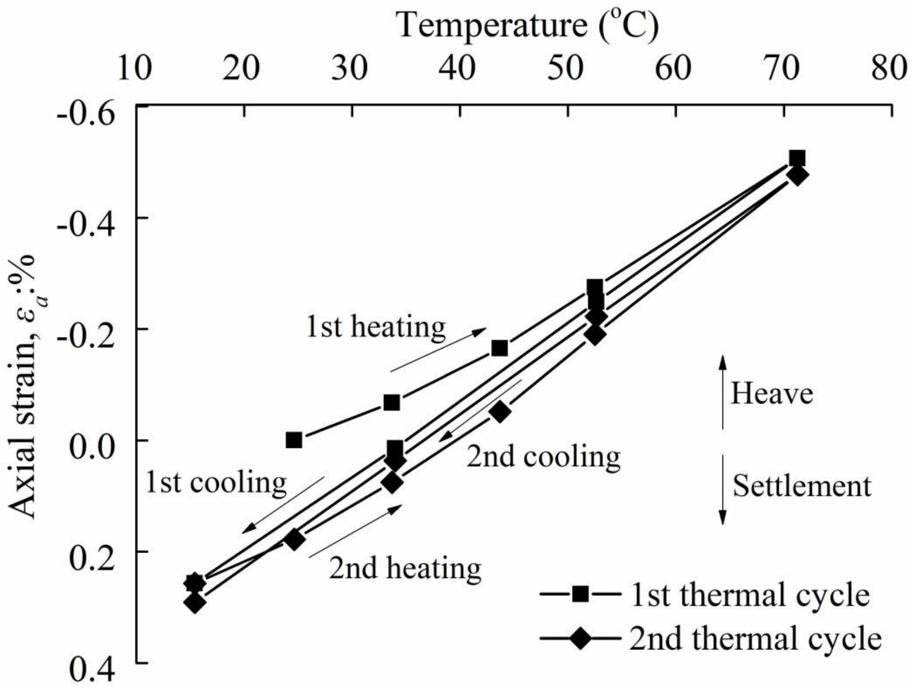


Figure 1.Thermal deformation of the oedometer system without the presence of a soil specimen

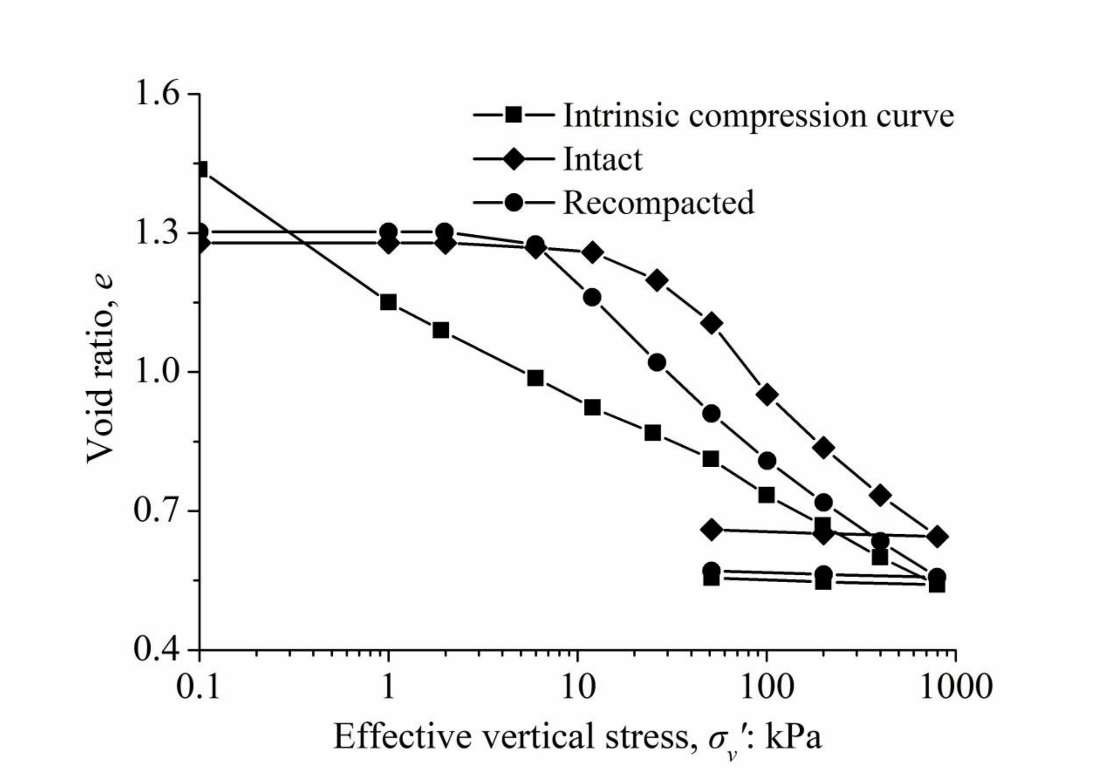


Figure 2. Soil intrinsic compression curve and compression curves of the intact and recompacted specimens

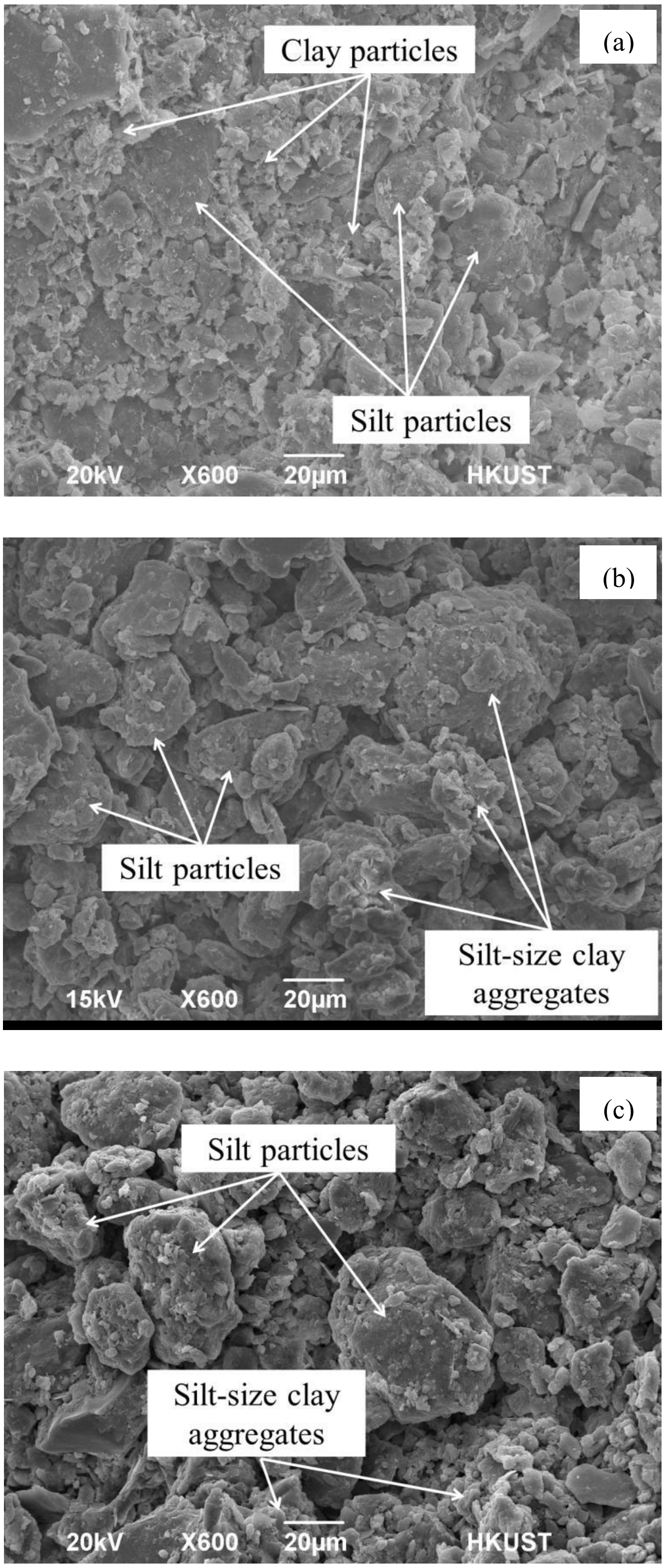


Figure 3. SEM photographs of (a) reconstituted specimen; (b) intact specimen; (c) recompacted specimen

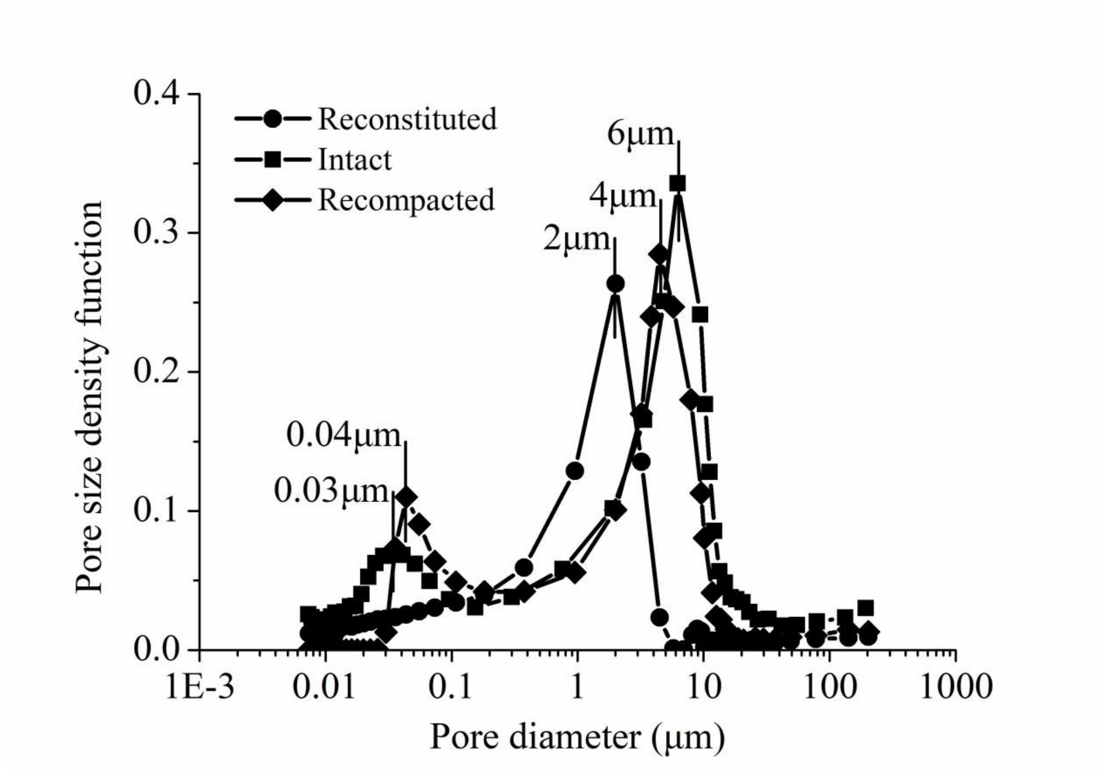
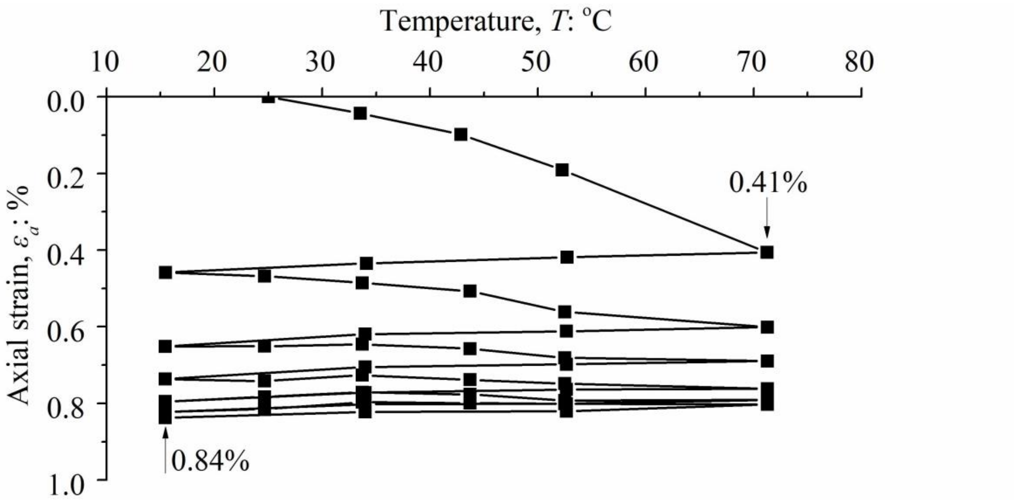
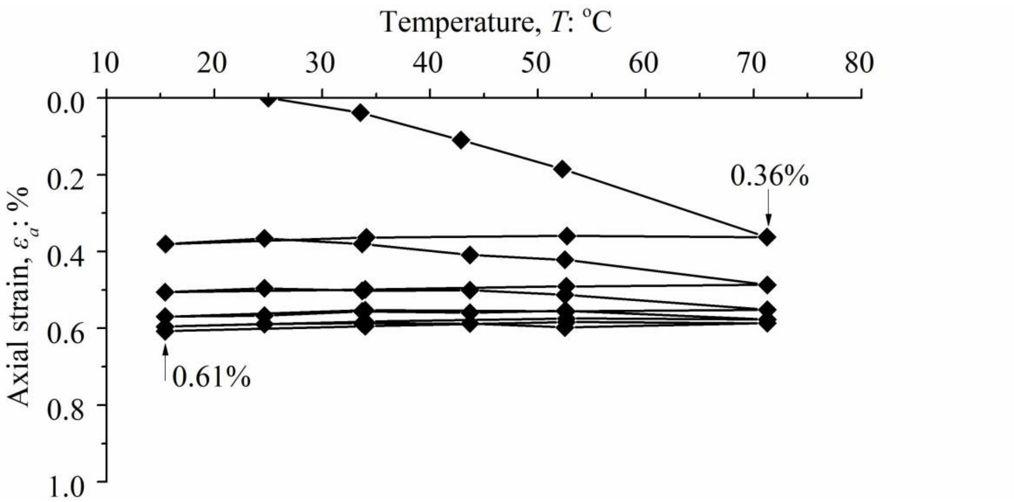


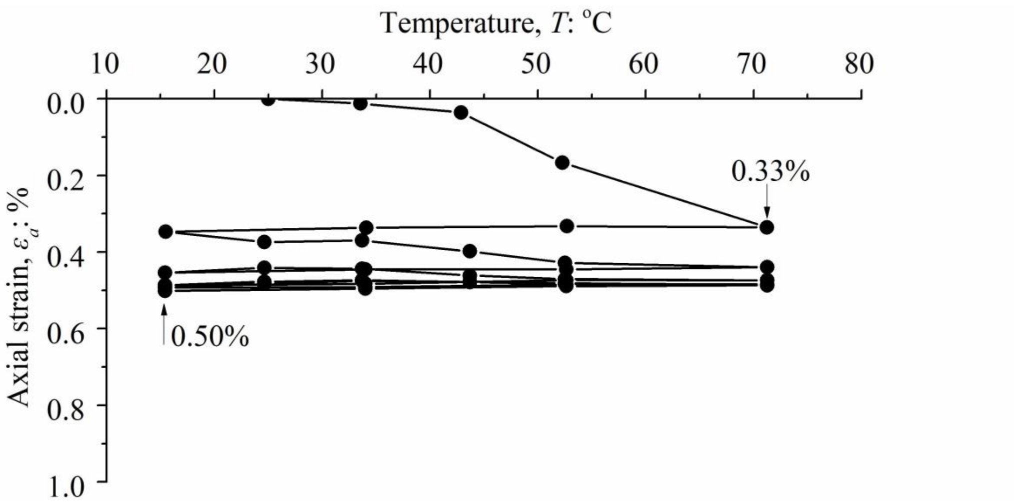
Figure 4 Pore size distributions of the reconstituted, intact and recompacted specimens



(a)



(b)



(c)

Figure 5. Thermal axial strains of (a) reconstituted specimen; (b) intact specimen; (c) recompacted specimen (σ_v' = 50 kPa)

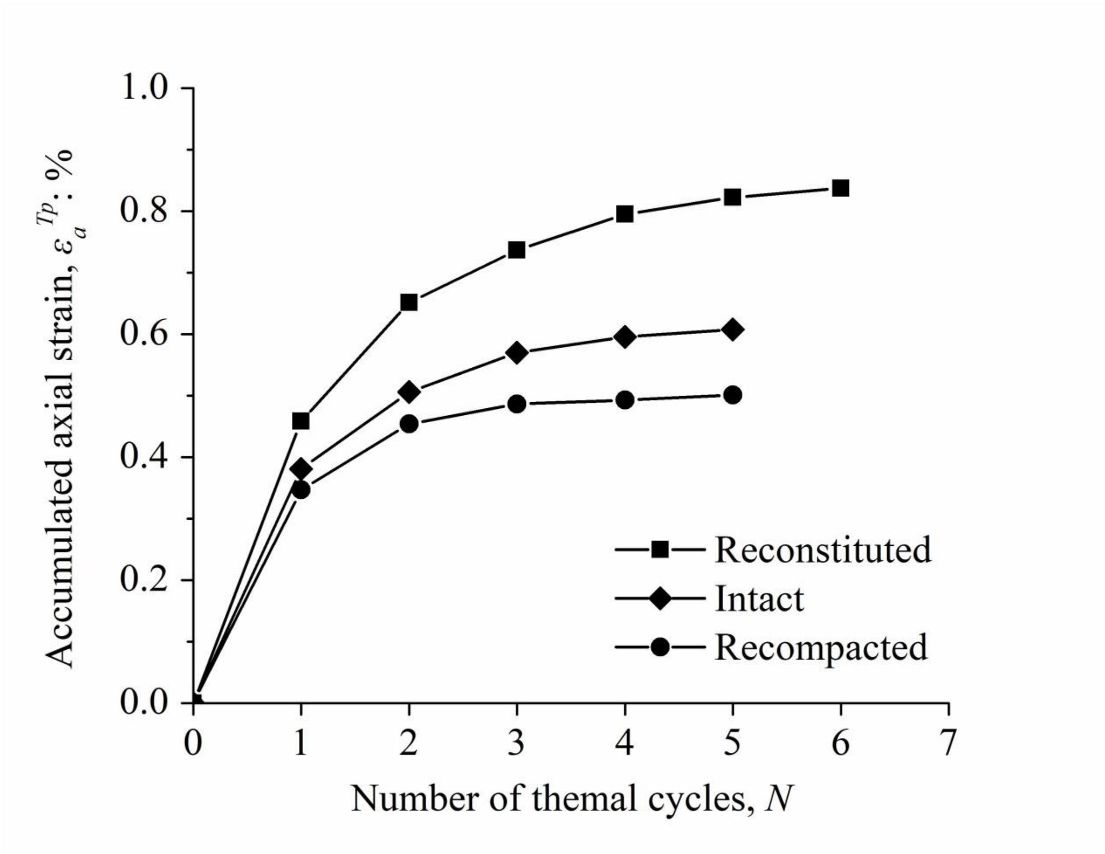


Figure 6. Accumulated plastic axial strains of the reconstituted, intact and recompacted specimens under thermal cycles (σ_v' = 50 kPa)