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Thermo-hydro-mechanical behaviour of partially saturated fine-grained soils in the context of energy geostructures

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Article

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Abstract
The multi-physical phenomena, particularly water content and temperature variations, governing the behaviour of soils should be considered in the design and analysis of the energy geostructures. Soil temperature and water content variations impose a significant risk on the stability and serviceability of existing and future geostructures. Although potential failure modes, impacts at a system scale, and the response of saturated soils to thermal loads are previously discussed, interpretation of the thermo-hydro-mechanical behaviour of partially saturated soils in the context of energy geostructures is not thoroughly investigated. In this regard, this paper brings together the experimental data from several laboratory investigations to attain a comprehensive understanding of the partially saturated fine-grained soils response under thermo-hydro-mechanical loading, which plays a vital role in the analysis of the soil behaviour and energy geostructures in contact with them. In this paper, the effect of thermal loading in different matric suctions and hydraulic loading at different temperatures on soil preconsolidation stress, water content variation, thermal and hydraulic conductivities, and compression indexes are studied. Furthermore, soil thermal deformation is studied in detail for different overconsolidation ratios and matric suctions.

1. Introduction

Though the thermo-hydro-mechanical (THM) behaviour of fully saturated soils is studied to an adequate level, several emerging problems in geotechnical and geo-environmental engineering pose multi-physics problems involving non-isothermal processes in unsaturated soils. The massive challenge of climate change has been highlighted since the industrial era due to the huge rise in greenhouse gas emissions (IPCC, 2014). The emissions are known as the root cause of few significant issues such as global warming, fluctuations in the groundwater level, and variations in precipitation patterns (Karl et al., 2009). As part of the mitigation strategy to face the challenge of climate change, energy geostructures are known as an efficient approach towards developing sustainable and environmentally friendly technologies to meet space heating-cooling needs while serving as structural supports (Laloui & Sutman, 2020). The importance of studying the THM behaviour of partially saturated soil is further highlighted by the coupled variations in temperature and water content of the surrounding soil within the context of energy geostructures.

Fundamental knowledge achieved in the framework of seasonal air temperature variations affecting the top layer of soils, variations in temperatures of soil samples obtained from different depths of the ground and their transportation to the laboratories (Burghignoli et al., 2000), long-term laboratory tests related to buried cables (Abdel-Hadi & Mitchell, 1981), heat storage (Slegel & Davis, 1977) or nuclear waste storage (Houston et al., 1985; McGinley, 1983) in the past several decades has formed the bedrock of the progress in this field. However, most of the studies in the field of partially saturated soils have been conducted at ambient temperature. Therefore, the effect of temperature variations on their behaviour is yet to be fully understood.

To address issues arising due to the employment of energy geostructures, obtaining experimental data on the thermo-mechanical behaviour of partially saturated soils, developing and quantitatively validating constitutive models, and finally employing them to predict the soil response are of paramount importance. In this regard, the THM behaviour of soils is studied at an adequate level to assist engineers in using available constitutive models for fully saturated conditions. In this paper, one step forward, a review of the thermo-hydro-mechanical behaviour of partially saturated

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soils is presented, which includes the synthesis of the latest experimental outcomes in this field. Nonetheless, in order to develop a general framework, extensive studies are still required to investigate the effect of further phenomena such as heating and cooling cycles, anisotropy, thermal fatigue, the time dependence of the impact of the thermal cycles, initial void ratio (Laloui et al., 2014; Vega & McCartney, 2014; Coccia & McCartney, 2016), and coupled transfer of water and heat via porous media.

Throughout this paper, the experimental data has been normalised by the ones obtained at room temperature and lowest matric suction (i.e., reference temperature and reference matric suction), water content or degree of saturation, or porosity, to emphasise the influence of temperature and suction variations. Furthermore, all the stress/suction units are presented in kPa, unit weights in kN/m^3, and temperature units in °C, unless otherwise stated.

2. Effects on soil characteristics

The thermal and mechanical history of the fine-grained soils plays a significant role in determining the temperature impact on shear strength and deformation. However, due to the influence of matric suction on soil behaviour, as well as the coupled nature of temperature and water content variations, this phenomenon becomes more complicated for unsaturated samples. In this regard, the impact of temperature and matric suction variations on preconsolidation stress and soil water content deserves a thorough evaluation through available experimental evidence.

2.1 Preconsolidation stress

There are only a few studies to examine the concurrent effects of matric suction and temperature variations on preconsolidation stress. Figure 1a shows the variation of effective preconsolidation stress by changes in matric suction. In this figure, the x-axis is normalised by matric suction equal to 50 kPa, which is selected to provide a reasonable range for the entire data set. The general trend shows that preconsolidation stress increases with increasing matric suction. This phenomenon is mainly associated with matric suctions above the air-entry value, as the degree of saturation does not change considerably until air-entry matric suction is exceeded (Salager et al., 2008; Uchaipichat & Khalili, 2009).

Salager et al. (2008) observed that for the lower values of matric suction, the rate of increase in preconsolidation stress with matric suction is higher, although the maximum imposed matric suction was limited to 300 kPa. On the other hand, the experimental data from the literature show continuous hardening with increasing matric suction (Lloret et al., 2003; Jotisankasa, 2005; Blatz et al., 2005; Tang et al., 2008; Mun & McCartney, 2014). Alsherif & McCartney (2016) proposed the power-law model to address this issue, by which the suction hardening effect on preconsolidation stress is estimated for the entire suction range. The model was successfully validated against literature data sets.

Figure 1b shows changes in effective preconsolidation stress by temperature where effective preconsolidation stress is observed to decrease with temperature for a fixed matric suction, and the rate of decrease is higher for the lower temperature values (Abuel-Naga et al., 2007a; Salager et al., 2008). In this regard, Eriksson (1989) observed that, for the temperature range of 5 °C to 55 °C, effective preconsolidation stress asymptotically reached a fixed value with increasing temperature. Contrarily, an initial decrease of preconsolidation stress was followed by an eventual increase for the temperature range of 30 °C to 70 °C in the study of Saix et al. (2000). However, the data in their study was analysed employing the net stress framework for samples with a matric suction of 4.9 kPa. The leading cause of this trend is believed to be thermal softening due to the thermal loading of normally consolidated soils (Romero et al., 2003) counteracting hardening due to hydraulic loading (Khosravi et al., 2020). For instance, the sample with higher matric suction shows higher effective preconsolidation stress during thermal loading (i.e., the effect of thermal softening becomes less prominent with increasing matric suction). However, the rate of effective preconsolidation stress evolution with temperature is observed to be suction-independent (François et al., 2007). Conversely, the rate of effective preconsolidation stress evolution with matric suction is observed to be either thermally dependent (Laloui et al., 2014) after the reinterpretation of Uchaipichat & Khalili (2009) data sets or independent (François et al., 2007).

In this regard, Alsherif & McCartney (2016) argued that the effect of temperature and matric suction on effective preconsolidation stress is, in fact, path-dependent according to the two series of experiments carried out with the same matric suction and temperature which were applied in the opposite orders. In one of these experiments, matric suction was first increased to 291 MPa, followed by heating up to 64 °C (ST path). The second one was first heated up to 64 °C, and then the matric suction was increased up to 317 MPa (TS path). After mechanical loading, it was observed that the specimen exposed to high matric suction before temperature increase showed higher effective preconsolidation stress. Thus, it was concluded that thermal hardening might happen depending on the succession order of thermal and hydraulic loading. Another example of the stress path dependency is virtual preconsolidation due to cyclic temperature variations before mechanical loading, similar to creep-deformation (Burghignoli et al., 2000; Sultan et al., 2002; Abuel-Naga et al., 2007b).

Alongside matric suction and temperature, Tidfors & Sällfors (1989) introduced clay content and the depositional environment as determining factors affecting preconsolidation stress where soils with higher activity experience more reduction in preconsolidation stress due to temperature increase (Laloui et al., 2014).

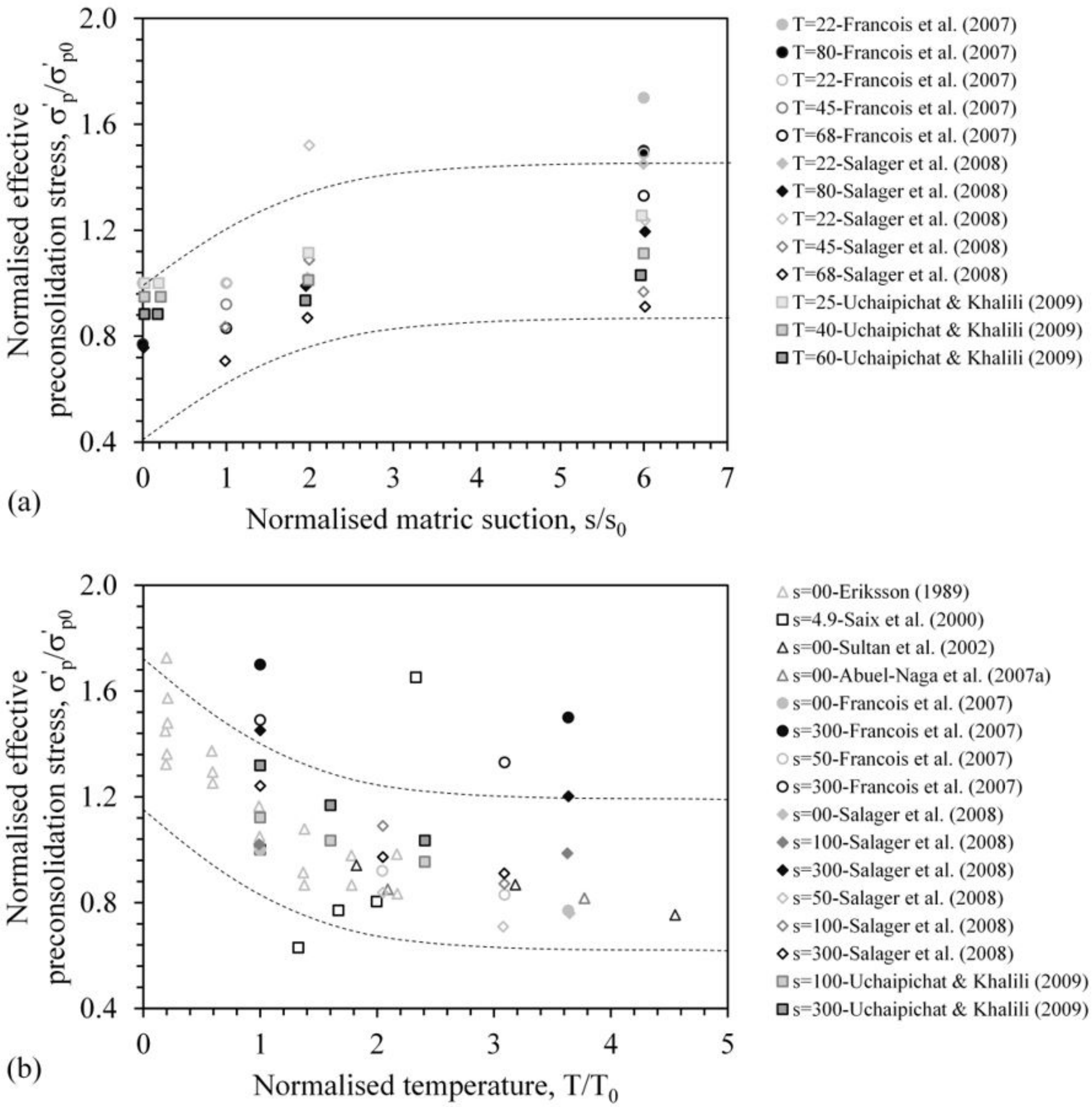

Figure 1. Evolution of preconsolidation stress with (a) matric suction (b) temperature.

2.2 Water content

Hydraulic processes near and beneath the ground surface can cause unsaturated conditions around energy geostructures during construction or service life, affecting shear strength and volume change behaviour. As shown in Figure 2a, the soil water content decreases with increasing matric suction (Olson & Langfelder, 1965; Krahn & Fredlund, 1972; Rao & Revanasiddappa, 2000). However, in low matric suctions before the air-entry value, the rate of change in water content is low and becomes more pronounced with increasing matric suction, which continues until the residual water content is reached. Furthermore, considering the tests performed at two different temperatures (Romero et al., 2001), it can be observed that in the lower range of matric suction and lower dry densities, the influence of elevated temperature on the water content evolution during hydraulic loading is more pronounced.

A comparison of samples with varying densities reveals a more evident change in water content due to increments in matric suction for loose samples. The role of the water regimes in soil pores can be considered a fundamental mechanism

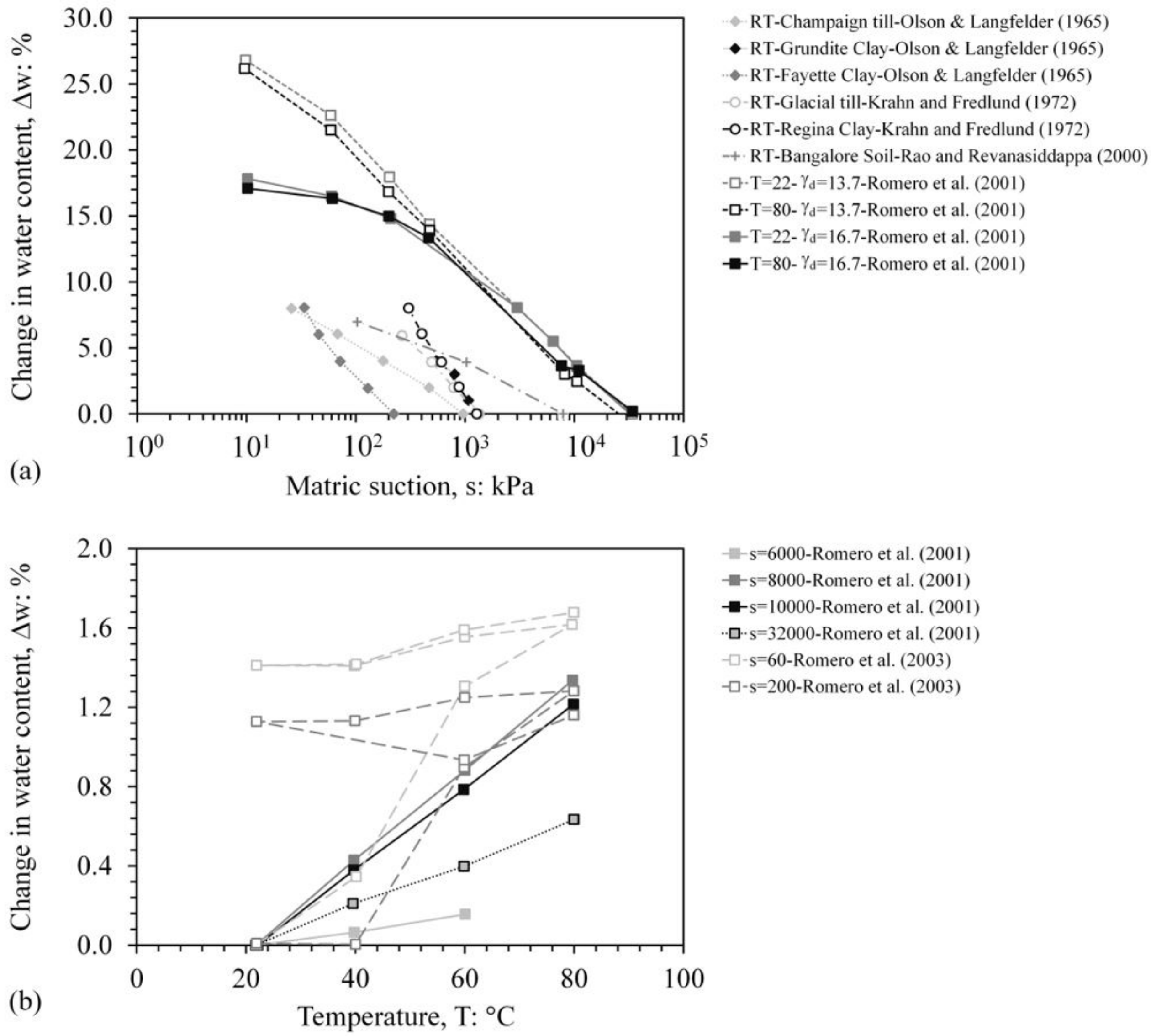

Figure 2. Changes in water content during (a) hydraulic loading (b) thermal loading.

to explain this phenomenon. In clayey soils, pores can be divided into two distinct classes: (i) an interlamellar space and an interparticle porosity between connected clay clusters (where absorbed water is located), and (ii) an interaggregate space between aggregates where free water exists (Laloui & Loria, 2019; Houhou et al., 2020). Soil pores become smaller by increasing soil dry density through compaction or by increasing the mechanical load. The water regime in the pores, thus, changes from free water to adsorbed water even at low suction values, reducing the amount of water drained from the sample due to hydraulic loading or elevated temperatures. However, adsorption is regulated at high matric suction, and the dry unit weight of the soil does not significantly affect the soil-water retention capacity (Romero et al., 2001; Garakani et al., 2018).

Figure 2b shows the amount of water drained due to thermal loading, which clearly increases with increasing temperature for relatively high suction values (i.e., 6000-32000 kPa). On the other hand, for suction values of 60 kPa and 200 kPa, no significant amount of water was drained out of the specimen when thermally loaded up to 40 °C, after which a considerable increase in the drainage rate was observed (Romero et al., 2003). This phenomenon was associated with a lack of appreciable volumetric change until reaching 40 °C by pointing out an apparent overconsolidation effect, which disappeared during the tests performed at higher suctions.

The effect of thermal loading on soil water content can be explained considering two fundamental driving mechanisms. First, as the thermal expansion rate of pore water is around seven to ten times that of most soil particles, thermal loading results in differential expansion of pore water and solids, urging excess water to drain out of the soil (Vega & McCartney, 2014). Furthermore, as the temperature rises, the viscosity of the pore fluid decreases, promoting the water drainage. Thus, lower water content is expected for a heated sample. However, heating appears to have a less pronounced effect on the degree of saturation, which can be attributed to the thermally-induced collapse of the soil skeleton, particularly in normally consolidated soils (Coccia & McCartney, 2016). Thus, the degree of saturation can be considered an essentially temperature-independent parameter, only slightly decreasing with increased temperature (Coccia & McCartney, 2016). The impact of thermal loading on the deformation behaviour of soils is further discussed later in Section 3.

3. Effects on volumetric behaviour

The serviceability of energy geostructures as structural support is governed by the thermal volume change behaviour of soils, which is a complex phenomenon due to an interplay between temperature, suction, and stress history. A review and synthesis of available experimental evidence on the thermal deformation of soils with different stress histories and matric suction, as well as temperature and matric suction impacts on compression indexes are presented in the following section.

3.1 Volumetric deformation

In the framework of the thermo-hydro-mechanical behaviour of soils, it is essential to predict soil deformation to mitigate displacement affecting serviceability during the life of a structure or a natural deposit. Many experiments are conducted, and variables such as stress history (François et al., 2007), thermal history, recent stress history, heating period, and constant high-temperature phases (Burghignoli et al., 2000), the time elapsed between the end of primary consolidation of the last applied mechanical load and the start of the thermal load (Campanella & Mitchell, 1968), soil type (Coccia & McCartney, 2016), plasticity index (Sultan et al., 2002; Sutman, 2013), and anisotropy (Laloui et al., 2014) are introduced as determining parameters affecting soil volumetric behaviour.

In Figure 3, the thermal axial strain per 1 °C temperature increase is plotted against *OCR* for fine-grained soils in different matric suctions. Similar to the response of saturated soils to thermal loading (Baldi et al., 1988; Graham et al., 2001; Cekerevac & Laloui, 2004; Abuel-Naga et al., 2005; Vega & McCartney, 2014; Di Donna & Laloui, 2015), overconsolidated partially saturated soils undergo dilation, while normally consolidated specimens contract, which is further investigated in Figure 4 (Saix, 1991).

Three factors are considered as fundamental driving mechanisms behind the volumetric response of soils during thermal loading. (i) The rearrangement of particles explaining the irreversible component of contractive strain, which is associated with the reduction in the preconsolidation stress during heating, leaving the normally consolidated soils in an unstable state (Laloui et al., 2014). This effect mainly depends on the properties of the soil structure, and its rate is considered to be pore water pressure-independent (Campanella & Mitchell, 1968). Furthermore, it is observed by Burghignoli et al. (2000) that the volume reductions occur at a virtually constant porosity during cooling and

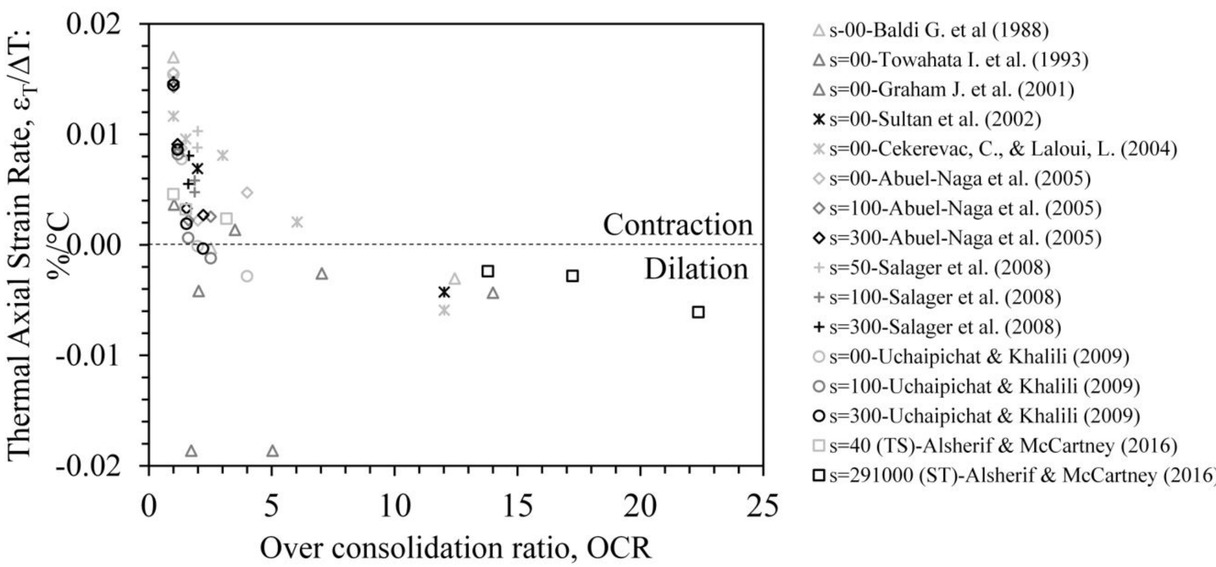

Figure 3. Effect of suction and overconsolidation ratio on thermal axial strain during thermal loading.

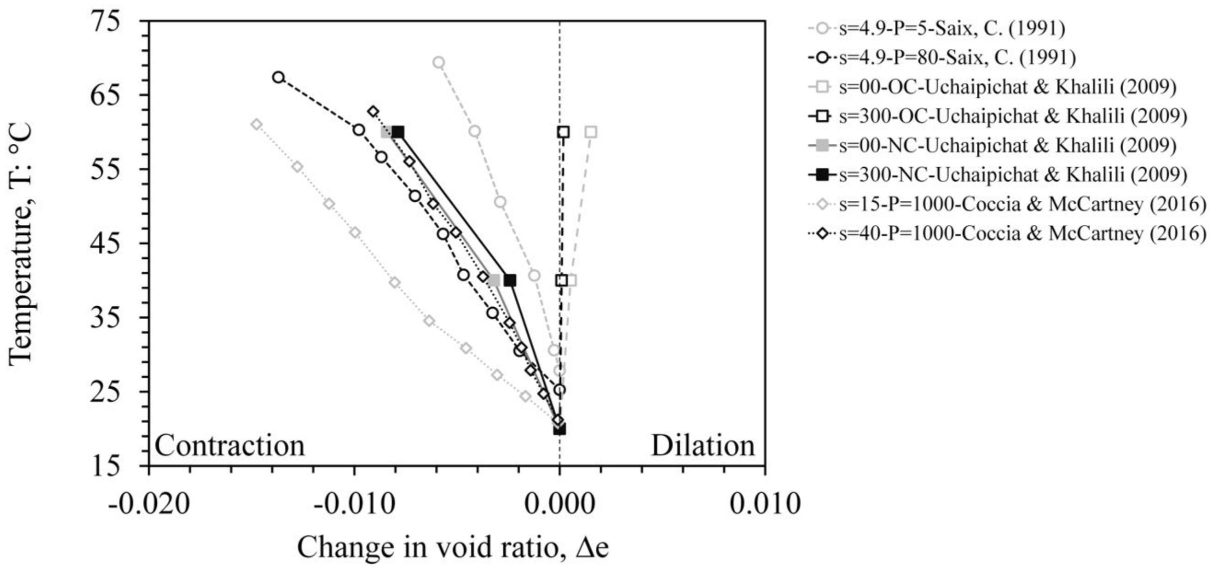

Figure 4. Changes in void ratio during thermal loading.

subsequent low-temperature state. Thus, there is no significant rearrangement of particles that may be an explanation for elastic contraction during cooling.

On the other hand, as an explanation for the reversible expansive strains, (ii) expansion of soil components, clay minerals, and pore water, and (iii) the increase in repulsive forces between clay particles undergoing thermal loading, which results in an increase in inter-particle spacing are proposed (Campanella & Mitchell, 1968; Laloui et al., 2014; Coccia & McCartney, 2016). The irreversible contraction component dominates for normally consolidated clays, while the reversible expansion component dominates for highly overconsolidated clays.

It is evident in Figures 3 and 4 that the tendency of highly overconsolidated soils to expand and normally consolidated to contract is common for both saturated and partially saturated soils. However, the associated volumetric strains are evidently smaller for partially saturated soils, compared to the saturated ones. This phenomenon can be attributed to the dependence of apparent preconsolidation stress on temperature and suction variations, where the yield surface tends to shrink with increasing temperature and expand with increasing suction, as previously presented in this paper. Thus, considering the soils initially on or close to the yield surface, the expansion of the yield surface with suction causes an increase in the thermo-elastic expansive portion of volumetric strains at the initiation of the heating phase, leading to an overall decrease in thermo-plastic contractive volumetric strains. On the other hand, a decrease in the thermo-elastic expansion of highly overconsolidated soils with increasing suction is also observed in Figure 4. This behaviour can be associated with the increase in effective stress being greater than that of the apparent preconsolidation stress, which leads to a reduction in the overconsolidation ratio and, thus, to lower thermo-elastic volumetric strains (Uchaipichat & Khalili, 2009).

In between the previously presented conditions, there exists an intermediate one in which temperature increase of highly overconsolidated samples will exhibit an initial elastic expansion within the yield surface, which is followed by a plastic contraction once the yield surface is reached, as the temperature is increased further (Sultan et al., 2002). For instance, in experiments conducted by Cekerevac & Laloui (2004), overconsolidated kaolinite (*OCR* = 12), exhibits contraction after the temperature reaches 50 °C during thermal loading. The extent of the reversible expansion/irreversible contraction parts of deformation due to the thermal loads depends on soil type, plasticity, and *OCR*. The temperature at which the transition occurs between thermal expansion and contraction increases with *OCR* (Sultan et al., 2002). Thus, even heavily overconsolidated soils may contract at high temperatures if the yield surface is reached (François & Laloui, 2008).

Considering the response of soils to cyclic thermal loads, a comparatively limited amount of additional contraction is observed for saturated soils during successive cycles (Campanella & Mitchell, 1968; Sultan et al., 2002; Vega & McCartney, 2014). The effect of thermal creep and the subsequent strain hardening are introduced as the underlying mechanisms for this response (Campanella & Mitchell, 1968; Burghignoli et al., 2000). It can also be explained by the fact that the yield surface shrinks, and irreversible plastic strains develop as temperature increases. The development of plastic strains leads to strain hardening and, thus, swelling of the yield surface (Sultan et al., 2002). As the yield surface expands in the subsequent thermal cycles, the soil remains within the yield loci and thus undergoes reversible strains (Hueckel & Baldi, 1990). However, cyclic stabilisation and the effects of thermal creep may still cause an additional minor amount of contraction (Campanella & Mitchell, 1968).

3.2 Deformation parameters

It is generally accepted that the compression index is independent of the stress ratio provided that the ratio between deviatoric stress and generalised mean effective stress is kept constant (Salager et al., 2008). To investigate this, the evolution of the compressibility index with matric suction and temperature are presented in this section. The data sets are categorised regarding the employed device, where "O", "I", and "TR" stand for Oedometer, Isotropic cell, and Triaxial cell, respectively.

Compressibility index variations with matric suction and temperature are shown in Figure 5 and 6, respectively. As observed in Figures 5a and 6a, swelling and compression indexes decrease as matric suction increases for data analysed in the framework of net stress (Romero et al., 2003; Tang et al., 2008; Salager et al., 2008; Uchaipichat & Khalili, 2009). This behaviour can be attributed to the lower thermo-elastic volumetric strain leading to lower values of compression indexes, as discussed in the previous section. However, the experimental data analysed in the context of effective stress shows a negligible matric suction effect on the evolution of the compressibility index (François et al., 2007; Salager et al., 2008).

Temperature effects on compressibility indexes are investigated in Figure 5b and 6b, where no specific trend is identified in saturated (Finn, 1952; Campanella & Mitchell, 1968; Di Donna & Laloui, 2015) and unsaturated conditions (Saix et al., 2000; Abuel-Naga et al., 2007c; Tang et al., 2008; Uchaipichat & Khalili, 2009; Coccia & McCartney, 2016). However, Romero et al. (2003) stated that in contrast with the swelling index, which is insensitive to temperature variations, the compression index increases slightly with increasing temperature for data analysed in the framework of net stress.

4. Effects on thermal and hydraulic conductivity

The extent to which the soil at the vicinity of energy geostructures is influenced by their operation highly depends on the thermal and hydraulic conductivities. Furthermore, the operation of energy geostructures is associated with a change in surrounding soil temperature and water content. Therefore, the evolution of thermal and hydraulic conductivities with temperature and water content of the soil is investigated in the following section.

4.1 Thermal conductivity

An understanding of how heat is transferred through the porous soil media is of high importance in fields of studies such as geothermal energy resources (White, 1973), radioactive waste disposal (Li et al., 2013), energy geostructures (Laloui & Sutman, 2019), soil science, and agriculture meteorology (Lu et al., 2007; Nikolaev et al., 2013). The three practical heat transfer mechanisms in unsaturated soils are conduction through particle-to-particle contacts, convection via water-vapour flow, and phase changes or latent heat transfer (Lu & Dong, 2015). Factors such as soil mineralogy (Brigaud & Vasseur, 1989), grain size distribution (Chen, 2008; Yun & Santamarina, 2008), soil structure (Chen, 2008), porosity (Brigaud & Vasseur, 1989; Tarnawski et al., 2011), water content (Hiraiwa & Kasubuchi, 2000; Lu & Dong, 2015), particle shape, cementation (Dong et al., 2015), and temperature (Sakaguchi et al., 2007; Nikolaev et al., 2013) are introduced as determining parameters affecting thermal conductivity of soils. Both intrinsic physical properties of each phase of soils and the environmental variation of each phase determine the thermal properties of the soil (Dong et al., 2015). Hence, it is necessary to consider properties and the volumetric fraction of each phase, as well as the medium geometry, to predict the thermal conductivity of the overall medium (Yun & Santamarina, 2008).

Figure 7a shows that the thermal conductivity increases significantly by increasing the degree of saturation. Generally, the thermal conductivity evolution with degree of saturation can be divided into three stages: (i) a slight increase as the degree of saturation increases to the permanent wilting point, (ii) a significant increase as the degree of saturation increases further to the field capacity, and (iii) a slight increase or decrease near the saturation (Nikolaev et al., 2013; Lu & Dong, 2015). The thermal conductivity evolution with degree of saturation in silty and clayey soils is smoother than in sandy soils, without distinct inflection points (Dong et al., 2015).

At a low degree of saturation, the thermal conductivity of the soil increases gradually since the water only coats the soil particles, and the pores between the soil particles are filled with air. At the permanent wilting point, the water menisci are formed and become gradually interconnected. The water fills the gaps between the soil particles resulting in a significant expansion of the heat transfer paths through the water film connecting the particles where conductive heat transfer occurs (solid-water-solid conduction) (Nikolaev et al., 2013; Lu & Dong, 2015). Variations in thermal conductivity at high degrees of saturation are small, as further changes in the size of occluded air bubbles do not effectively change the paths of conductive heat transfer (Nikolaev et al., 2013; Lu & Dong, 2015).

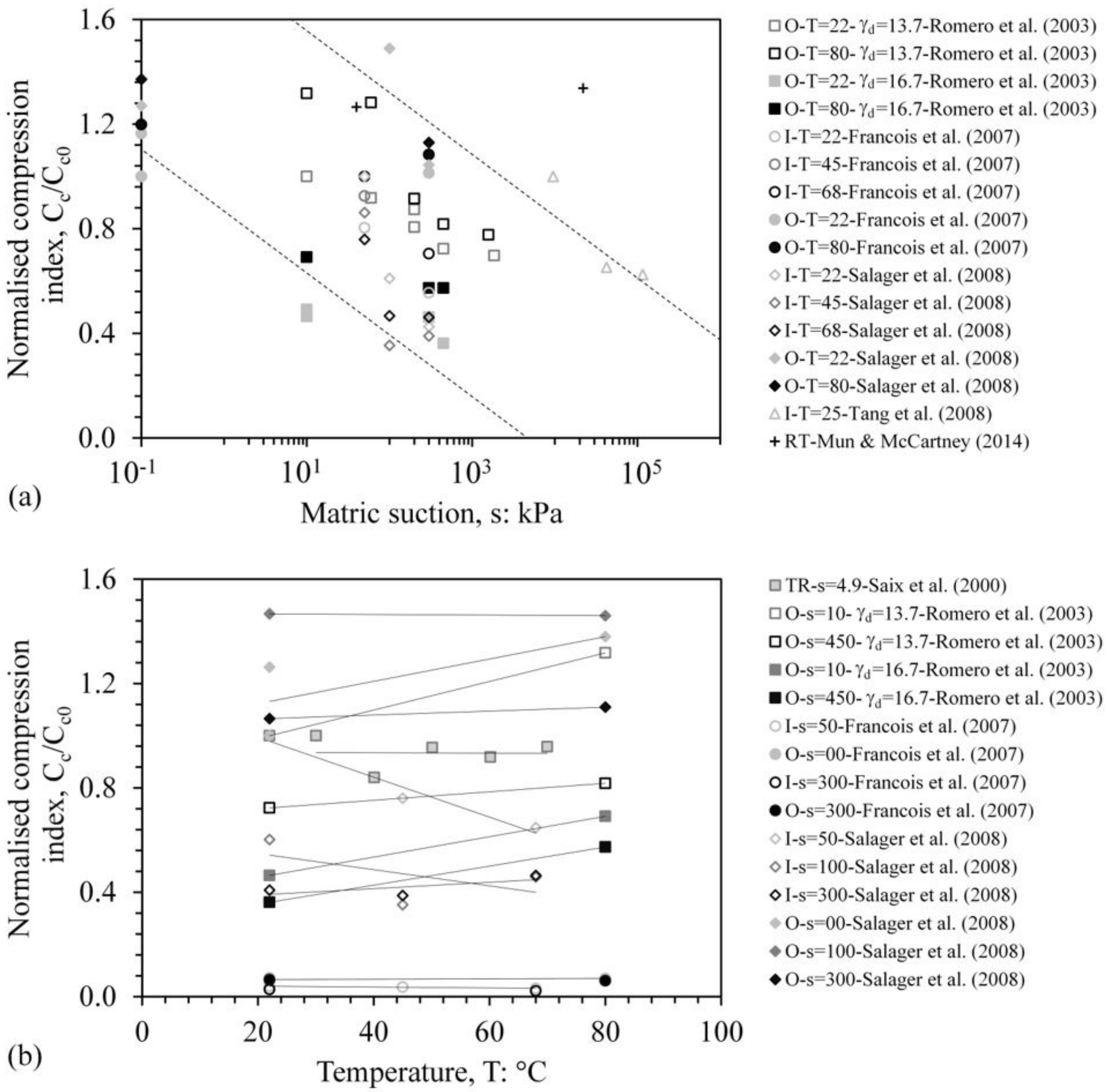

Figure 5. Changes in swelling index with (a) matric suction (b) temperature.

Latent heat transfer due to vapor migration is more pronounced in higher temperatures, which leads to an apparent thermal conductivity higher than the one through pure heat conduction. Therefore, it can be observed that the evolution of thermal conductivity with degree of saturation is not affected by temperature change when the soil temperature is increased up to the room temperature (RT). Nevertheless, when the temperature is increased further, thermal conductivity varies sharply with degree of saturation. Moreover, it can be observed from Figure 7a that for tests carried out at high temperatures (e.g., 72-75 °C), there exists a degree of saturation above which the thermal conductivity ceases to increase further. In fact, it can be observed from the tests on Ottawa sand by Nikolaev et al. (2013) that when the specimens were heated to 72 °C, even a slight decrease in thermal conductivity occurred after a certain degree of saturation. This phenomenon was reported to be caused by the formation of small air pockets surrounded by soil particles and water, which hinder the water vapour movement and thus result in a decrease in heat transfer due to minimal mass transfer (Nikolaev et al., 2013; Lu & Dong, 2015).

The evolution of thermal conductivity with porosity is presented in Figure 7b. Although a distinct decrease of thermal conductivity with porosity is observed for all

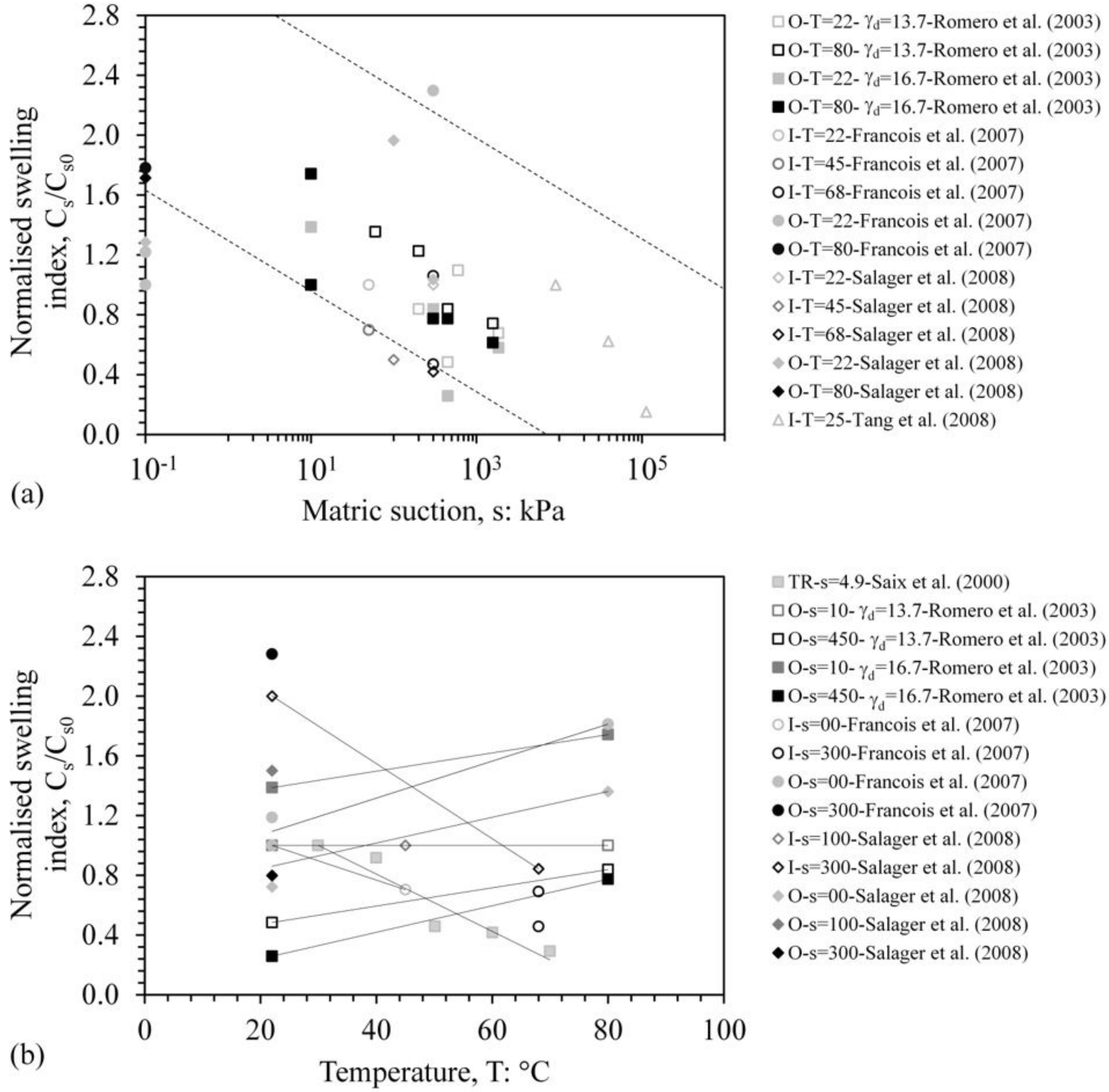

Figure 6. Changes in compression index with (a) matric suction (b) temperature.

specimens, the trend becomes more evident in dry specimens compared to the saturated ones (Johansen, 1977). This is due to the fact that the main pathways for thermal conduction between dry soil grains are limited to grain contact points, which are restricted as the porosity increases (Chen, 2008). Nevertheless, for saturated soils, a higher porosity implies more water available in soil pores, facilitating solid-water-solid heat conduction and thus resulting in a less severe reduction in thermal conductivity due to porosity increments (Tarnawski et al., 2011).

The effect of temperature variations on thermal conductivity is shown in Figure 8. In the dry condition, as shown in Figure 8a, the thermal conductivity generally increases when the temperature increases. On the other hand, Figure 8b indicates contradictory trends for the thermal conductivity variation with temperature, considering saturated soils. For instance, both increasing and decreasing trends can be observed comparing two distinct thermally loaded saturated Ottawa sand specimens (Tarnawski et al., 2009; Nikolaev et al., 2013).

As previously mentioned, the thermal conductivity of any mixture is related to the thermal properties of each phase; thus, the temperature impact on each soil component should be considered to explain the overall thermal conductivity

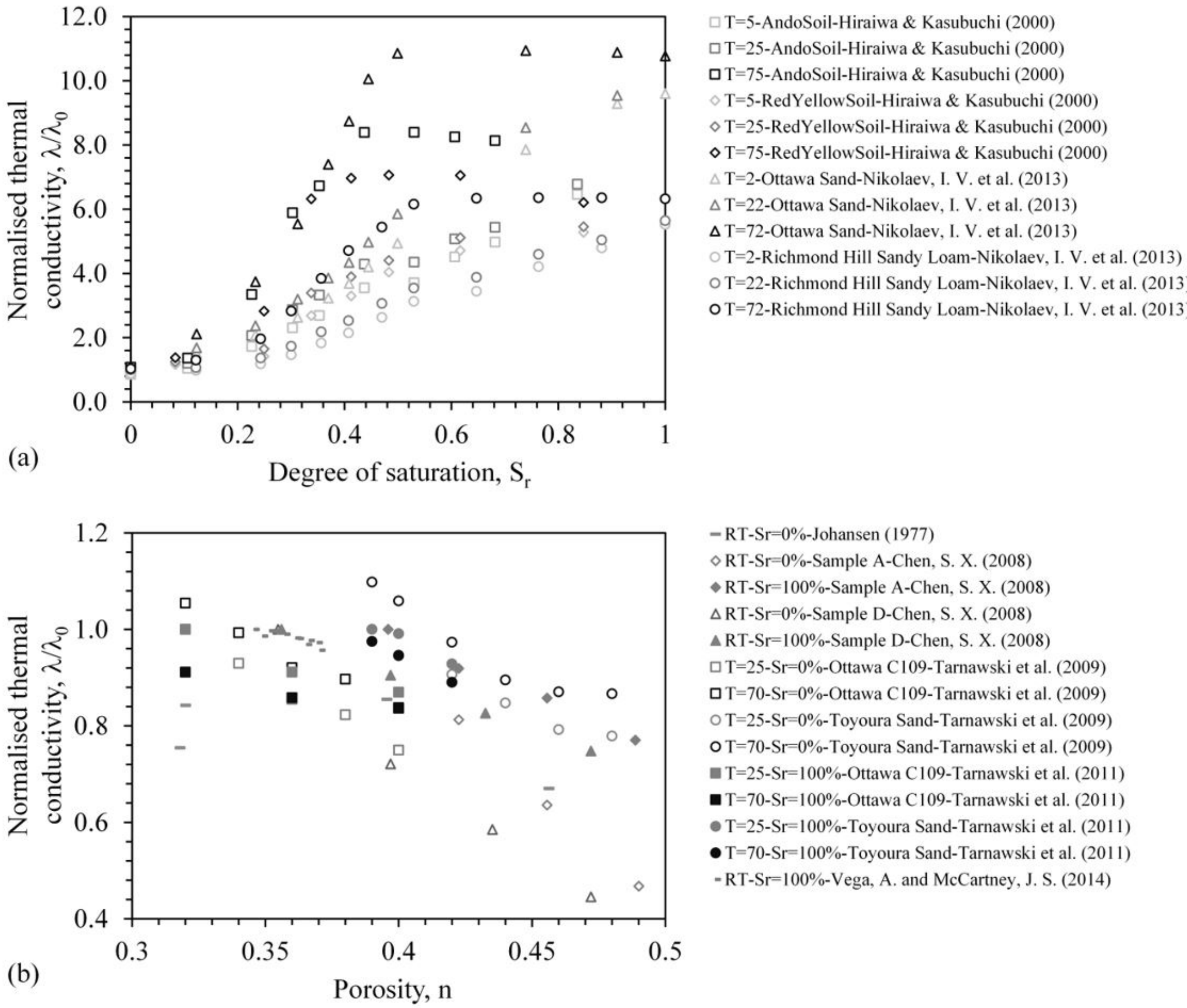

Figure 7. Evolution of thermal conductivity with (a) degree of saturation (b) porosity.

evolution with temperature (Sakaguchi et al., 2007; Gens, 2010). The thermal conductivity of soil minerals, except feldspar, decreases with increasing temperature, while water and air thermal conductivities are inversely temperature-dependent parameters at least for the temperature range of 0-100 °C (Farouki, 1981). The soil porosity intrinsically controls the function of each thermally impacted soil component in the thermal conductivity determination. The presence of water and air in the pore space not only affects the overall thermal conductivity due to their individually temperature-dependent nature but also due to the water and air acting as insulators for soil grains. Therefore, the higher the porosity, the less pronounced is the effect of temperature increase on soil grains in terms of thermal conductivity reduction. Furthermore, the heat conduction through the water and air between solid particles decreases (reduction of thermal bridges), while the transfer of latent heat increases (liquid-island theory) as temperature increases (Sakaguchi et al., 2007). However, the soil skeleton collapse due to thermal loading, particularly considering normally consolidated soils, enhances heat conduction.

In the dry state, the factors enhancing thermal conductivity surpass the decreasing ones and lead to an increase in thermal conductivity with temperature, as shown in Figure 8a. Nonetheless, a reduction in thermal conductivity with increasing temperature is reported for low volumetric water content (θ) Toyoura sands, i.e., $\theta \leq 0.07$ (Sakaguchi et al., 2007). The decrease in conduction with increasing temperature, which overcomes the increase in the transfer of latent heat, was considered a potential reason behind this phenomenon by the authors. However, experiments performed on the mixture of Toyoura sand and kaolinite show an increasing trend of thermal conductivity during thermal loading (Sakaguchi et al., 2007). The reason

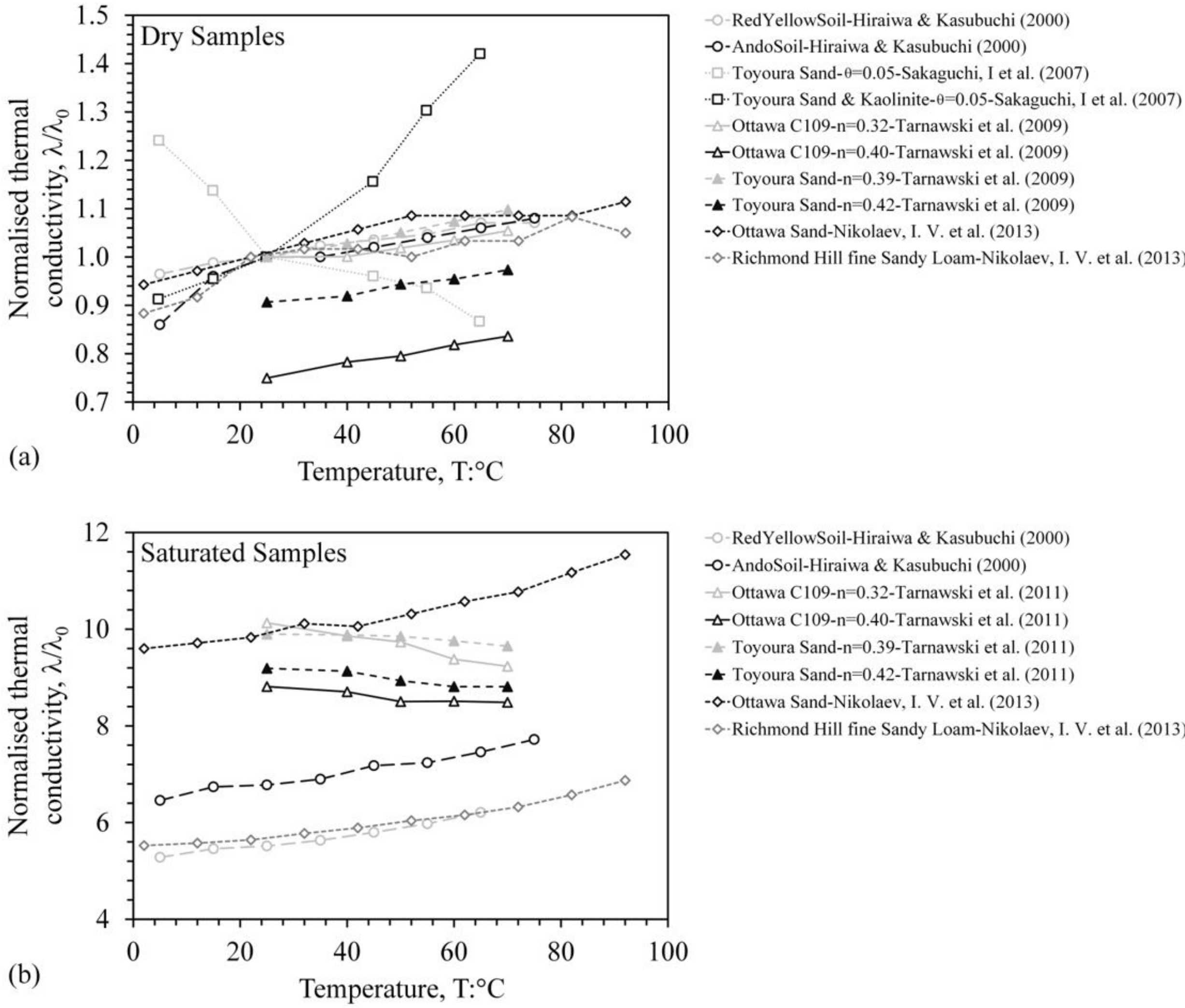

Figure 8. Evolution of thermal conductivity with temperature for (a) dry samples (b) saturated samples.

is associated with the added kaolinite, which not only has higher thermal conductivity than air and water but also enhances the thermal bridges, especially in the nearly dry state (Farouki, 1981; Sakaguchi et al., 2007).

In the saturated state, regarding the lower insulating capability of water compared to air, Tarnawski et al. (2011) found a decreasing trend in thermal conductivity variation with temperature for saturated Ottawa and Toyoura sand. For the higher porosity specimen, there was more water and less temperature impact on the thermal conductivity of the quartz and thus less reduction in soil thermal conductivity for the Ottawa sand. However, other studies performed on Ottawa sand, or the other soils, suggest that increasing thermal conductivity components dominate over the decreasing ones when loaded thermally (Hiraiwa & Kasubuchi, 2000; Nikolaev et al., 2013).

4.2 Hydraulic conductivity

Hydraulic conductivity of soils depends on the number of parameters such as mineral composition, soil density, fluid properties (e.g., viscosity and chemistry), and temperature (Ye et al., 2013). Water presence in soil pores facilitates water movement leading to higher hydraulic conductivity, as shown in Figure 9a. It is also evident that temperature increments result in higher hydraulic conductivity (Constantz, 1982). However, this trend is not observed for Norfolk sandy loam soil, where hydraulic conductivity was measured at different points in a Lucite flow cell (Hopmans & Dane, 1986).

In this regard, Figure 9b shows a clear trend of increase in hydraulic conductivity with temperature for fully saturated specimens (Towhata et al., 1993; Cho et al., 1999). The temperature impact on the matric potential, the

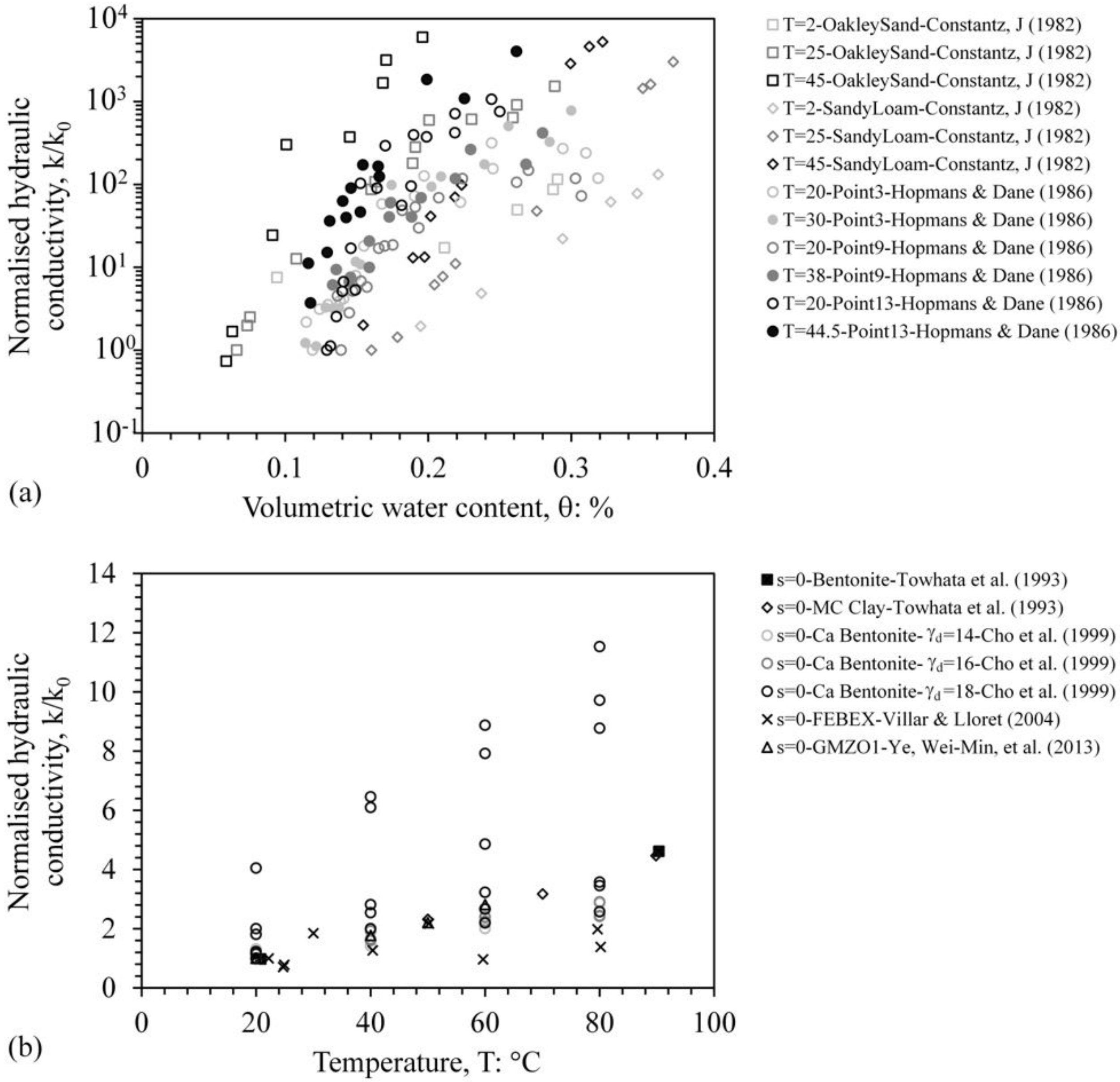

Figure 9. Evolution of hydraulic conductivity with (a) temperature (b) volumetric water content.

surface tension of the soil water, and the diffuse double-layer thickness are all considered fundamental driving mechanisms behind the temperature-sensitivity of hydraulic conductivity (Constantz & Murphy, 1991). Moreover, a decrease in water viscosity with increasing temperature leads to higher hydraulic conductivity (Hopmans & Dane, 1986; Constantz & Murphy, 1991; Delage et al., 2000). Although the temperature dependence of the viscosity of soil water may vary from that of free water (Constantz & Murphy, 1991; Romero et al., 2001), heating is also associated with the movement of high-density adsorbed water to large pores, increasing the proportion of free water in the porous (inter-aggregate) channels (Villar & Lloret, 2004). This phenomenon can be considered as an increase in temperature enlarging the effective water flow crossing area (Ye et al., 2013). Finally, fabric changes and redistribution of pores due to thermal loading are also inherently considered as responsible for changes in hydraulic conductivity (Romero et al., 2001).

5. Conclusions

It is of paramount importance to investigate the THM behaviour of soils to gain insight into the multi-physical phenomena that govern the behaviour of energy geostructures such as energy piles. Thermal and hydraulic variations can be considered among the most notable phenomena affecting the surrounding soils. Although temperature variations do not directly lead to adverse effects compared to hydraulic loading, they still govern or modify coupled processes, such as soil shrinkage. Therefore, the thermal behaviour is primarily studied to reveal the response of fine-grained soils to temperature variations, as granular soils are known to have an elastic response to thermal loads. In this regard, the results of the laboratory investigations carried out in the context of unsaturated soils are gathered to obtain comprehensive knowledge of soil response to THM loading within the framework of energy geostructures. Some of the conclusions drawn from the laboratory testing campaigns are as follows:

- The history of soils is preserved in their structure, considering the stress and other environmental changes that have occurred since their deposition, and has a significant impact on the strength and deformation characteristics. The preconsolidation stress is a critical factor in predicting the consolidation settlement of existing and future structures. Although preconsolidation stress is a stress path dependent parameter under THM loading, clear trends in its response to temperature and matric suction variations can be deduced for results analysed in the framework of effective stress. As evidenced by existing experimental studies, an increase in temperature tends to reduce the effective preconsolidation stress due to thermal softening. On the other hand, a rise in matric suction increases effective preconsolidation stress, at least for matric suctions higher than the air-entry value;
- Water content affects the volumetric behaviour of soils to a great extent. The water content of soils surrounding energy geostructures is susceptible to change due to their thermal functioning or a change in groundwater level. As water content decreases, desiccation cracks and shrinkage become more probable. On the other hand, excess pore water pressure is generated with a higher groundwater level, leading to lower effective stress and thus lower shear strength. In this regard, water content variation with temperature and matric suction is studied, and a much higher drainage rate is noticed during hydraulic loading compared to temperature increase. Nonetheless, the amount of water drained under hydraulic loading for fine-grained soils is determined by the dry density and temperature of the soils. For matric suctions less than the residual value, as the adsorbed water portion of the dense specimens is higher than the one of loose samples, more water will be retained in a sample with higher density. However, adsorption governs the retention mechanism in higher suctions, and thus the density effect disappears afterwards. Furthermore, as temperature increases, the viscosity of free water decreases, and the water content decreases even before the hydraulic loading begins. Thus, tests conducted at higher temperatures show less water content variation during hydraulic loading;
- Soil deformation is one of the most critical issues threatening the serviceability of infrastructures. Land subsidence and soil shrinkage due to temperature increase on the one hand and swell or collapse behaviour due to change in the degree of saturation on the other, are common failure modes that could affect the surrounding soil of the energy geostructures. In fact, the function of energy geostructures can exacerbate those failure modes. For instance, water drains out of the soil as heat is transferred to the surrounding soil via the energy geostructures, increasing the suction stress and thus the effective stress. As a result, the overburden pressure exceeds the bearing capacity of the soil, resulting in land subsidence. For fine-grained soils, normally consolidated ones undergo contraction while highly overconsolidated soils dilate when loaded thermally. Factors such as stress path may, however, change the dilative behaviour in overconsolidated soils. (i) Particle rearrangement, (ii) expansion of soil components, and (iii) repulsive forces between clay particles are factors that contribute to the volumetric response of soils. The results also show that compressibility indexes are somehow temperature independent, though they decrease with increasing matric suction;
- As thermal conductivity increases, fluctuations in temperature due to operation of energy geostructures occur in greater extent, and hence thermal loads have a more significant impact on the soil media. Both water content and temperature variation control the thermal conductivity of soils. The thermal conductivity generally increases with the degree of saturation. For tests conducted at temperatures above 70 °C, an initial increase is followed by an eventual decrease, although the extent of temperature increase is well above the expected variations within the framework of energy geostructures. Enhanced solid-water-solid thermal conduction is introduced as the primary cause of thermal conductivity variation with increasing degree of saturation. However, in the case of thermal conductivity evolution with temperature, contradictory trends are observed. The measured data indicates that thermal conductivity may increase with temperature while decreasing trends are also observed in near dry state and saturated conditions. Thus, associating a single mechanism is not sufficient to fully describe this phenomenon,

which requires considering each phase property and the medium geometry variation with temperature;

- The experimental evidence on hydraulic conductivity shows that it increases with a rise in temperature or water content. The matric potential, the surface tension of the soil water, the diffuse double-layer thickness, and pore redistribution plays a paramount role in hydraulic conductivity variation with temperature.

In summary, projected changes in the temperature and water content of the soils surrounding energy geostructures may lead to significant changes in soil behaviour. Although individual changes in soil properties can pose their own challenges assuming a single driver, the compounding effect of multiple drivers and the influence of variation of soil properties on each other can be more significant and escalate the failure possibility. The extent of soils impacted by THM loading will increase as thermal and hydraulic conductivity increases. The water content and soil temperature will change to a greater extent, leading to a more significant change in the preconsolidation stress, affecting deformation characteristics and soil strength to a greater extent.

Declaration of interest

The authors have no conflicts of interest to declare that are relevant to the content of the paper.

Authors' contributions

Amirhossein Hashemi: conceptualization, data curation, writing – original draft. Melis Sutman: supervision, writing – review & editing.

List of symbols

C_c	compression index
C_{co}	reference compression index
C_s	swelling index
C_{so}	reference swelling index
e	void ratio
k	hydraulic conductivity
k_0	reference hydraulic conductivity
n	porosity
OCR	overconsolidation ratio
p	net confining stress
s	matric suction
s_0	reference matric suction
S_r	degree of saturation
T	absolute temperature
T_0	absolute temperature
w	gravimetric water content
γ_d	soil dry density
ε_T	thermal axial strain
ε_v	volumetric strain
θ	volumetric water content
λ	thermal conductivity
λ_0	reference thermal conductivity
p'	preconsolidation stress
$p'0$	reference preconsolidation stress
v	vertical stress

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