Thermal effects on water retention behaviour of unsaturated collapsible loess

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ABSTRACT

Temperature has a significant influence on water retention curve (WRC) because temperature affects surface tension of water and volumetric behaviour of soil. However, in previous studies on thermal effects on WRC, the difference in suction induced volume change of soil specimen at various temperatures are always insignificant. With increasing temperature, the wetting-induced collapse of loess increases. This study aims to investigate thermal effects on WRC of collapsible loess. Wetting-drying tests were carried out on compacted loess specimens at temperatures ranging from 5 to 50°C. During the wetting process, volumetric water content at a given suction at 50°C is 20% smaller than that at 5°C. This is because when temperature increases from 5 to 50°C, surface tension of water decreases by 10% and wetting-induced volumetric contraction increases by three times. The observed thermal effects on volumetric water content of loess are about four times as that of Boom clay in previous study. Because thermal effects on wetting-induced volume change of collapsible loess are much more significant than Boom clay. During drying, the air entry value (AEV) of loess decreases with increasing temperature at a rate of 0.16%/°C. The rate is smaller than those of Boom clay and a silty clay (with rates of 0.21% and 0.45%/°C) in the literature. For collapsible loess, with increasing temperature, the decrease of AEV induced by smaller surface tension are partially compensated by effects of larger wetting-induced collapse on AEV.

Keywords: temperature; loess; water retention behaviour

1. Introduction

For many geotechnical engineering problems encountered in non-isothermal conditions, temperature has an important influence on water retention curve (WRC) and further influence the hydro-mechanical behaviour of unsaturated soils. (Gens et al. 1998; Laloui 2010; Xu et al. 2016). For example, the maximum temperature in landfill could be about 55°C (Klein et al. 2001), which may result in an increases in temperature in landfill cover soil. The thermally induced change of retention capability can affect rainfall infiltration and gas emission of landfill cover and make the underground water as well as atmosphere contaminated. Moreover, in underground repositories for high-level radioactive waste disposal, high temperature may reduce of retention capability of buffer soil and cause leakage of nuclear pollutant. So far, some researchers have made efforts to study thermal effects on water retention behaviour of unsaturated soils (Romero et al. 2001; Tang and Cui 2005; Laloui et al. 2013; Cai et al. 2014; Li et al. 2016). It has been found that with increasing temperature, the retention capability of unsaturated soils decreases as the surface tension of water decreases. According to the theoretical work conducted by Zhou et al. (2014), both thermally induced change of surface tension of water and change of suction induced soil deformation have an influence on WRC. However, in most of previous experimental studies on thermal effects on WRC, volume change of soil specimen during wetting and drying are always ignored. Experimental investigation on thermal effects on WRC of unsaturated soil with consideration of volume deformation is still limited.

Loess is widespread all over the world, such as in semi-arid and arid areas in China, France and the United States (Rogers et al. 1994; Peng et al. 2018). Loess is one of the typical collapsible soils and may collapse significantly when subjected to wetting (Barden et al. 1973; Ng and Menzies 2007; Jiang et al 2017). At a given stress condition, the collapse volumetric strain of loess specimen increases with decreasing suction. With increasing stress, the wetting-induced collapse of loess increase first and then decrease (Sun et al. 2007; Vilar and Rodrigues 2011; Jiang et al. 2012; Ng et al. 2018). Moreover, Ng et al. (2018) found that at a given stress condition, with increasing temperature, wetting-induced collapse of loess increases. Some researchers have studied the water retention behaviour of unsaturated loess (Muñoz-Castelblanco et al. 2012; Ng et al. 2016b; Haeri et al. 2017). Previous experimental results showed that wetting-induced collapse can influence water retention behaviour of unsaturated loess significantly. However, most of previous researches on water retention behaviour of unsaturated loess were conducted at room temperature. Thermal effects on WRC of collapsible loess have seldom been paid attention to.

The principal objective of this study is to investigate thermal effects on WRC of collapsible loess. A series of wetting-drying tests were conducted on unsaturated collapsible loess at various temperatures. Three temperature values were chosen, namely typical room temperature of 23°C, a lower temperature of 5°C and a higher temperature of 50°C. Each test was conducted at confining pressure of 50 kPa. After reaching target temperatures of 5, 23 and 50°C, a wetting-drying cycle was applied to each soil specimen. Thermal effects on water retention behaviour of collapsible loess are analysed.

2. Material and methods

2.1 Soil type and specimen preparation

The testing material used in this study is loess from Xi'an City, Shaanxi province, China. Table 1 summarises the geotechnical properties of the clay together with chemical analyses. The tested loess contains clay, silt and sand, with fractions of 28%, 71.9% and 0.1%, respectively. The liquid limit and plasticity index are 37% and 19%, respectively. The tested soil can be described as a lean clay (CL) in accordance with the Unified Soil Classification System (ASTM 2011). The mineralogical analysis shows that the tested loess mainly consists of quartz, calcite and montmorillonite. The chemical characterisation of the soil is essentially dominated by SiO_2 and CaO oxides.

To prepare compacted loess specimens, initially, the soil was oven-dried at 105℃ for 24 hours and then passed through a 2 mm sieve. De-aired water was added and mixed with the dry soil to reach a target compaction water content of 10.9%. Then, the wet soil was sealed inside a plastic bag and stored in a humidity- and temperature-controlled room for 24 hours in order to achieve moisture equalization. Each compacted specimen (76 mm in diameter and 20 mm in height) was compacted in two layers statically for the target void ratio of 1.17. The determination of initial water content and void ratio is based on the in-situ condition of the tested loess. After static compaction, the initial suction of compacted loess specimen was measured to be 180 kPa.

2.2 Test programme and apparatus

This research aims to investigate thermal effects on water retention behaviour of collapsible loess. Three suction- and temperature-controlled water retention tests (T5, T23 and T50) were conducted on unsaturated loess at various temperatures of 5, 23 and 50℃.

The experimental study is performed using a temperature-controlled double cell triaxial apparatus for unsaturated soils (Ng et al. 2016a). The double cell equipped with a differential pressure transducer is for measuring total volume change of unsaturated soil specimens. The measuring accuracy is about 0.03% volumetric strain for soil specimens with diameter of 76 mm and height of 20 mm. By monitoring water flow in and out through a ballast tube connected with an air trap and a burette, the water volume change can be obtained. Matric suction is controlled by adopting the axis translation technique (Hilf 1956). The temperature control system is used to control and monitor soil temperature by heat exchange using a spiral copper tube connected to a heating/ cooling bath. When thermal equilibrium is achieved, the temperature is quite stable and the fluctuation is about 0.2°C. More details of the testing apparatus can be found in Ng et al. (2016a).

2.3 Test procedures

The stress path of each soil specimen is shown in Fig. 1. Each triaxial test includes five steps: isotropic compression, wetting to 100 kPa, changing temperature, wetting to 0.1 kPa and finally drying back to 400 kPa. Firstly, each test was performed with increasing confining pressure to target value of 50 kPa (A→B). Then, the second step was wetting to 100 kPa (B→C), which needs about one week to reach suction equilibrium. Suction equilibrium is achieved with a small rate of water content change (<0·09%/day) (Chiu and Ng 2012). During the above-mentioned two steps, there is about 9% contractive volumetric strain observed in each soil specimen. Thus, it can be assumed that at current stress state, all the specimens are normally consolidated. The following step was for thermal equalisation. Soil specimen in the test (T5) was cooled 5°C (C→D2) and that in the test (T50) was heated to 50°C (C→D1). Temperature of the soil specimen conducted under room temperature (T23) kept unchanged. This step lasted for 48 hours to achieve equilibrium state, for soil temperature to reach target temperature, thermally induced volume change and water content change to reach equilibrium and thermally induced excess pore water pressure to dissipate. The fourth step was wetting from 100 to 0.1 kPa step by step (100-50-20-10-1-0.1) (D1→E1, D2→E2, C→E3). The last step was drying from 0.1 to 400 kPa step by step (0.1-1-10-20-50-100-200-400) (E1→F1, E2→F2, E3→F3). Similarly, each suction in the last two steps lasted for one week in order to reach suction equilibrium. At each suction level, the equilibrium water content and void ratio of soil specimen both were determined.

3. Results and discussion

3.1 Thermal effects on volume change during wetting and drying

Fig. 2 shows volume changes of compacted loess during the wetting-drying cycle at three different temperatures. Void ratio of compacted loess at each temperature keeps decreases with decreasing suction. This is because meniscus water, which can provide a stabilizing effect on soil skeleton (Wheeler et al. 2003), becomes less at a lower suction. Thus, wetting results in a decrease of yield stress and yielding of soil specimen occurs.

Moreover, cumulative volumetric strains induced by wetting from 100 to 0.1 kPa of the tested loess are 4.1%, 5.6% and 11.7% at 5, 23 and 50°C, respectively. When temperature increases from 5 to 50°C, the wetting-induced volume contraction increases by about 3 times. This is because for unsaturated collapsible loess, at a higher temperature, the reduction of stabilizing inter-particle normal force becomes smaller (Ng et al. 2018). Wetting-induced softening of yield stress increases with increasing temperature. Thus, for normally consolidated soil specimen, contractive volumetric strain due to a certain suction reduction increases with increasing temperature. According to Romero et al. (2003), the swelling volumetric strain of Boom clay during wetting from 200 to 60 kPa at 80°C (2.5%) is about 20% larger than that at 22°C (2.1%). Compared with Boom clay (Romero et al. 2003), the thermal effects on wetting induced volume change of collapsible loess is much more significant. During wetting, Boom clay swells is mainly because it contains a significant percentage of active clay minerals (e.g. montmorillonite) (Gens and Alonso 1992; Gatabin et al. 2016). The crystalline of the contained active clay minerals swelling caused by hydration of exchangeable is likely to be insensitive to temperature variation. For loess, the wetting induced collapse is due to wetting induced softening of yield stress and destruction of initial metastable structure, rather than related to the mineral contents. At a higher temperature, wetting induced softening becomes more significant, resulting in more significant volumetric collapse (Ng et al. 2018). During drying process from saturated condition to suction of 400 kPa, soil volume decreases slightly.

3.2 Thermal effects on water retention behaviour of unsaturated loess

Fig. 3 shows water retention behaviour of collapsible loess at three different temperatures. The initial volumetric water content decreases slightly with increasing temperature. The initial volumetric water content at 50°C is about 8.7% smaller than that at 5°C. This is because the surface tension of water decreases nearly 10% when temperature increases from 5 to 50°C (Vargaftik et al. 1983; François and Ettahiri 2012). Thus, the initial volumetric water content becomes smaller at a higher temperature. In addition to surface tension of water, temperature also has an influence on water density. The density of water decreases with increasing temperature when temperature is over 4°C. The change of water density is only 1% when temperature increases from 5 to 50°C (Kell 1975). Thermal effects on surface tension of water are much more significant than thermal effects on water density.

During the wetting process, as expected, the volumetric water content increases with decreasing suction. The volumetric water content at 50°C is about 20% smaller than that at 5°C under a given suction. This is because the surface tension of water decreases with increasing temperature, as discussed previously. More importantly, the wetting-induced collapse at 50°C is nearly three times as that at 5°C, as can be seen from Fig. 2. The relationship between incremental volumetric water content $d\theta_w$ and incremental void ratio de is:

$$d\theta_w = \frac{dS_r}{1+\frac{1}{e}} + \frac{S_r de}{(1+e)^2} \quad (1)$$

where S_r represents degree of saturation. As can be obtained from Equation (1), with a given change of degree of saturation, larger decrease of void ratio will result in a larger increase of volumetric water content. For the tested loess, when wetting from 100 to 0.1 kPa, the degree of saturation of soil specimen at 50°C increases from 42% to 89% and that at 5°C increases from 45% to 95%. Thermal effects on dS_r are almost negligible. With a given change of degree of saturation, larger wetting-induced collapse at 50°C results in smaller volumetric water content. Under room temperature of 23°C, the volumetric water content during wetting is close to that at 5°C. Because the difference in wetting-induced volume contraction at 5 and 23°C (4.1% and 5.6%, respectively) is less significant.

Romero et al. (2003) found that for unsaturated Boom clay, the water content at 80°C is about 5% smaller than that at 22°C. The observed average thermal effects on volumetric water content per degree of collapsible loess in this study are about four times as those of Boom clay. The difference is mainly related to temperature-dependent volume change during wetting. Thermal effects on wetting-induced volume change of collapsible loess is more significant than Boom clay, as discussed in previous section. For collapsible loess, with increasing temperature, both smaller water surface tension and larger wetting-induced collapse results in a prominent reduction in volumetric water content.

In the following drying process, the volumetric water content of soil specimen decreases when the matric suction keeps increasing. The intersection of the line extended from the constant slope part of the drying curve and the axis of suction at saturation can be estimated as the air entry value (AEV) of each specimen (Vanapafli et al. 1999). Obtained from Fig. 3, the AEVs of the tested collapsible loess at 5, 23 and 50°C are 10, 9.5 and 9.2 kPa, respectively. AEV becomes smaller at a higher temperature as the surface tension of water decreases. Similarly, Romero et al. (2003) and Cai et al. (2014) found that for Boom clay and a silty clay, AEVs also decreases with increasing temperature. Fig. 4 shows the comparison between the tested loess and other soils in the literature in terms of thermal effects on AEV. The vertical axis is the ratio of AEV at a certain temperature T and AEV at room temperature T_0. It can be found that the decreasing rate of AEV with increasing temperature of collapsible loess is 0.16%/°C. AEVs of a silty clay (Cai et al. 2014) and Boom clay (Romero et al. 2003) show a similar trend, but with higher rates of 0.45% and 0.21%/°C, respectively. Compared with Boom clay and a silty clay in previous studies, AEV of the tested loess is less sensitive to temperature change. For tested collapsible loess, larger wetting-induced collapse at a higher temperature results in a smaller void ratio before drying. According to Ng and Pang (2000) and Zhuang et al. (2017), smaller void ratio may induce a smaller pore size distribution and a larger AEV. As a result, with increasing temperature, thermal effects on AEV of tested loess are less significant.

4. Summary and conclusions

Water retention curves of collapsible loess at temperatures of 5, 23 and 50°C are investigated in this study. It is found that during the wetting process, the volumetric water content at a given suction at 50°C is about 20% smaller than that at 5°C. When temperature increases from 5 to 50°C, the surface tension of water decreases about 10%. The wetting-induced volume contraction at 50°C is 11.7%, about three times as that at 5°C. With a similar change of degree of saturation, larger wetting-induced collapse at 50°C results in smaller volumetric water content. The volumetric water content during wetting at 23°C is close to that at 5°C as the difference in wetting-induced collapse at 5 and 23°C (4.1% and 5.6%, respectively) is less significant. The observed thermal effects on volumetric water content of collapsible loess are much more significant compared with that of Boom clay in previous research. This is because for Boom clay, thermal effects on wetting-induced volume change is less significant than tested loess. With increasing temperature, a combined effect of smaller water surface tension and larger wetting-induced collapse results in a prominent decrease in volumetric water content of loess.

During the drying process, AEV of collapsible loess decreases slightly with increasing temperature at a rate of 0.16%/°C. However, for Boom clay and a silty clay in previous studies, AEV decreases significantly with increasing temperature as the surface tension of water decreases (with rates of 0.21% and 0.45%/°C, respectively). AEV decreases as surface tension becomes smaller at a higher temperature. However, for collapsible loess, smaller void ratio induced by larger wetting-induced collapse results in a smaller decrease of AEV with increasing temperature.

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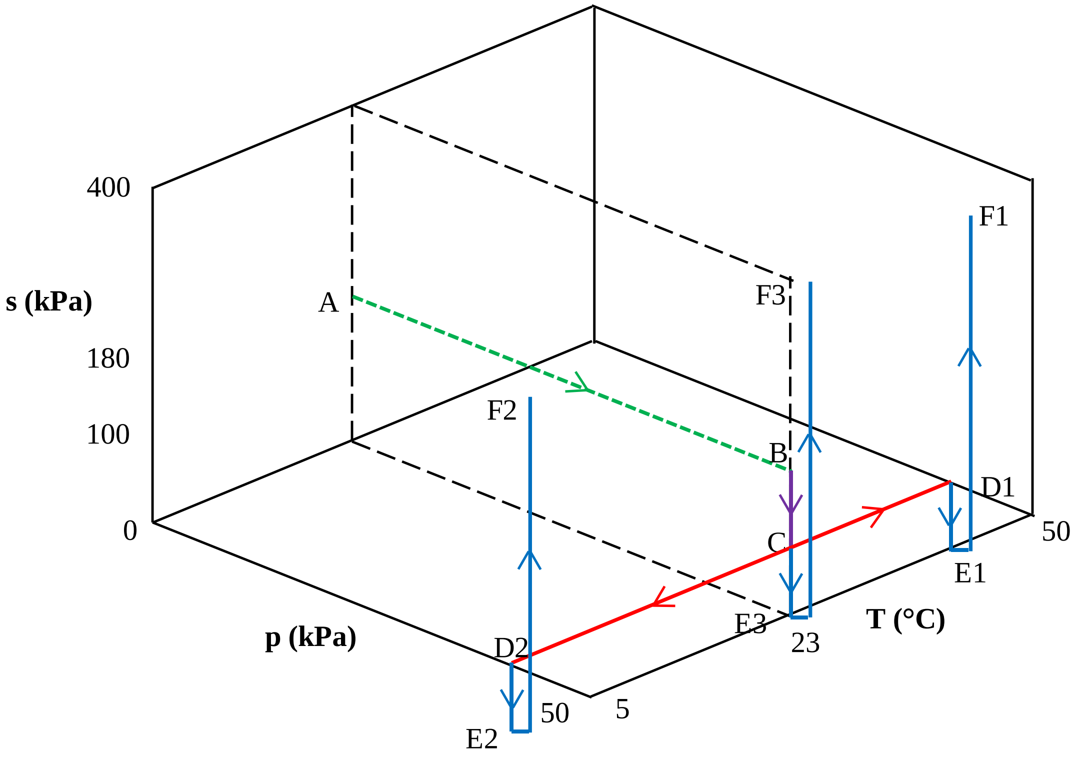
Table 1 Physical and chemical properties of tested loess

Soil properties	Values
Specific gravity	2.69
In-situ water content (%)	10.9
In-situ dry density (kg/m^3)	1237
Maximum dry density (kg/m^3)	1680
Optimum water content (%)	18.1
Grain size distribution	
Sand content (%)	0.1
Silt content (%)	71.9
Clay content (%)	28.0
Liquid limit (%)	36
Plastic limit (%)	19
Plasticity index	17
Chemical constituents	
SiO_2	57%
CaO	21%
MgO	10%
Al_2O_3	7%
Fe_2O_3	4%
K_2O	1%



Test ID	Stress path
T5	A→B→C→D2→E2→F2
T23	A→B→C→E3→F3
T50	A→B→C→D1→E1→F1

Fig. 1 Thermo-hydro-mechanical path of each specimen

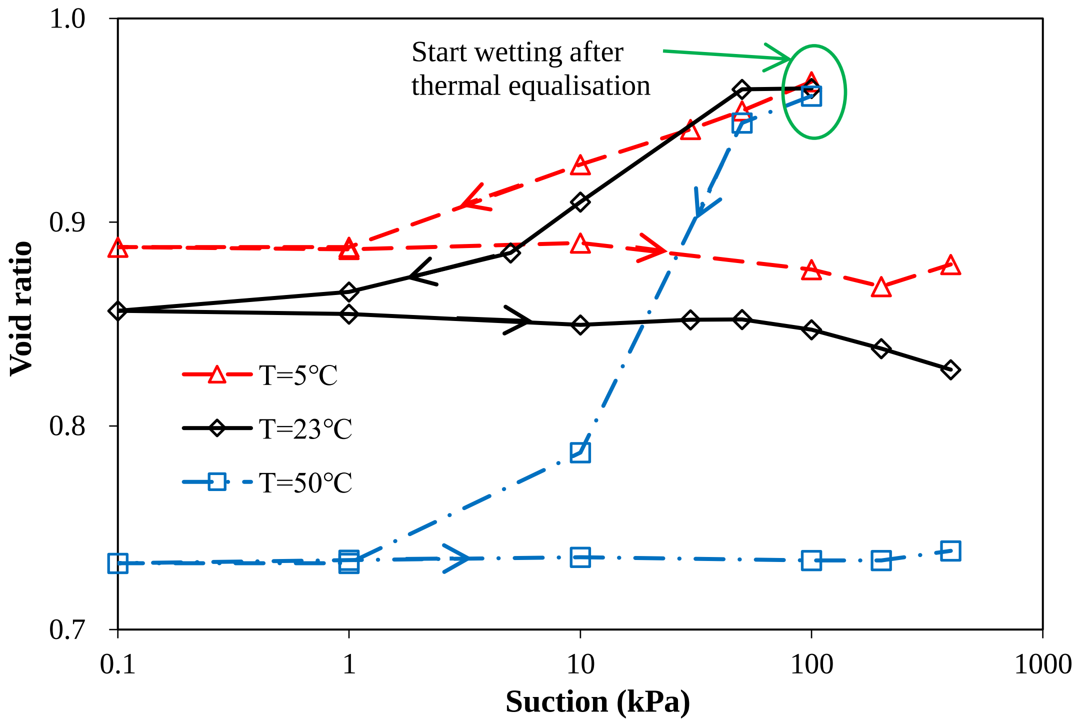


Fig. 2 Thermal effects on volume change of unsaturated loess during wetting-drying cycle

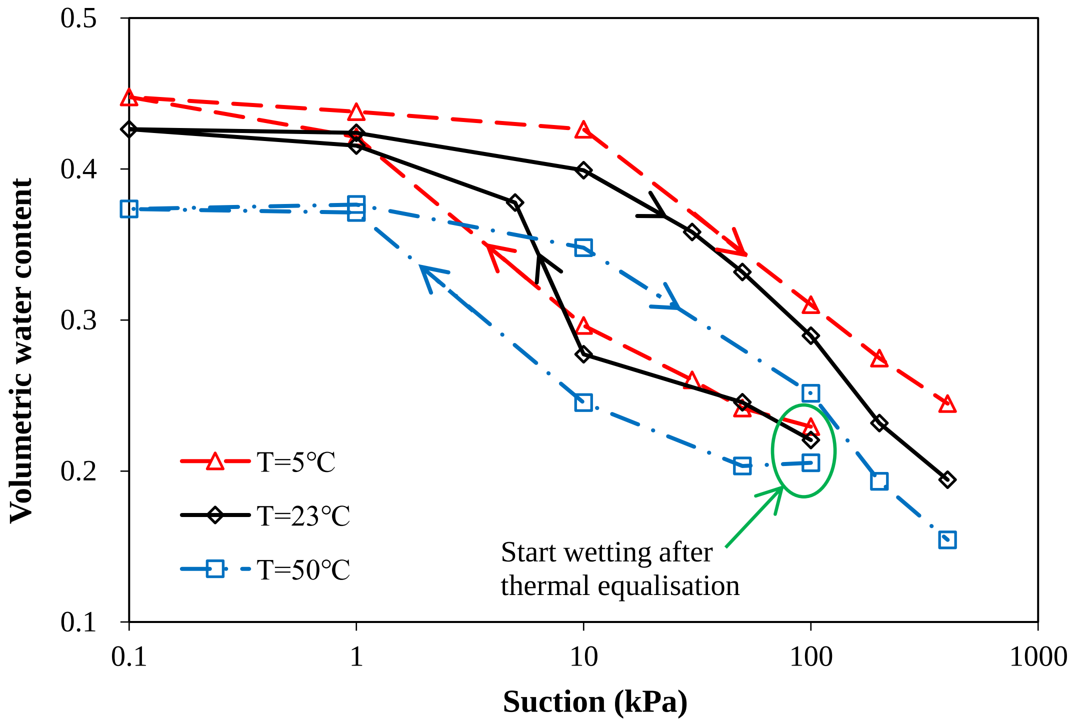


Fig. 3 Thermal effects on water retention curve of unsaturated loess

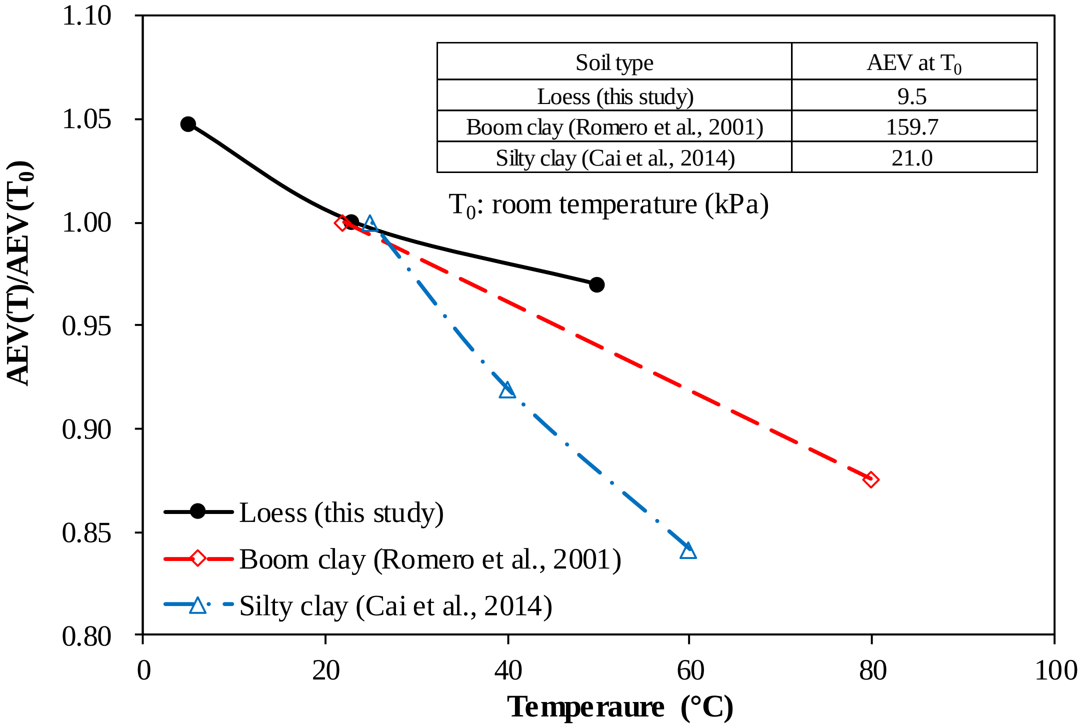


Fig. 4 Thermal effects on air entry value (AEV)