Thermal effects on the shear behaviour of unsaturated intact and recompacted loess

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ABSTRACT: The shear behaviour of intact and recompacted loess was studied using a suction- and temperature-controlled direct shear apparatus. The results found that intact specimens exhibit a higher shear stiffness and larger dilatancy than recompacted specimens at a given suction and temperature. Moreover, at suctions of 0 and 200 kPa, the shear stiffness and dilatancy of recompacted specimen increase with temperature. These increases in shear stiffness and dilatancy are mainly attributed to the heating induced strain hardening effects. On the contrary, at suction of 200 kPa, as soil temperature rises from 20 to 60ºC, the shear stiffness and dilatancy of intact specimens decrease by 35% and 68%, respectively. It is evident that intact specimens and recompacted specimens experience opposite thermal effects.

1 INTRODUCTION

Understanding the shear behavior of soils at various suctions and temperatures is vital for the ultimate limit state design of geo-energy structures such as energy pile founded in unsaturated soil (Uchaipichat and Khalili, 2009; Alsherif and McCartney, 2015). Due to the inherent soil structure, intact soil behaves differently from recompacted soil in terms of mechanical and hydraulic properties (Muñoz-Castelblanco et al., 2012; Ng et al., 2016). The effects of suction (Ng and Zhou, 2005) and temperature (Uchaipichat and Khalili, 2009; Alsherif and Mccartney, 2015) on the soil shear behaviour have mainly been studied for recompacted soil. However, the effects of soil structure on the shear behaviour of unsaturated loess at different temperatures are not fully understood.

The effects of temperature on the shear behaviour of unsaturated recompacted soil at low and high suction were studied by Uchaipichat and Khalili (2009) and Alsherif and Mccartney (2015), respectively. At low suction (below 300 kPa), soil shear stiffness and peak shear strength decreased as temperature increased. At high suction (above 100 MPa), thermal effects on the peak shear strength depended on the stress history, i.e., loading sequence of suction and temperature. However, the effects of soil structure on the shear behaviour were not considered in the two studies.

The objective of this study is to investigate the effects of soil structure on the shear behaviour of an unsaturated loess at different temperatures. To achieve this objective, a series of shear tests at different suctions and temperatures were conducted on intact and recompacted loess specimens through a suction and temperature controlled direct shear box apparatus (Ng, et al., 2017). The micro- structures of intact and recompacted loess at the in-situ and as-compacted state respectively were measured with a scanning electron microscope (SEM). The measurements were interpreted to reveal the differences in shear behaviour between unsaturated intact and recompacted loess.

2 TEST PROGRAM AND PROCEDURES

A series (see Table 1) of suction- and temperature-controlled direct shear tests was designed to study the thermal effects on the shear behaviour of unsaturated intact and recompacted loess at suctions of 0 and 200 kPa. The temperatures tested were 20 and 60ºC.

Figure 1 shows the thermo-hydro-mechanical path of each test before shearing. After specimen preparation, the initial stress state of recompacted and intact specimens was controlled at point O (suction=223 kPa) and O' (suction=239 kPa) respectively. A net normal stress of 50 kPa was firstly applied at constant water content for each specimen (i.e., recompacted specimen: O-A; intact specimen: O-A'). After applying vertical stress, soil specimens were wetted by decreasing suction from initial values to 200 and

0 kPa (i.e., A/A’-B1 and A/A-C1) respectively. Then each specimen was subjected to suction equalisation. After suction equalisation, soil temperature was increased from 20 to 60 ºC monotonically at intervals of 10 ºC. The cut-off criterion of suction and thermal equalization was based on both the water content change (less than 0.04%/day, Sivakumar (1993)) and volumetric strain rate (less than 0.025%/day, Romero et al., (2003)). After the suction and thermal equalisation, the specimen was sheared at constant suction and temperature. In this study, a small shearing rate of 0.0015 mm/min was adopted to allow the excess pore water pressure to dissipate.

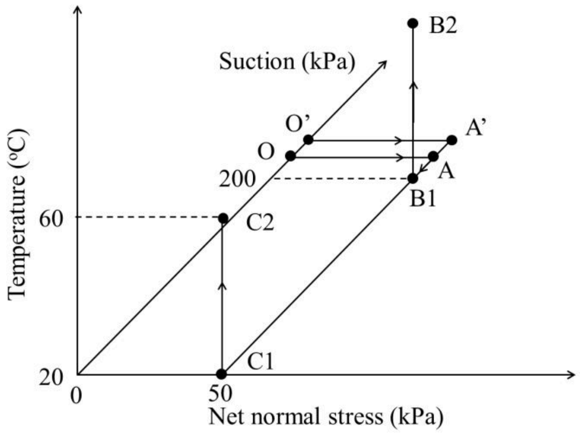


Figure 1. Thermo-hydro-mechanical test path before shearing

Table 1 Test programs and soil states in each test

Test ID	Suction (kPa)	Temperature (ºC)	Initial state		After compression		After wetting		After heating		After shearing	
			e	S_r (%)	e	S_r (%)	e	S_r (%)	e	S_r (%)	e	S_r (%)
IS0T60	0	O’-A’-B1-E1-E2	1.09	22.7	1.08	22.9	1.05	94.2	1.05	94.9	0.96	98.9
RS0T60	0	O-A-B1-E1-E2	1.11	23.0	1.09	23.5	0.94	93.0	0.93	93.8	0.84	99.6
IS200T60	200	O’-A’-B1-B2	1.09	22.7	1.08	22.9	1.06	25.1	1.05	25.1	1.07	25.1
RS200T60	200	O-A-B1-B2	1.11	23.0	1.09	23.5	1.07	25.9	1.06	25.9	1.06	26.1

3 TEST MATERIAL AND SPECIMEN PREPARATION

3.1 *Properties of the test material*

The loess used in this study was taken from Xi'an, Shaanxi province of China. High quality undisturbed block samples were collected at a depth of 3.5 m from an excavated pit. The in-situ gravimetric water content of the intact loess is 9.2% and the dry density is 1.29 g/cm^3. According to ASTM D 2487 (ASTM, 2006), the test loess is classified as clay of low plasticity. Information about the other physical properties of the test soil were given by Ng et al. (2017).

3.2 *Specimen preparation*

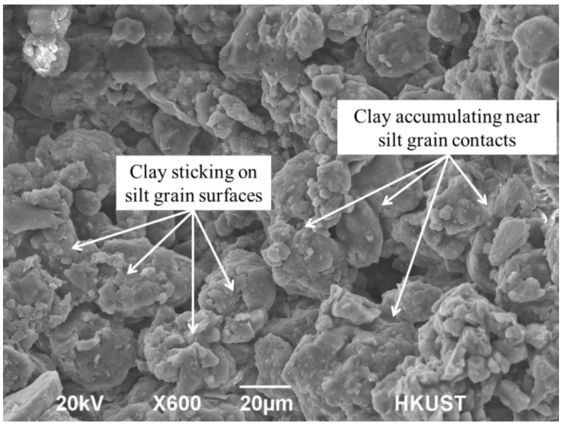
Both intact and recompacted loess were tested in this study. The preparation of an intact specimen involved first cutting a small soil block of appropriate size from the block sample. A square ring (50.8 mm × 50.8 mm × 21.5 mm) was pushed into the soil block. The top and bottom of the specimen were trimmed with a wire saw. All of the work was carried out in a humidity-controlled room in order to reduce moisture loss. After completing specimen preparation, the initial suction of an intact specimen was determined by the null-type axis translation technique to be 239 kPa. More details of each specimen, such as the void ratio and degree of saturation, are shown in Table 1.

For the recompacted specimens, the soil was firstly oven-dried and then passed through a 2 mm British Standard (BS) sieve. The prepared soil was evenly spread on a plastic plate and de-air water was sprayed on the soil to slightly increase its water content. The wetted soil was mixed thoroughly with a blender until it reached the same gravimetric water content of 9.2% as intact specimens. The mixture kept in a sealed plastic bag for moisture equalisation. The static compaction method was used to prepare the recompacted specimens. After compaction, the measured dry density is 1.28 g/cm^3. The initial water content was determined to be 9.5%.

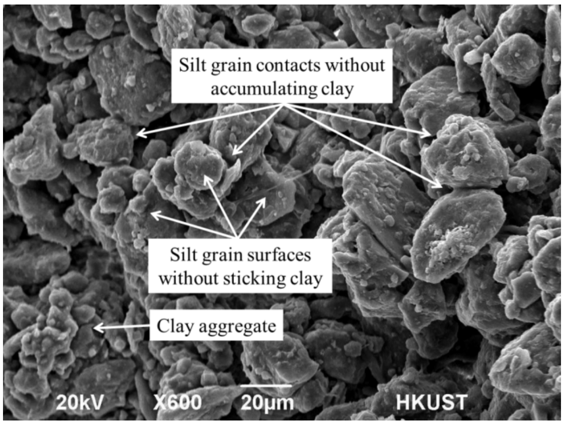
4 INTERPRETATION OF TEST RESULTS

4.1 *Microstructure of intact and recompacted specimens*

Figure 2 shows the SEM measurements for intact and recompacted loess at the in-situ and as-compacted states, respectively. For both intact and recompacted specimens, subangular silt grains with diameters of a few tens of micrometres dominate in the SEM observations. This is consistent with the particle size distribution results showing that the test soil consisted of 72% silt-size grains (from 2 to 63 μm). More importantly, the 28% clay fraction is distributed differently in intact and recompacted loess. For intact loess, as shown in Figure 2(a), the clay particles tend to stick firmly to the silt grain surfaces as well as accumulating near the silt grain contacts. For recompacted loess, as shown in Figure 2(b), a small amount of clay particles stick to the silt grain surfaces. In addition, the silt grains establish direct contact. Most clay particles in recompacted loess seem to have formed clay aggregates. The distribution of clay particles in recompacted loess is mainly attributed to the specimen preparation method used in this study. The grinding and sieving dislodged the clay particles which had stuck to the grain surfaces and accumulated near the grain contacts. The prepared soil was mixed with water thoroughly to reach a water content of 9.5%. For the subsequent compaction, the clay particles tended to form aggregates because the compaction was conducted dry of the optimum water content, i.e., 18.2% (Delage et al., 1996).



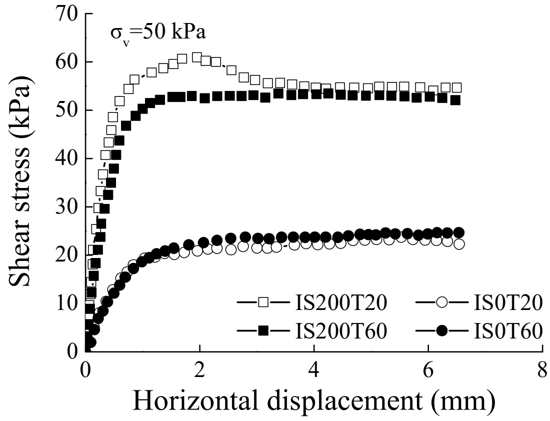
(a)



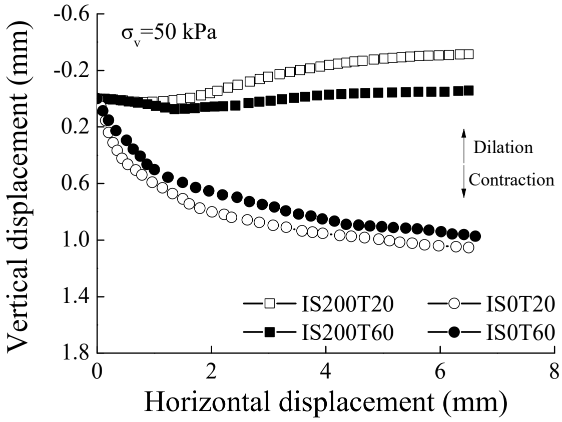
(b)

Figure 2. Different distribution modes of clay particles: (a) intact specimens; (b) recompacted specimens

Figure 3 shows thermal effects on the shear behaviour of intact specimens at suctions of 0 and 200 kPa. At suction of 0 kPa, negligible thermal effects are observed in the stress- displacement relationship and deformation behaviour at different temperatures. At suction of 200 kPa, as soil temperature increases from 20 to 60 ºC, the shear stiffness and peak shear strength decrease by 35% and 12%, respectively.



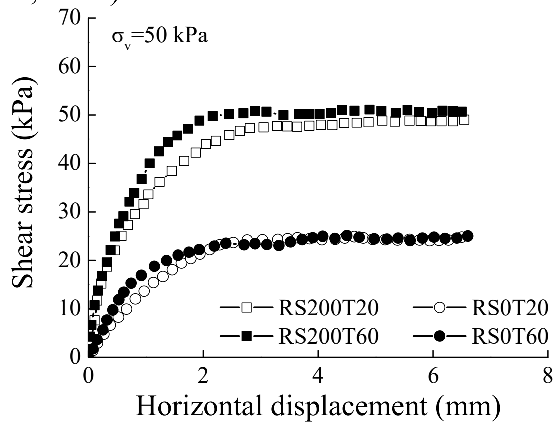
(a)



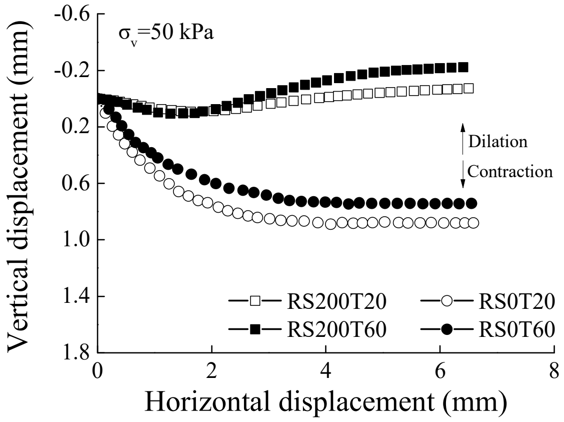
(b)

Figure 3. Thermal effects on the shear behavior of intact specimen (a): stress-displacement relationship; (b): deformation behavior.

The dilation decreases with an increase in temperature. These observations imply that thermal effects on the stress strain behaviour of intact specimens are more significant at higher suction. It should be noted that at the suction of 200 kPa, a contractive plastic volumetric strain of 0.45% is induced with an increase in soil temperature. According to previous studies, an increase in shear stiffness and peak shear strength would result in subsequent mechanical loading because of plastic strain hardening effects (Cekerevac and Laloui, 2004). In this study, the intact specimens tested at the suction of 200 kPa are close to the in-situ stress state and the soil structure is highly preserved (see Figure 2 (a)). The plastic soil strain of 0.45%, which is mainly attributed to particle rearrangement (Campanella and Mitchell, 1968), is expected to partially destroy the soil structure instead of inducing strain hardening for intact specimens. Then the shear stiffness and peak shear strength would decrease with an increase in soil temperature at the suction of 200 kPa. In addition, the critical shear strength at suctions of 0 and 200 kPa seems to be independent of temperature for intact specimens. A similar conclusion was drawn for both saturated and unsaturated soil in previous studies (Cekerevac and Laloui, 2004; Uchaipichat and Khalili, 2009).



(a)



(b)

Figure 4. Thermal effects on the shear behavior of recompacted specimens: (a): stress-displacement relationship; (b): deformation behavior.

Figure 4 shows thermal effects on the stress–displacement behaviour of recompacted specimens. As soil temperature increases from 20 to 60 ºC, the shear stiffness increases by 47% and 34% at suctions of 0 and 200 kPa, respectively. With an increase in temperature, contractive deformation is reduced at suction of 0 kPa while dilation is enhanced at the suction of 200 kPa. These observations suggest that the recompacted specimens become stiffer with an increase in soil temperature. This behaviour is different from that seen in the intact specimens (see Figure 3) which shows a reduction in shear stiffness and peak shear strength as temperature increases. For the recompacted specimens, as soil temperature rises from 20 to 60 ºC, plastic volumetric strains of 0.48% and 0.51% are observed at suctions of 0 and 200 kPa, respectively. The plastic volumetric strain is expected to induce strain hardening for recompacted specimen. Then the shear stiffness increases with an increase in soil temperature at suctions of 0 and 200 kPa. Uchaipichat and Khalili (2009) carried out a series of temperature-controlled triaxial tests on an unsaturated recompacted silt. They found that the shear stiffness and peak strength decrease with an increase in soil temperature. Their observation is different from what observed in the current study, where both the shear stiffness and peak strength of recompacted loess increase with an increase in temperature. The observed differences between these two studies may be explained by the differences in thermal volume change of recompacted silt and loess. In the study of Uchaipichat and Khalili (2009), as temperature rises from 20 to 60 ºC, the specimens show very small plastic contraction (less than 0.2%) and even expansion. This suggested thermal softening, i.e., the preconsolidation pressure and hence over-consolidation ratio decreases with an increase in temperature (Zhou and Ng, 2016), dominates soil behaviour. In the current study, however, plastic contractive volumetric strains of about 0.5% are observed with an increase in soil temperature from 20 to 60 ºC, inducing significant volumetric strain hardening of soil specimen. In addition, at a given horizontal displacement (i.e., around 1 mm), the mobilized shear stress at 60°C is about 10% larger than that at 20°C. This small difference induced by thermal hardening may be neglected when considering possible experimental artifacts and statistic variability.

5 CONCLUSIONS

For recompacted specimens at suctions of 0 and 200 kPa, the shear stiffness and dilatancy increase with temperature. The shear stiffness and maximum dilatancy increase by up to 47% (s=0 kPa) and 63% (s = 200 kPa), respectively. These increases in shear stiffness and dilatancy are mainly because of the continuous plastic volumetric contraction during heating, inducing strain hardening effects. On the contrary, thermal effects on the stress strain behaviour of intact specimens are negligible at zero suction. At suction of 200 kPa, as soil temperature rose from 20 to 60 ºC, the shear stiffness, maximum dilatancy and peak shear strength of intact specimens decrease by 35%, 68% and 12%, respectively. These observations imply that thermal effects on intact specimens are different from those on recompacted specimens. The difference is likely because heating-induced plastic strain, in addition to plastic strain hardening effects, also destroys the resistant structure of intact specimens.

6 ACKNOWLEDGEMENTS

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