This is a post-peer-review, pre-copyedit version of an article published in Bulletin of Engineering Geology and the Environment. The final authenticated version is available online at: https://doi.org/10.1007/s10064-020-01899-4.

Volume change behaviour of a saturated lateritic clay under thermal cycles

Authors: C. W. W. Ng, D.B. Akinniyi and C. Zhou*

*Corresponding author

Author's affiliation and address:

Name: Charles Wang Wai Ng

Title: CLP Holdings Professor of Sustainability

Affiliation: Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

E-mail: cecwwng@ust.hk

Name: Damilola Bashir Akinniyi

Title: PhD Student

Affiliation: Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

E-mail: dbakinniyi@connect.ust.hk

Name: Chao Zhou

Title: Assistant Professor

Affiliation: Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

E-mail: c.zhou@polyu.edu.hk

Abstract

Many lateritic soils contain goethite and hematite, which have a low thermal expansion coefficient and also enhance the formation of soil aggregates. The influence of these minerals on the thermo-mechanical soil behaviour, however, has not been well understood. In this study, cyclic thermal strain of a small number of specimens of saturated lateritic clay was investigated over a temperature range of 5 to 70^{o}C using a thermal oedometer equipped with an invar ring. Both compacted and reconstituted specimens, which were expected to have different degrees of aggregation, were tested. The soil was characterised in terms of its mineralogy and microstructure determined respectively using x-ray diffraction (XRD) and scanning electron microscopy (SEM). It was found that an existing well-known empirical equation over-estimated the thermal expansion coefficient of normally consolidated (NC) lateritic clay by about 3 times. The discrepancy is mainly because the goethite and hematite in the lateritic clay enhance the formation of aggregates and stiffen the specimen. Even the reconstituted specimen contains many aggregates, as clearly revealed by the result SEM tests and. Goethite and hematite have much lower thermal expansion coefficient (TEC) than many clay minerals. On the other hand, it was found that both NC compacted and reconstituted specimens showed an accumulation of irreversible contraction under cyclic heating and cooling, but at a decreasing rate, where for a given number of thermal cycles, the measured thermal strain of NC reconstituted specimens was about 30% lower than that of the NC compacted specimens. This is mainly because the NC reconstituted specimen is much higher than the NC compacted specimen, even though they had experienced the same effective stress.

Keywords: Lateritic soil, Hematite, Goethite, Aggregate, Thermal cycles.

Introduction

Lateritic clays are widely distributed in the tropical and subtropical regions of the world, e.g. Brazil, Nigeria, India and China (Gidigasu, 1976; Paige-Green et al., 2014). They have been extensively used as construction materials in various applications, such as clay liners for waste disposal sites (Osinubi & Nwaiwu, 2006; Boscov et al., 2011). In the design of a liner, volumetric strain of clay is an important parameter because excess volumetric strain would induce cracks in the liner (Osinubi & Nwaiwu, 2006). Furthermore, according to Aldaeef & Rayhani (2015), daily and seasonal thermal cycles can cause volume change of the clay liner and other earthen structures such as embankments made of lateritic soils worldwide. Up to now, however, the influence of cyclic temperature variation on the volume change of lateritic clay is not well understood (Gadzama et al., 2017). As far as the authors are aware, no studies on cyclic thermal behavior have been reported in literature so this study based on a test small number of specimens of one lateritic soil is a timely contribution to knowledge of the topic. The volume change behaviour of soils (Favero et al., 2016; Abuel-Naga et al., 2007; Ng et al., 2016a; Ng et al., 2016b; Ng et al., 2017; Zhou & Ng, 2018; Ng et al., 2019b; Di Donna and Laloui, 2015) and rocks (Ersoy et al., 2007; Liu et al., 2017) under thermo-mechanical loads has been extensively studied by many researchers. However these results for other soils may not be applicable to lateritic soil, because the latter contain secondary minerals such as goethite and hematite which have low thermal expansion coefficients and are able to enhance the formation of soil aggregates (Schwertmann and Fitzpatrick, 1992). It is still unclear how these minerals affect the thermo-mechanical behaviour of soil.

In this study, a thermal oedometer was used to investigate the cyclic thermal strains of one particular lateritic clay. Both compacted and reconstituted specimens were tested. To interpret the cyclic thermal behaviour, soil mineralogy and microstructure were determined using X-ray diffraction (XRD) and scanning electron microscopy (SEM), respectively.

Test soil and specimen preparation

A lateritic soil weathered from a granitic parent rock in South West Nigeria, Africa was studied. Its physical properties were determined following the ASTM standards and these are summarized in Table 1. Accordingly, it was classified as a sandy lean clay according to the unified soil classification system (ASTM, 2011). The minerals present in the soil which were identified using the X-ray diffractometer and summarized in Table 2, comprised quartz, hematite, goethite, gibbsite and kaolinite. Goethite and hematite are secondary minerals formed during intense chemical weathering of the granitic parent rock and are rarely found in other soil types (Gidigasu, 1976). Goethite is a hydroxide of iron, and hematite is an oxide of iron. More properties of the soil were reported by Ng et al. (2019a).

To prepare compacted specimen, oven-dried soil was mixed water with a water content of 9%. Then, the soil was compacted to a dry density of 1.33 Mg/m^3 using the under-compaction method proposed by Ladd (1976). On the other hand, the reconstituted specimen was prepared by mixing a dry soil with de-aired water to a gravimetric water content of 1.5 times the liquid limit. The slurry was then poured in a one-dimensional consolidometer and consolidated to an effective vertical stress of 50 kPa. To saturate soil specimens, they were submerged in de-aired water inside the oedometer chamber subjected to a vacuum of 80 kPa for about 24 hours (Ng et al., 2019b). Furthermore, the water content and void ratio of all specimens were measured after tests and this confirmed that all specimens were fully saturated. During the heating and cooling process, all specimens were submerged in water which prevented moisture loss from the specimens and ensured they were fully saturated. After tests, the values of the water content of each specimen was measured by oven drying

To investigate the microstructure, three specimens were prepared in the same method as described above. After preparation, 5 mm cubes were trimmed from each specimen, rapidly frozen using liquid nitrogen and placed in a freezing unit with a vacuum chamber and dried by sublimation of the frozen water at a temperature –40^{o}C. Thereafter, the dried specimens were tested directly using SEM equipment. It should be pointed out that the freeze-drying technique is one of the most appropriate methods for dehydrating soil specimens for microstructural analysis (Penumadu and Dean 2000). Its major advantage is that during the rapid freezing process, soil water does not have enough time to recrystallize. The liquid water changes to the solid state directly, without altering the volume and texture of soil specimen (Penumadu and Dean 2000).

Test program and test equipment

The 5 specimens were subjected to cycles of heating and cooling in a thermal oedometer equipment with an invar ring. As the thermal expansion coefficient (TEC) of invar is about 30 times smaller than that of the soil skeleton, lateral strain of soil specimen during heating and cooling was negligible. Details of the experimental programme are summarized in Table 3. The normally consolidated (C-NC) and over-consolidated (C-OC) tests were in duplicates while one reconstituted (Re-NC) specimen was tested. The duplicate specimens were tested to demonstrate repeatability of the test results. The measured soil strains were compared with other fine-grained soils using empirical correlation between thermal strain and plasticity index (PI). The essence of this comparison was to highlight the influence of mineralogy on the response of the lateritic specimens. The thermal properties of several soil minerals were also investigated and used in the interpretation of the experimental results. The vertical strain of soil specimen was measured using a LVDT with an accuracy of 0.025%. A pore-water pressure transducer was installed at the bottom of the specimen to monitor the pore water pressure. More details of the equipment are reported in Ng et al. (2019b). Previous studies revealed that the cyclic thermal strain of a specific soil is mainly affected by the over-consolidation ratio (OCR), specimen preparation method and temperature history (Cekerevac

& Laloui, 2004; Vega & McCartney, 2014; Ng et al., 2019b). These factors are all properly considered in this test program, even though it only consists of five tests, as shown in Table 3.

Test procedures

Each test was carried out in two stages: mechanical consolidation and cyclic heating and cooling. Figure 1 shows the compression curves obtained during one-dimensional consolidation and the initial state of each specimen before thermal cycles. The slope of the compression line (λ) was 0.08 and 0.09 for the compacted and reconstituted specimens respectively. Figure 2 shows the stress paths for specimens where the C-NC and Re-NC specimens were consolidated to an effective vertical stress of 50 kPa (A→B), which is higher than their pre-consolidation stress. Hence, the specimens are on the Normal Compression Line (NCL) in Figure 1. The normal compression line (NCL) denotes the relationship between void ratio and effective stress during primary loading. When the state of a soil specimen is on the NCL, the current effective stress of the specimen is the maximum one experienced by the specimen in its stress history. Specimen C-OC was initially consolidated to an effective vertical stress of 200 kPa (A→ D) and unloaded to 50 kPa (D →B), making it over-consolidated with an over-consolidation (OCR) equal to 4. Over-consolidation ratio (OCR) is the ratio of the maximum effective stress in the stress history to the current effective stress. It is widely used to describe the stress history of soil specimen. Lateritic soils are usually found in an over-consolidated condition, particularly at the shallow depths (Ajayi, 1985).

At the second stage, the specimens were subjected to thermal cycles under drained conditions in the temperature range from 5 to 70°C ($B \rightarrow C_1 \rightarrow C_2 \rightarrow B$ per cycle). During the heating and cooling process, all specimens were submerged in water to prevent moisture loss and keep the soil specimens fully saturated. After calibration using two thermocouples installed at the boundary and centre of the soil specimen, the estimated rates of thermal loading averaged 2 and 5°C/hour during heating and cooling, respectively. Furthermore, the maximum excess pore-water pressure generated at the bottom of the soil specimens was less than 2 kPa, which confirmed that the selected thermal loading rates were appropriate.

Interpretation of experimental results

Cyclic thermal strain of compacted specimens

Figure 3a shows the response of the C-NC specimen during four heating and cooling cycles. The volumetric strains of the two duplicated specimens were very close, with a maximum difference of 0.05%, suggesting the measured results have a high repeatability. A contractive strain of 0.15% was observed on the first heating from 20 to 70^{o}C. During the subsequent cooling, a slight contraction was first observed from 70 to 30^{o}C. Starting from 30^{o}C, the specimens showed a much larger contraction rate down to 5^{o}C. Similarly, through heating and cooling tests on loess (a clay with low plasticity), Ng et al. (2016a) observed a significant change in the contraction rate during the cooling process. In fact, the soil tested by Ng et al. (2016a) was about 30% looser than in the present tests and they attributed this behaviour to particle rearrangement induced by the cooling. For the second heating, an expansion was observed from 5 to 30^{o}C, thereafter, the soil contracted up to 70^{o}C. During the second cooling, specimens first expanded down to about 40^{o}C and then contracted until the end of the second cycle at 5^{o}C. The responses during the third and fourth cycles were qualitatively similar to those during the second cycle. After four cycles, the specimens became stable.

Figure 3b shows the thermally induced volumetric strain of the C-OC lateritic specimen. The difference in the measured volumetric strain for the duplicates was very small, at below 0.02%. Compared with the C-NC specimen, the thermal strain was much smaller, which is probably because of the dense packing of the soil particles/aggregates in the C-OC specimen.

Some previous researchers (Demars and Charles, 1982; Sultan et al., 2002; Abuel-Naga et al., 2007) have presented correlations for thermally induced strains in clays with plasticity index (PI), as shown in Figure 4a. For fair comparison, all these soils were tested in a NC condition and their volumetric strain was normalized by their temperature increments ranging from 40 to 50°C. The experimental results were fitted using an exponential equation, as shown in the figure, which provides a reasonable fit for all soils including the lateritic clay, however, the thermal strain of the lateritic clay is over-estimated by about three and half times. To explain the uniqueness of the lateritic clay, its TEC is determined from the average slope of the temperature-strain relation during the cooling process. The average TECs obtained from the cooling slope are essentially reversible and related to the thermal contraction of the solid particles (Sultan, et. al., 2002). Figure 4b shows the comparisons of the TECs for the other fine-grained soils. For the lateritic clay, the TEC estimated from the cooling slope for the reconstituted specimen was about 0.6 x 10^{-3}%/°C. It can be seen that the TECs well fit a linear equation, except the lateritic clay. The low TEC of the lateritic clay is mainly because it contains about 30% of hematite and goethite, the TECs of which are about 40% and 60% lower than that of quartz respectively (see Table 2). Hence, the change in soil particle size is much smaller in the lateritic clay and the thermally induced particle rearrangement and volumetric strain in the lateritic clay is therefore much smaller. The thermal expansion coefficients of goethite and hematite were measured by Gleason et al (2008) and Huotari & Kukkonen (2004) using a Bragg-(G) diamond cell, in which the temperature and deformation of specimen were respectively controlled and monitored. Based on the measured deformation-temperature relation, the thermal expansion coefficient was calculated.

Cyclic thermal strain for reconstituted specimens

Figure 5 shows the response of the Re-NC specimen during heating and cooling cycles. Its cyclic thermal strain was qualitatively similar to that of C-NC specimen (see Figure 3a) and its irrecoverable contractive strain induced by four thermal cycles was 0.25%, which was about 30% lower than the total strain measured in C-NC specimens. The behaviour of the lateritic clay in this study was not consistent with the findings of Ng et al. (2019b) where a higher thermal strain was measured for a reconstituted loess clay than for the compacted specimen. To further explain unique behaviour of the lateritic clay, the microstructures respectively shown in Figures 6a and 6b, of the Re-NC and C-NC specimens were studied using SEM tests. The microstructure of the C-NC lateritic clay was also compared with that of NC loess, which has a similar PI. Smaller aggregates are observed in the Re-NC specimen, which hence is more compressible. After compression, the Re-NC specimen therefore became denser and more stable as shown in Figure 1, so the thermal strain was lower than for the C-NC specimen, the difference being a consequence of a higher density.

Figure 6b and 6c compare the SEM images of the C-NC lateritic clay and a compacted loess, where both specimens were prepared at similar water content and dry density (Ng et al., 2019b). The average diameters of the aggregates in the lateritic and loess specimens were about 90 µm and 45 µm, respectively. The reconstituted specimen had smaller aggregate size than the recompacted specimens. Considering that these two specimens had the same void ratio, the reconstituted specimen would be expected to have less intra-aggregate pores and more inter-aggregate pores. Since soil compressibility is mainly controlled by inter-aggregate pores, the reconstituted specimen would be more compressible (Vallejo & Zhou, 1994).

Conclusions

This paper reports a unique experimental study of the cyclic thermal properties of a lateritic clay, with four compacted specimens and a reconstituted specimen tested. As far as the authors are aware, this small study is the first investigation of cyclic thermal strains of lateritic clays to be published. In addition, to better understand the differences between lateritic clay and other clays, extensive data from the literature were collected and analysed. It is found that the thermal strain of the compacted lateritic specimen in a normally consolidated state is over-estimated by about three times using a well-known semi-empirical equation, which was proposed based on experimental results of non-lateritic soils. The discrepancy is attributed to the presence of goethite and hematite, which possess relatively low thermal expansion coefficients, in the lateritic clay.

The reconstituted and compacted lateritic NC specimens show an accumulation of volumetric contraction during cyclic heating and cooling. The thermal strain of reconstituted specimens is smaller than that of compacted specimen by about 30%. The difference is mainly because during the preparation of reconstituted specimen, some small particles are separated from the aggregates, as revealed by the SEM. Hence, the reconstituted specimens were compressed to a state with a lower void ratio, prior to the application of thermal cycles.

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 AoE/E-603/18, 16212218 and PolyU 162048/17E.

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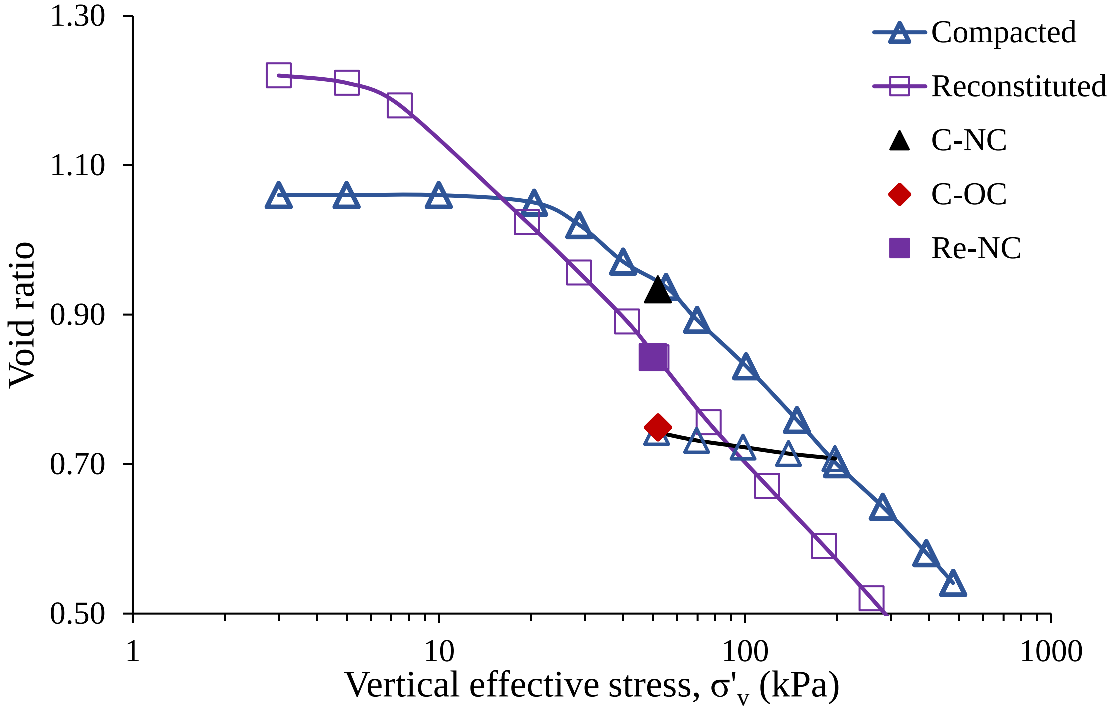


Fig. 1. Compression curve for compacted and reconstituted lateritic specimens and initial state of the three specimens prior to thermal cycles

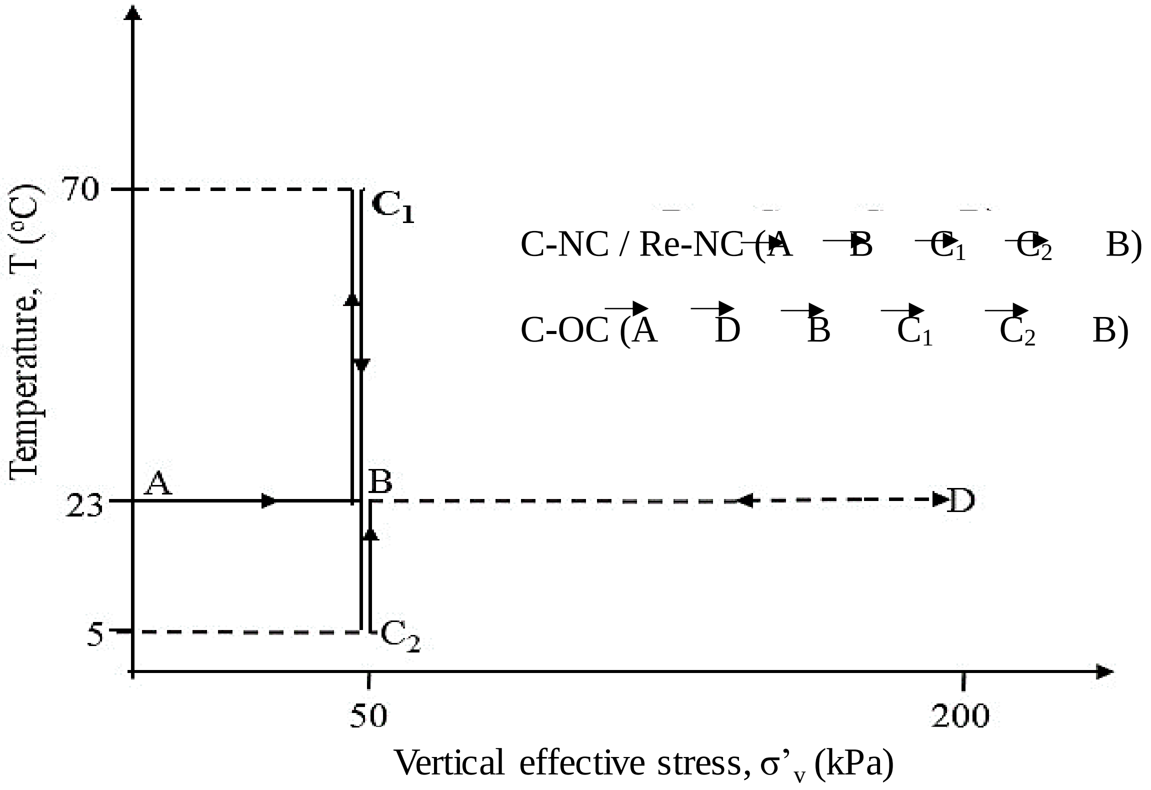
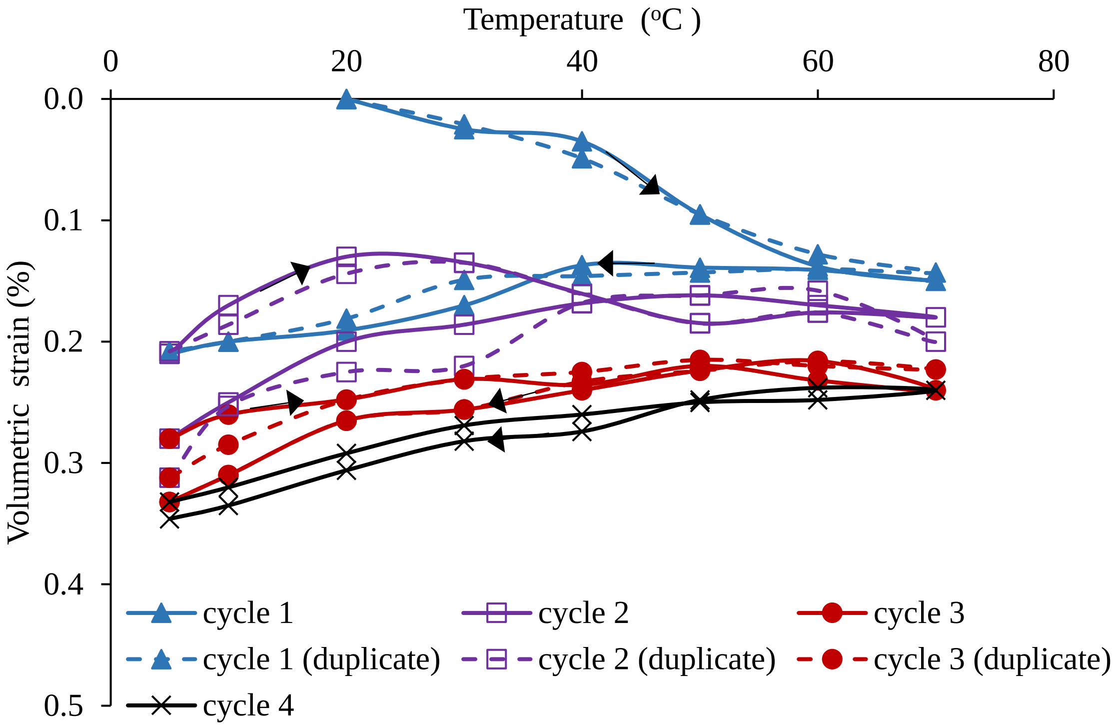
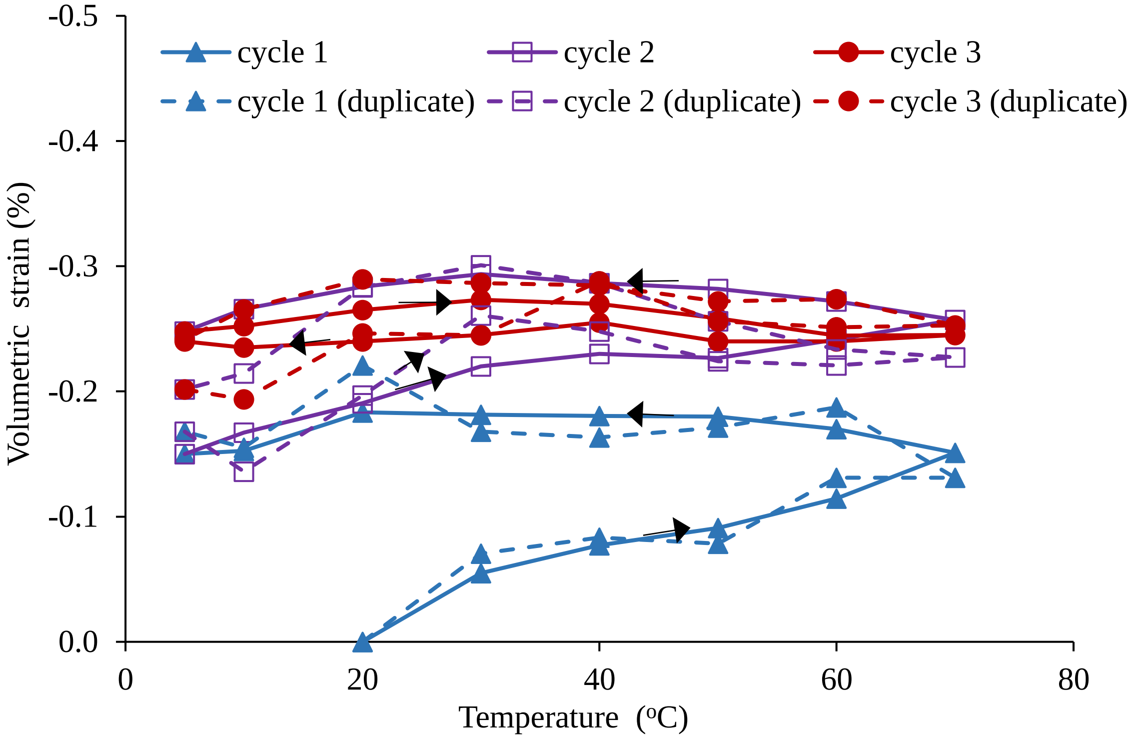


Fig. 2. Thermo-mechanical path of the three lateritic specimens

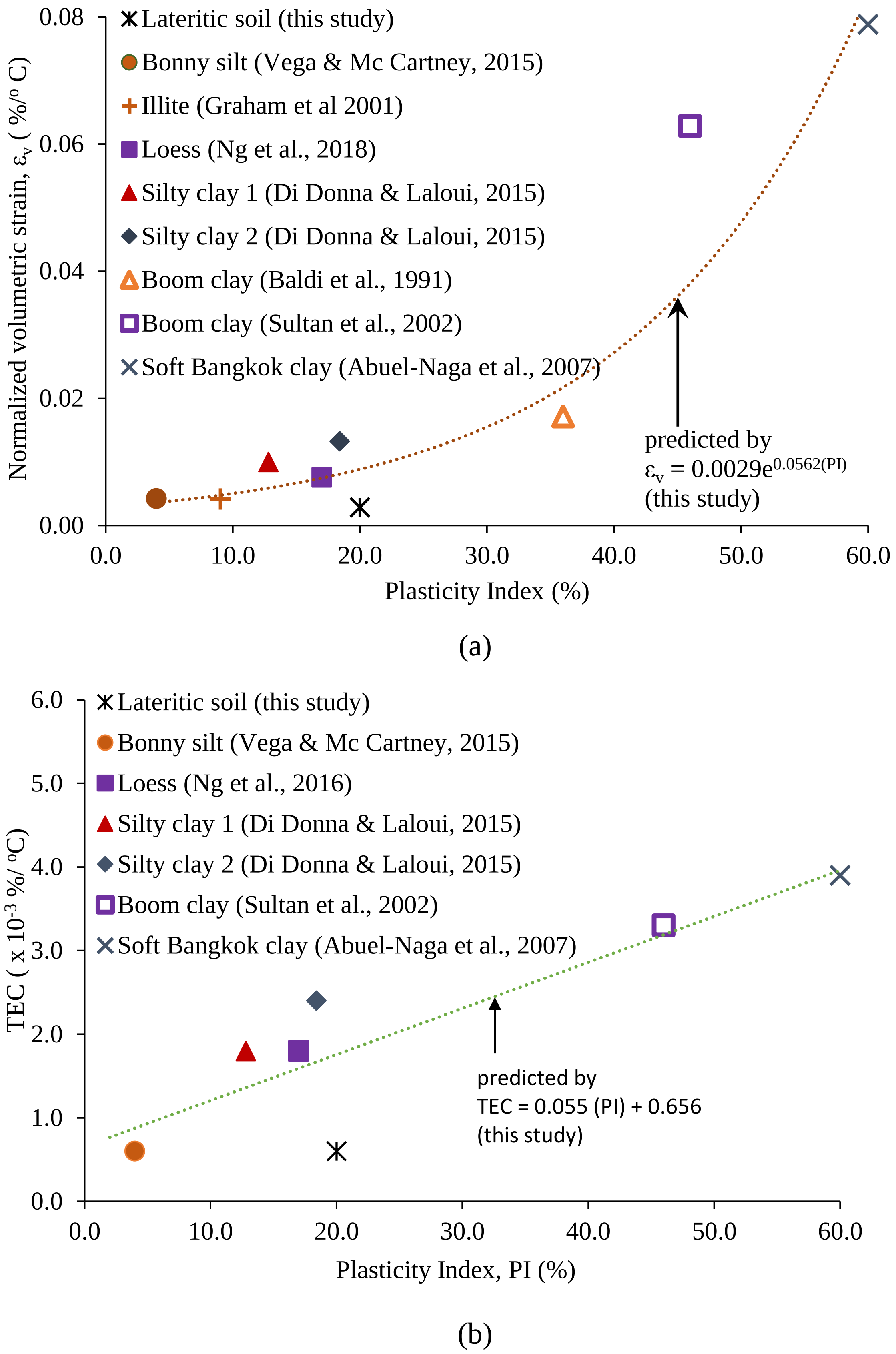


(a)



(b)

Fig. 3. Measured thermal strain of lateritic compacted specimens (two duplicates at each condition): a) normally-consolidated specimen (C-NC) and b) over-consolidated specimen (C-OC)



(a)

(b)

Fig. 4. The relationship between (a) plasticity index of soil and normalized volumetric strains (b) plasticity index of soil and thermal expansion coefficient for different NC clays (ΔT=60–70 °C, T_o=20–25 °C)

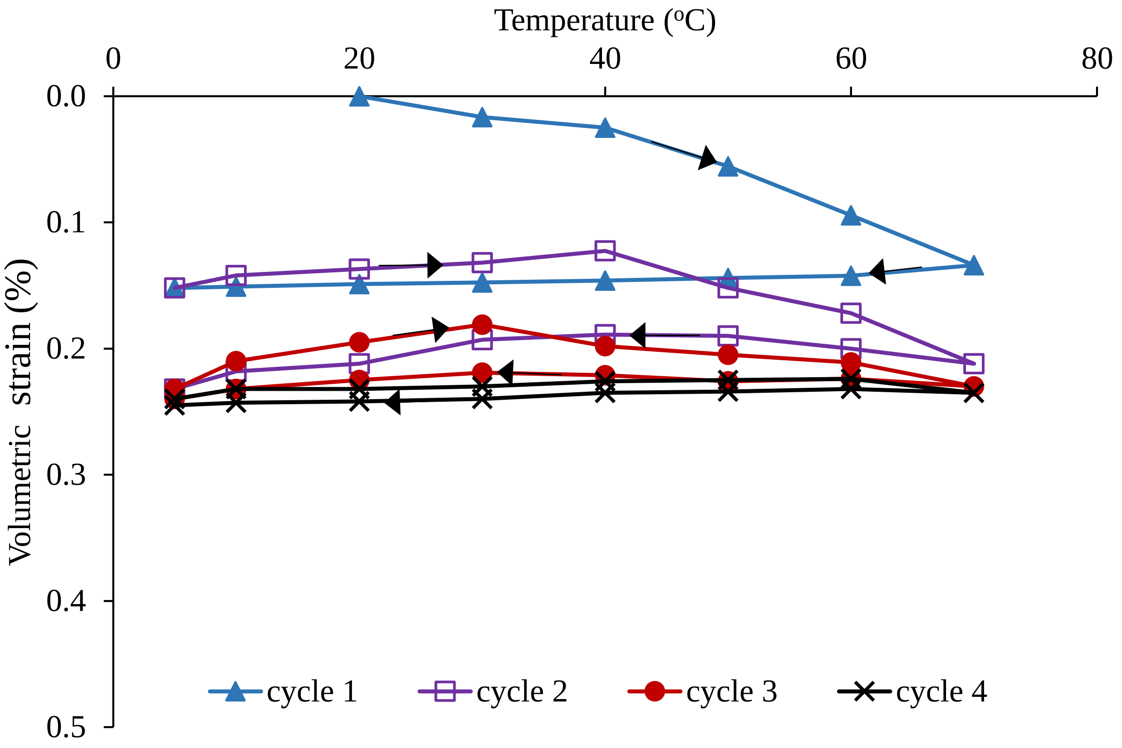


Fig. 5. Measured thermal strain of reconstituted lateritic specimen at normally-consolidated condition (Re-NC)

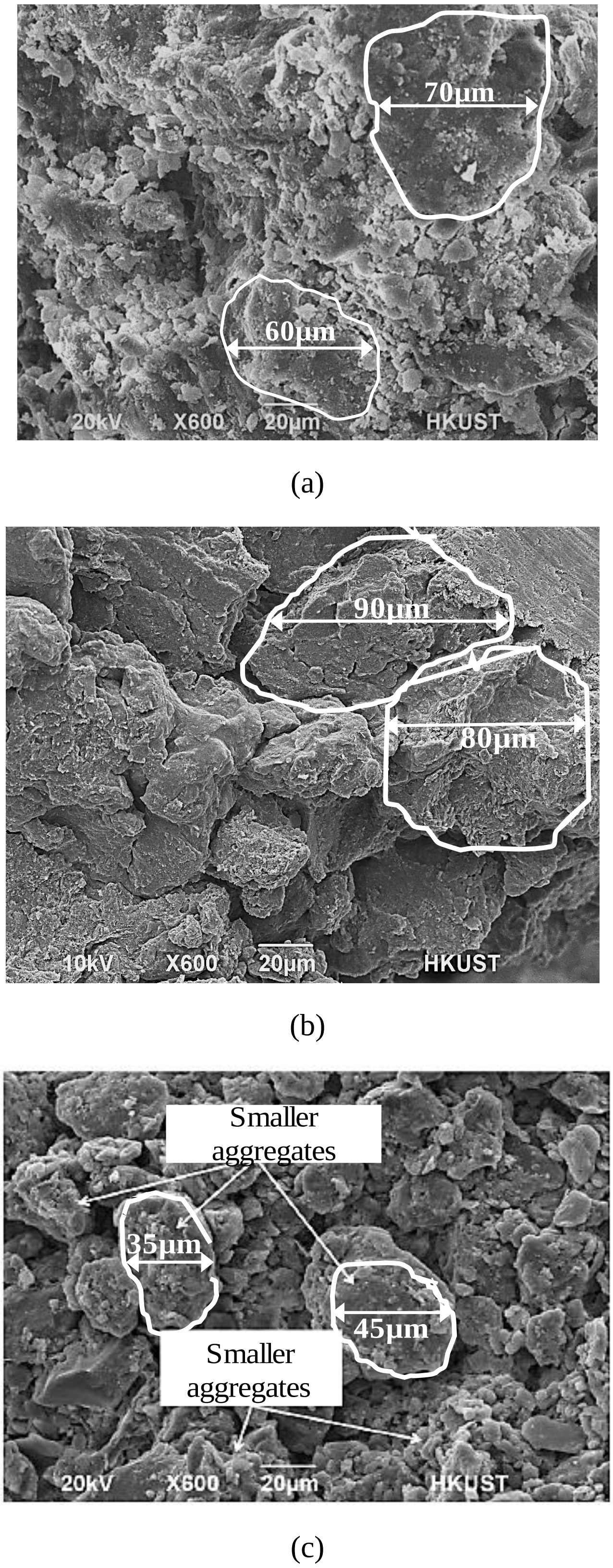


Fig. 6. SEM image of microstructure of (a) Re-NC (b) C-NC lateritic clay (this study) and (c) loess (Ng et al., 2019)

Table 1. Physical properties of the lateritic soil studied.

Index Test	Lateritic Soil
Standard compaction test	
Maximum dry density: Mg/m^3	1.696
Optimum water content: %	20
Grain size distribution	
Percentage of sand: %	42
Percentage of silt: %	16
Percentage of clay: %	42
Specific gravity	2.67
Atterberg limits	
Liquid limit: %	44
Plastic limit: %	24
Plasticity index: %	20
Soil classification based on USCS (ASTM,2011)	CL

Table 2. TEC values for major minerals in the lateritic soil and some other typical soils (data from Gleason et al. 2008; Huotari and Kokkonen, 2004; McKinstry, 1965)

Soil Type	Mineral(s)	TEC ($10^{-6}/^{o}C$)	Quantity (%)
Lateritic soil (this study)	Quartz	0.5	65
	Hematite	0.3	17
	Goethite	0.2	9
	Kaolinite	5.2	9
Other soils	Illite	1.5	N.A.
	Muscovite	3.5	
	Talc	3.7	
	Halloysite	6.0	
	Chlorite	11.1	

Table 3. Details of test programme

Specimen ID	Specimen preparation method	Initial void ratio	Void ratio prior to thermal cycles	Void ratio after thermal cycles
C-NC*	Compacted	1.005	0.934	0.928
		0.993	0.926	0.922
C-OC*	Compacted	1.113	0.751	0.756
		0.996	0.753	0.757
R-NC	Reconstituted	1.220	0.843	0.841

Note: the effective vertical stress during heating and cooling is maintained at 50 kPa

*there are two duplicated specimens for the test condition