Suction effect on the thermal properties of compacted kaolin

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ABSTRACT: The thermal properties of samples of compacted white kaolin were investigated after suction application using vapor equilibrium in wetting and drying paths. The samples tested were compacted for the same water content and void ratio was changed to achieve different structures due to compaction. The water retention curve of the samples was determined using a water dewpoint device and through vapor equilibrium. Volumetric heat capacity, thermal diffusivity and thermal conductivity were measured in those samples using a thermal probe. A relationship between thermal conductivity and degree of saturation was defined for each void ratio and compared with the expressions suggested in the literature. The curves degree of saturation versus thermal conductivity during wetting and drying paths were defined. A good fitting was found considering the relationship between thermal conductivity and degree of saturation, converted to suction using the water retention curve. Thermal conductivity increased with the degree of saturation and with decreasing void ratio, a result expected because of the increasing contribution of the solid phase in case of void ratio, and of water in case of the degree of saturation.

1 INTRODUCTION

The quantification of the thermal properties of soils is required for many purposes. Some examples are the design of thermoactive structures, green covers and sensors development for soil suction measurement. For the particular case of shallow geothermal systems, the heat exchangers between the soil and structure are installed in superficial layers and, therefore, are affected by seasonal changes in the degree of saturation due to soil-atmosphere interaction. In this case the thermal properties of the soil changes, and therefore the heat transfer efficiency. Suction measurement in soils can be a good way to monitor such systems.

No suggestion is found in the literature for equations relating thermal conductivity and suction, however suction can be estimated from soil thermal conductivity after proper calibration. This is because thermal conductivity depends on the degree of saturation, and therefore can be related with suction. Such principle has been used in sensors development (Sattler and Fredlund, 1989; Shuai and Fredlund, 2000).

The correspondence between the thermal properties (volumetric heat capacity, thermal diffusivity and thermal conductivity) and total suction in compacted kaolin with different void ratios was investigated. These properties were measured in samples with suction applied by vapor equilibrium in wetting and drying paths. The measurements done allowed finding a relationship between the degree of saturation and thermal conductivity in wetting and drying paths. The curves degree of saturation versus thermal conductivity were defined and adjusted by existing expressions from the literature.

The water retention curve was also measured. The paper ends analyzing the relationship between total suction and thermal conductivity, and how the water retention curve can be related with thermal conductivity.

2 THERMAL PROPERTIES OF SOILS

In soils, heat flows through the three phases present – solid, liquid and gas – must be considered. Thermal conductivity of the soil depends on the amount and proportion of each phase present. This is important because the thermal conductivities of each phase differs about one order of magnitude. In fact, solid thermal conductivity varies between 1.4 to 3 W/m/K, for distilled water is around 0.591 W/m/K and for dry air is around 0.024 W/m/K, all values for 20ºC and 1 atmosphere (Farouki, 1981).

Fixing porosity, several expressions can be found in the literature to relate thermal conductivity

λ with the degree of saturation S_r, assuming parallel, series or geometric average arrangements for the different phases (Farouki, 1981):

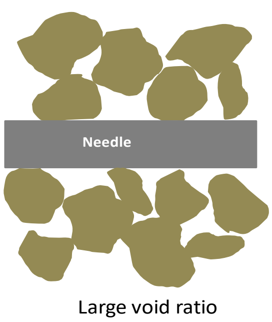
$$\lambda = \lambda_{sat} * \sqrt{S_r} + \lambda_{dry} * \left(1 - \sqrt{S_r}\right) \quad (1)$$

$$\lambda = \lambda_{sat}^{S_r} * \lambda_{dry}^{1-S_r} \quad (2)$$

$$\lambda = \lambda_{sat} * S_r + \lambda_{dry} * (1 - S_r) \quad (3)$$

In these equations λ_{sat} and λ_{dry}, are the soil thermal conductivity when saturated and dry, respectively.

Thermal conductivity is also affected by void ratio because, in a fixed volume, the amount of water and air in the pores depends on voids volume. This is illustrated in Figure 1 for a dry soil. In this case, the material with lower void ratio has higher thermal conductivity than that of the material with low void ratio, because it has the largest amount of solids. The differences will be less important for full saturated materials, as there is less contrast between the thermal conductivity of solids and water than that of solids and dry air.



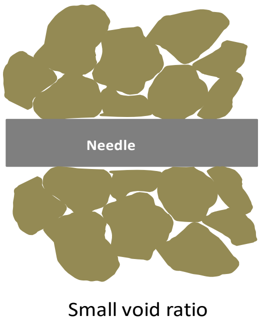


Figure 1. Influence of void ratio in thermal conductivity.

3 MATERIAL AND METHODS

The samples studied were prepared with commercial white kaolin. This clayey soil has liquid limit of 51% and plasticity index of 21% (MH accordingly with the unified soil classification system). Solid particles density is 26.1kN/m^3. From X-Ray diffraction tests the main minerals present are kaolin, quartz and muscovite (Gingine, 2017).

The tests were performed on samples compacted with fixed water content of 25%, for void ratios of 0.7± 0.05, 0.9± 0.05 and 1.2± 0.05. The samples were compacted in PVC moulds (3 cm diameter, 6 cm height, Figure 2.a). They were kept in the moulds during vapour equilibrium (Figure 2.b), controlled by changes weight. After equilibrium, thermal conductivity, heat diffusivity and volume heat capacity were measured using a thermal probe (Figure 2.c), followed by suction measurement using water potentiometer equipment WP4C. The samples were tested under room temperature (20ºC± 2ºC).

The measurements were done in a total of 10 samples for each void ratio: 4 for the wetting path, 4 for the drying path, one full saturated and the other dried in laboratory environment (RH=53% and s=87 MPa for 20ºC). The correspondence between relative humidity RH and suction applied by vapour equilibrium is presented in Table 1 (conversion done using the well know Kelvin's law). Partially saturated solutions of NaCl were used to apply these different suctions, prepared as suggested by Romero (2001).

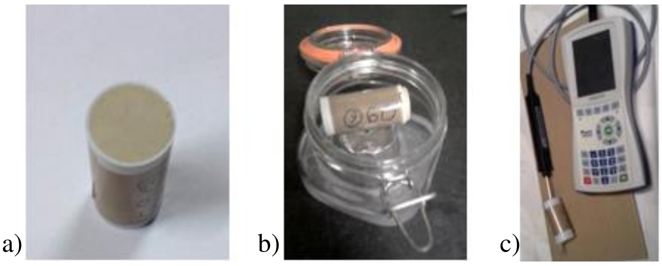


Figure 2. Samples inside the PVC moulds: a) after compaction; b) under vapour equilibrium; c) during the measurement of thermal properties at room temperature.

Table 1. Mass of NaCl used in distilled water for vapour equilibrium, and corresponding relative humidity RH and suction for 20ºC.

m_{NaCl} (g/dm^3)	RH (%)	s (MPa)
13.546	99.3	1
15.000	96.6	5
20.000	89.5	15
26.775	74.9	39

The samples were dried at laboratory environment before vapour equilibrium for the wetting branch. The samples of the drying branch were saturated before vapour equilibrium. Volume changes due to these preliminary treatments and during vapour equilibrium were not detected and therefore void ratio was assumed constant.

The thermal properties measured were the volumetric heat capacity, thermal diffusivity and thermal conductivity. Thermal probe ISOMET 2114 was used. It consists in a 10 cm long and 2.3 mm diameter steel needle inserted into the soil. A hole was drilled with the needle diameter previously to its insertion, to minimize disturbance and avoid breakage of the driest samples. Water was not used in drilling. The samples were kept in vapour equilibrium at least 24h after drilling and before using the ISOMET probe, to recover equilibrium state. Further details can be found in Sousa (2018).

4 EXPERIMENTAL RESULTS AND DISCUSSION

4.1 *Water retention curve*

The water retention curves found are presented in Figure 3. Van Genuchten expression (Van Genuchten, 1980) was used to fit the experimental data:

$$S_r = \frac{e}{G_s} w = \left[1+\left(\frac{\psi}{P}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} \tag{4}$$

In this equation e is voids ratio, G_s is the density of the solid particles, ψ is total suction, w is water content and P and λ are calibration constants (Table 2). It was assumed constant volume during wetting and drying.

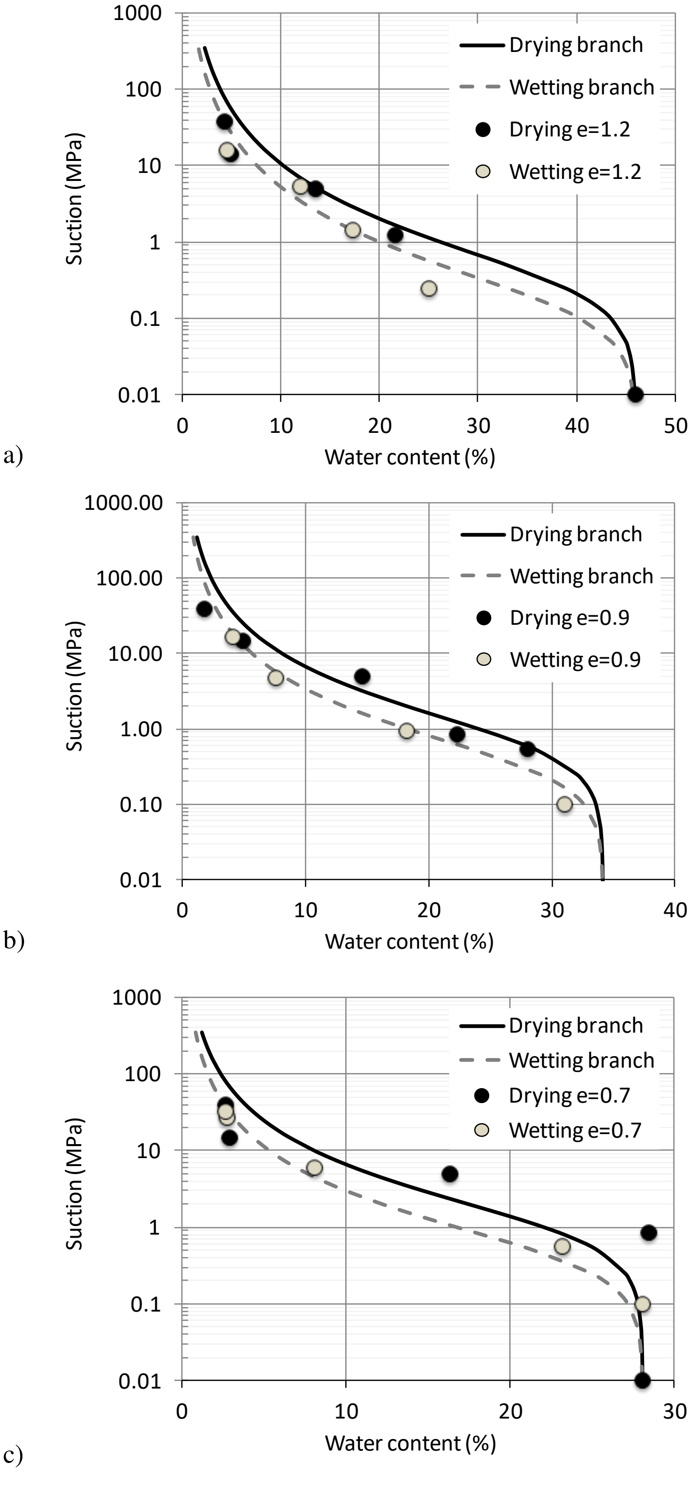


Figure 3. Water retention curve adjusted using Van Genuchnten's equation for: a) e=1.2; b) e= 0.9 and c) e=0.7.

Table 2. Calibration parameters of the water retention curve.

	Branch	Wetting	Drying
e= 0.6	*P* (MPa)	0.45	1.00
	λ	0.35	0.35
e= 0.9	*P* (MPa)	0.45	0.70
	λ	0.35	0.35
e= 1.2	*P* (MPa)	0.15	0.30
	λ	0.30	0.30

4.2 *Thermal properties*

Concerning volumetric heat capacity, cp, and thermal diffusivity, *a*, for fixed void ratio the values measured were very similar for all samples. The average values are presented in Table 3. Increasing values were found for decreasing void ratio, which increased slightly with the degree of saturation. This may be interpreted by the increasing contribution of the solid and liquid phases.

Table 3. Average values for the volumetric heat capacity and thermal diffusivity found for the different void ratios.

	e= 0.7	e= 0.9	e= 1.2
cp (J/m^3/K)	1.526×10^6	1.638×10^6	1.715×10^6
a (m^2/s)	0.776	0.628	0.505

Thermal conductivity is more affected by the presence and amount of liquid and air phases in the soil than these two properties. This is shown in Figure 4, presenting the values measured for each degree of saturation or water content.

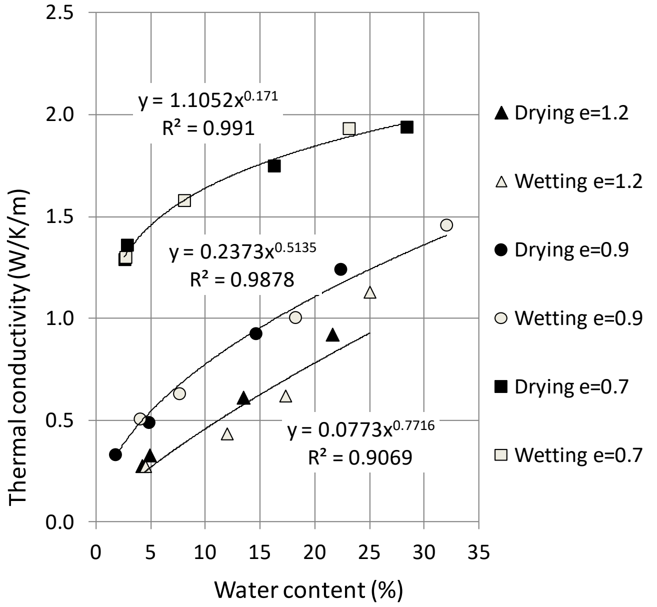


Figure 4. Thermal conductivity versus water content for the different void ratios.

The relationship found between thermal conductivity and water content are presented also in

Figure 4. Identical trends can be found when the degree of saturation i-s used instead of water content, assuming constant void ratio during wetting and drying paths. It can be seen in Figure 4 that the values appear to be independent from the hydraulic path followed and all can be adjusted with good fitting using an exponential relationship. Error increases with void ratio, probably because the void volume increases with void ratio and the contact between the needle and the soil may become less effective. In addition, there is an increasing difficulty in preparing homogeneous samples with the largest void ratio investigated.

This is illustrated in Figure 5, which includes scanning electron microscope photographs of the compacted samples showing the large pores obtained for void ratio of 1.2. This pore size cannot be detected using mercury intrusion porosimetry tests (Cardoso and Dias, 2017), and for this reason these tests were not done for the research presented in this paper.

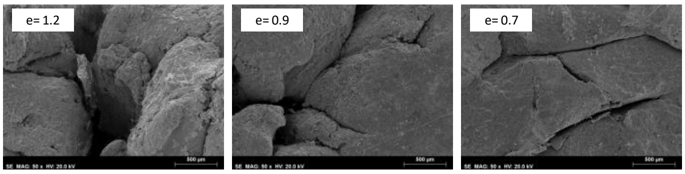


Figure 5. Photographs of the samples prepared with different void ratios showing the presence of large pores.

The dry and saturated thermal conductivities can be computed using the fitting equations presented in Figure 4. Adopting the theoretical value for the saturated water content function of void ratio and 0.1% for the saturated and dry water contents, respectively, it was found the values for λ_{sat} and λ_{dry} presented in Table 4. For the dry case the water content used corresponds to the residual value measured after drying the laboratory environment (RH 40%, 20ºC). A null value could not be used in the fitting equation because it would lead to a null conductivity, which is unrealistic.

Table 4. Saturated and dry thermal conductivity estimated for the different void ratios.

	e= 0.7	e= 0.9	e= 1.2
w_{sat} (%)	26.8	34.5	45.9
λ_{sat} (W/m/K)	1.939	1.527	1.455
λ_{dry} (W/m/K)	0.745	0.073	0.019

It can be seen in Table 4 that both dry and saturated conductivities increase with decreasing void ratio. This is explained by the contribution of the solid phase to soil conductivity. In fact, since the solids have the highest conductivity value when compared with the liquid or air phases, the solid phase earns relevance for decreasing void ratios. This also explains the differences between the dry and the saturated values, as the differences are in the different thermal conductivity of water and air.

The equations found in the literature for quantifying thermal conductivity based on the degree of saturation (Eqs. 1, 2 and 3) can be used to fit the experimental data.

As previously presented, there are three expressions proposed in the literature for describing thermal conductivity as function of the degree of saturation (Equations, 1, 2 and 3). They were calibrated using data from Table 4. The predictions found using them are presented in Figure 6. As expected, for all void ratios the best fitting equation is equation (1) because it is an exponential relationship in S_r (with exponent 0.5 in this case) similar to those found to best fit the experimental data in terms of water content previously presented in Figure 4.

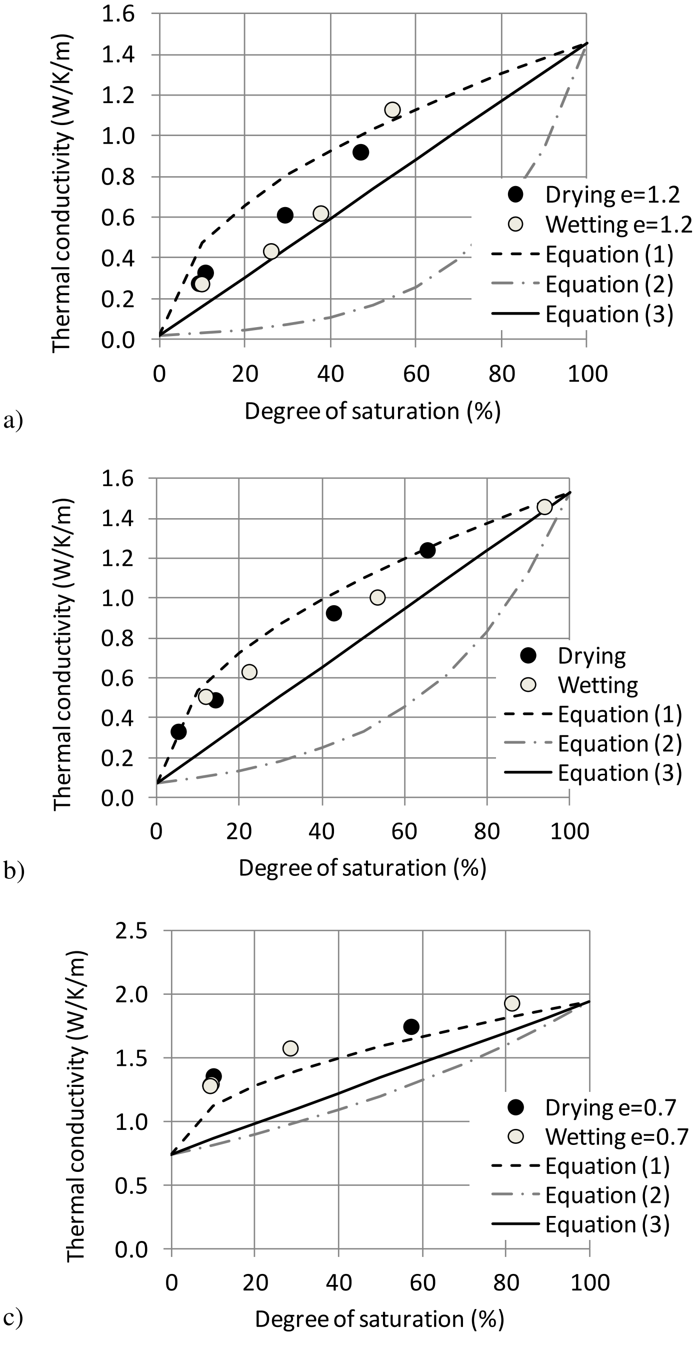


Figure 6. Thermal conductivity versus degree of saturation: a) e= 1.2; b) e= 0.9 and c) e= 0.7.

In Figures 4 and 6 is hard to distinguish the wetting and drying paths for void ratios 0.7 and 0.9, and error may be affecting the values measured for 1.2. It can be concluded that hysteresis in thermal measurements is negligible.

5 TERMAL CONDUCIVITY VERSUS SUCTION

Figure 7 presents the experimental data measured for both wetting and drying branches concerning thermal conductivity and suction. The hysteresis observed was introduced by suction, as it was found before that similar paths were found for wetting and drying branches when relating thermal conductivity with water content.

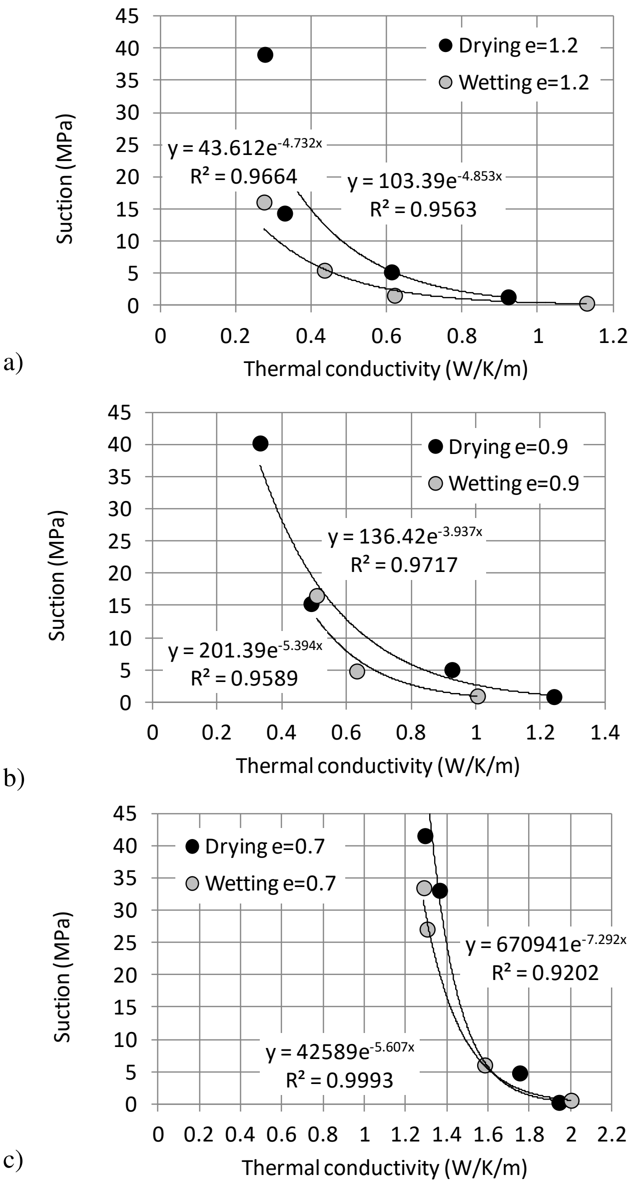


Figure 7. Suction versus thermal conductivity.

It can be observed in Figure 7 that thermal conductivity is higher for the drying branch than for the wetting branch. This is a hysteretic behavior which may be explained by the phase of water in each branch. In fact, during wetting the water is added in liquid form, and therefore it contributes to increase the influence of the thermal conductivity of the liquid phase. On drying, water is in form of vapor due to evaporation, and therefore it exists in the gas phase. The thermal conductivity of humid air, even if higher than the dry value, is lower than the thermal conductivity of liquid water, and therefore this decreases soil's thermal conductivity. This should have been observed in Figures 4 and 6 as well and must be investigated deeper in the future.

An alternative way to present Figure 7 is shown in Figure 8 for void ratio e=0.9, in which a logarithm scale was used for suction. Similar results can be found for the other void ratios. The experimental points do not align following an exponential relationship. This curve fitting procedure is not acceptable: thermal conductivity cannot be negative for very dry cases and the saturated thermal conductivity cannot be different for the wetting and drying branches.

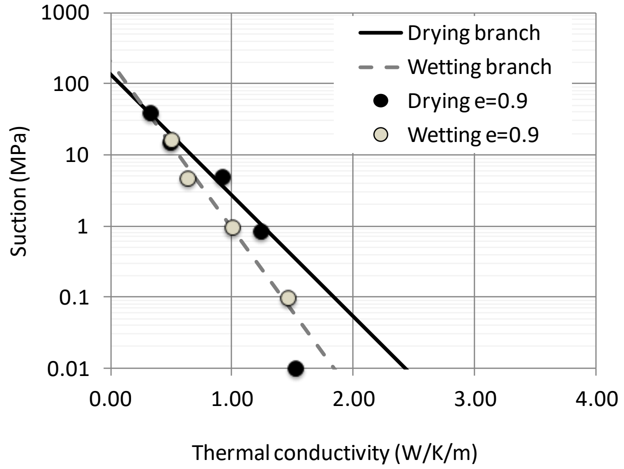
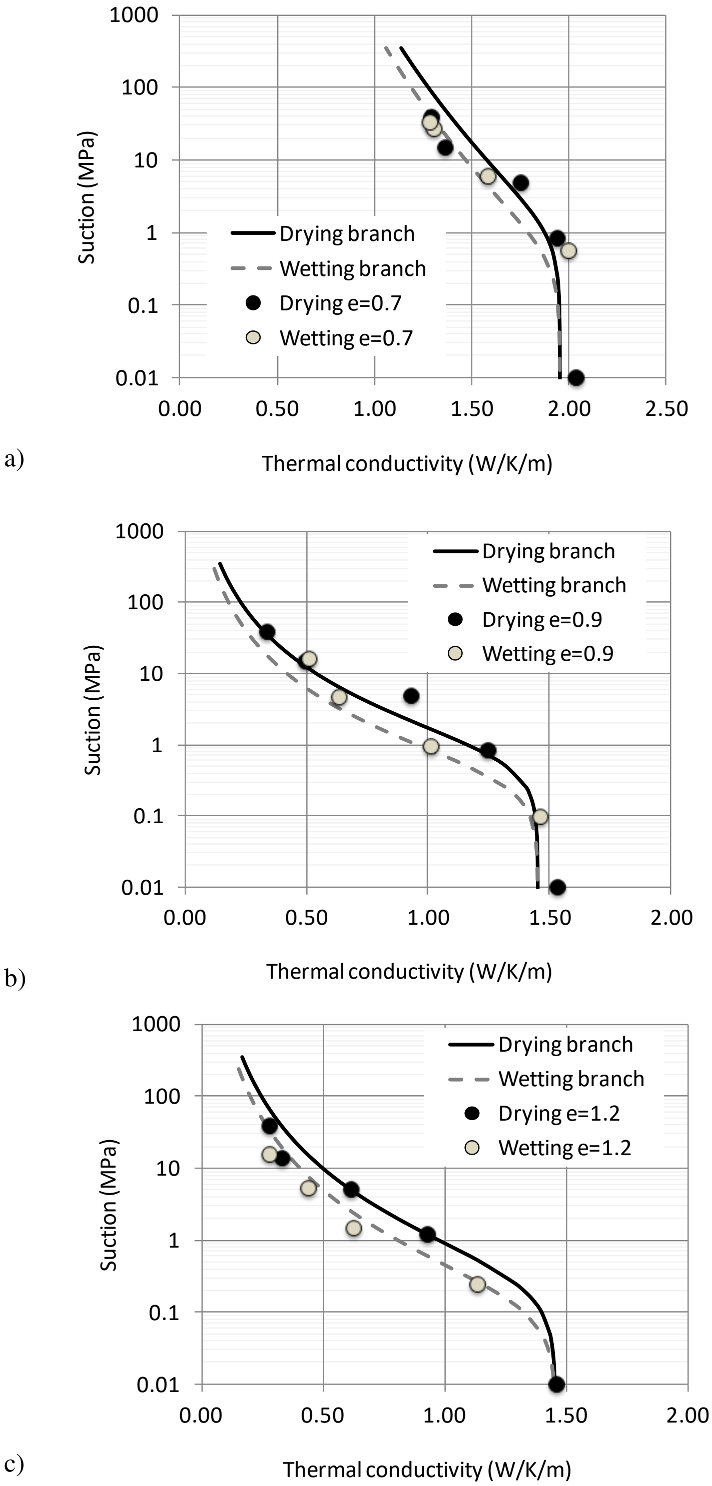


Figure 8. Suction versus thermal conductivity fitted using the equations presented in Figure 5 for e=0.9.

The alignment of the experimental points in Figure 8 suggests a fitting relationship considering water content, or degree of saturation, instead of thermal conductivity. The shape would be similar to the water retention curve, in Figure 1. This must be considered naturally because thermal conductivity can be written in terms of the degree of saturation.

Thermal conductivity can be plotted from the degree of saturation using the fitting equations presented in Figure 4 for each void ratio. Then, the computed degree of saturation can be related with suction using the water retention curve (Equation 4). The curves found using this procedure are presented in Figure 9 for all void ratios studied. Curve fitting achieved is quite acceptable in these cases and is similar to that found when defining the WRC (in Figure 3).

This is a relatively simple process because only one equation for the thermal conductivity in function of the soil water content is necessary, besides the water retention curve. Both can be easily determined in laboratory. In the absence of experimental data to find the thermal conductivity in function of the soil water content, however, thermal conductivity must be estimated using one of the equations from literature (Eq. 1, 2 or 3). Using this procedure, however, the experimental error in estimating thermal conductivity and on defining the WRC can be affecting the results in significant manner.



a)

b)

c)

Figure 9. Suction versus thermal conductivity fitted using the equations presented in Figure 4 and the water retention curve.

6 CONCLUSIONS

Thermal conductivity and its relationship with degree of saturation and suction was determined for samples compacted with the same water content and different void ratio. Thermal conductivity increased with the degree of saturation and with decreasing void ratio, a result expected because of the increasing contribution of the solid phase in case of void ratio, and of water in case of the degree of saturation.

Exponential relationships between thermal conductivity and the degree of saturation best fitted the results for all void ratios studied. Similar equations were suggested in the literature. No hysteresis was found, however it must be investigated deeper in the future.

When relating the thermal resistivity and suction, the best way to fit the results was found to be by considering the degree of saturation and its relationship with suction through the water retention curve, and with thermal conductivity through the equations previously determined. Error will be minimized if both are measured for the same soil.

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