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Relationship between thermal conductivity and soil–water characteristic curve of pure bentonite-based grout

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ABSTRACT

The relationship between the soil–water characteristic curve (SWCC) and thermal conductivity of pure bentonite and bentonite–sand grouts used as backfilling materials in ground heat exchangers was investigated in a laboratory experiment. The mix proportions utilized in this study were bentonite to 20% and 30% of the total weight, adding quartzite sand to 30% and 50% of the total weight (bentonite + water). Mixed grout specimens were prepared in rectangular parallelepiped shapes. The thermal conductivity, volumetric water content and matric suction of unsaturated specimens were measured as the saturated specimens were slowly dried at room temperature until there was little change in the measured values. The matric suction and thermal conductivity showed a bilinear relationship, with a breaking point identifying the air-entry value (AEV) and the SWCC describing the relationship between the matric suction and the volumetric water content (VWC). As the matric suction slowly increased to the AEV, the VWC of the specimens decreased, whereas the thermal conductivity increased; then, beyond the AEV, it rapidly decreased again. That is, as the specimens dried out, attaining the maximum at the AEV, their thermal conductivity decreased. The thermal conductivity and the VWC showed a parabolic relationship with the maximum thermal conductivity value at around the VWC corresponding to the AEV of each specimen. Revised empirical equations representing the relationship between these two parameters were suggested for prediction of the thermal characteristics of bentonite-based grout in geothermal heat pump applications.

1. Introduction

Due to environmental and energy-supply issues such as global warming and fossil-fuel depletion, geothermal energy is seeing increasing use as a sustainable resource. In this context, ground-source heat pump (GSHP) systems and geothermal heat pump (GHP) systems have been adapted for geothermal energy use. These are heating and cooling systems that provide residential and commercial buildings with heat in winter and cooling in summer. This technology relies on the fact that, at depth, the Earth has a relatively constant temperature, warmer than the air in winter and cooler than the air in summer. GHP systems exchange heat with the ground, often by means of vertical closed-loop geothermal systems such as a vertical U-tube borehole heat exchanger [1]. In this system, the borehole is backfilled with grouting materials, which provide a heat-transfer medium between the heat exchanger and the surrounding ground (e.g. soils or rock) and also controls groundwater movement to prevent contamination of water. Granular bentonite-water grouts are commonly used in GHP systems [2,3] as well as in other applications such as radioactive waste confinement [4].

Grouting materials' thermal conductivity is one of the key properties of GSHP systems. Bentonite, for example, has a relatively low thermal conductivity that typically ranges from 0.65 to 0.90 W/mK under the saturated condition [5]. Because the low thermal conductivity of bentonite makes it unsuitable as a filler material for GSHP systems, some additives need to be mixed into bentonite grouts to improve it in them respect. In this context, the thermal characteristics of pure bentonite (bentonite only) and bentonite–sand grouts, in their varying mixed proportions, have been studied under both saturated and dried conditions [5–9]. The results indicated that adding sand as an additive improves the thermal conductivity of grouts, and that grouts under saturated conditions showed much higher thermal conductivity than those under dried conditions. Thus, the thermal conductivity of grouts varies with their mix proportions and water contents.

The ground in which the borehole is dug is not completely saturated or dried; rather, those qualities vary with borehole depth

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and in situ ground-water conditions. As in situ ground-water conditions changes, the water condition of the ground varies accordingly. This variation can affect the water contents and thermal conductivity of grouting materials. Due to the fact that direct measurement of grouting materials' thermal properties is practically impossible after installation, prior characterization of those properties for varying water contents is key to the performance prediction and efficiency maintenance of GHP systems [9]. However, the effects of varying water contents on the thermal properties of bentonite-based grout for GSHP systems under unsaturated conditions, have only rarely been investigated. Kim et al. [10] found a parabolic relationship between the thermal conductivity and volumetric water content (VWC) of bentonite grouts, [11–14], unlike the other studies, which showed that the thermal conductivity only decreased with decreasing VWC. Kim et al. [10] also speculated that this parabolic relationship might be related to the soil–water characteristic curve (SWCC). The SWCC is a conceptual and interpretative tool by which the behavior of unsaturated soils can be understood [15]; it defines the relationship between matric suction and VWC or the degree of saturation [16].

In this study, the effects of varying VWC and matric suction on the thermal conductivity of bentonite and bentonite–sand grouts were investigated. Also, the SWCC of the bentonite and bentonite–sand grouts was identified to explain the phenomenon of the parabolic relationship between the VWC and thermal conductivity.

2. Soil–water characteristic curve

Fig. 1 shows a typical soil–water characteristic curve (SWCC), which is an important tool for evaluation of the engineering behaviors of unsaturated soils. The SWCC is generally defined as the relationship between the VWC and the matric suction of the soil. The VWC is defined as the ratio between the volume of water and the total volume of the specimen. The soil matric suction, one of the most important parameters of unsaturated soils [17], is defined as the difference between the pore-air pressure and the pore-water pressure. The SWCC consists of three zones: the saturated zone, the transition zone, and the residual zone. In the saturated zone, almost all the soil pores are filled with water. The pore-water is in tension in this zone; however, the soil, owing to capillary forces, remains essentially saturated. When matric suction is applied to the water in the soil pores, the water is first drained from the largest pores, which are then occupied by air. The matric suction required for removing the water from the largest pores is known as the air entry value (AEV), and the area between the zero matric suction and the AEV is referred to as the saturated zone [18]. Beyond the AEV, the increase of matric suction causes a rapid rate of VWC loss until the residual water content is reached. Matric suction corresponding to residual water content is referred to as residual suction, by which the desaturation ends, and the water begins to be held in the soil by adsorption forces. The area between the AEV and the matric suction in which the residual condition is reached is called the transition zone. In the residual zone, the curve exhibits an asymptotic line at a low degree of saturation. Water still exists, but considerable matric suction is needed to drain even a small amount of water from the pores [19].

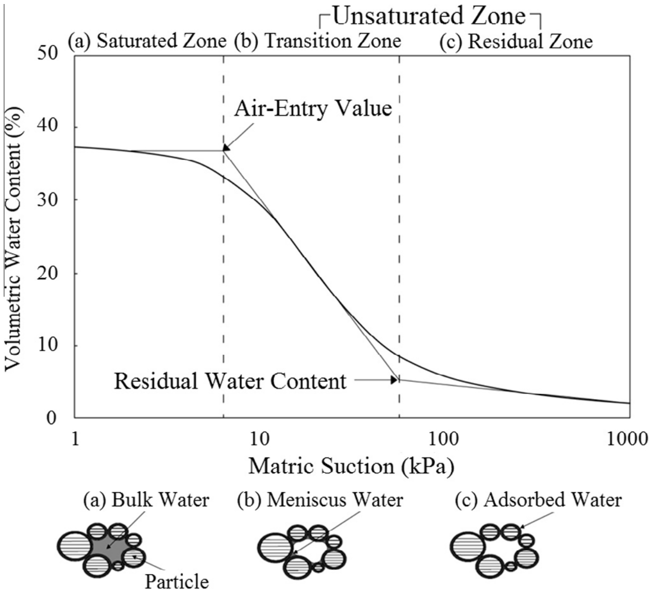

Fig. 1. Soil–water characteristic curve showing zones of unsaturation.

The pore water within unsaturated soils exists in three forms (Fig. 1): (a) bulk water within those void spaces that are completely flooded, (b) meniscus water surrounding all inter-particle contact points that are not covered by bulk water, and (c) adsorbed water, which, tightly bound to the soil particles, acts as parts of the soil skeleton. The relationship between the SWCC and the pore-water forms is shown in Fig. 1 [20].

Fig 2 shows a typical SWCC, which depends on the size and arrangement of the pores, for three different types of soil. The AEV generally increases not only with the plasticity of the soils but with decreasing grain-size. Other factors such as the stress history also affect the shape of the SWCC [18,21].

3. Materials and methods

3.1. Grouting materials

Bentonite is an absorbent aluminium phyllosilicate, essentially impure clay consisting mostly of montmorillonite [22]. Volclay®

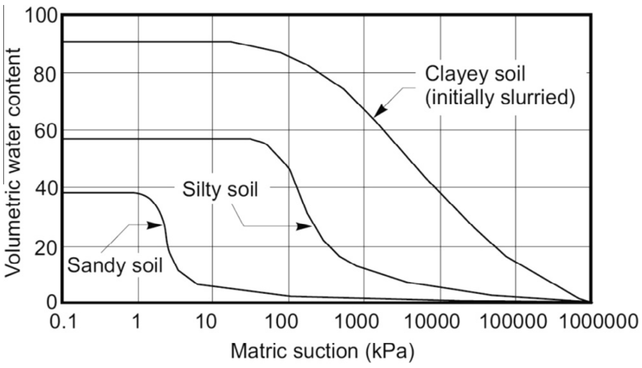

Fig. 2. Typical SWCC for different types of soil [18].

Table 1
Physical properties of Volclay® bentonite.

Permeability (cm/s)	Swelling (ml/g)	Montmorillonite content (%)	Thermal conductivity (W/mK)	Specific gravity
$\leqq 1 \times 10^{-7}$	12.5	≦90	0.74	2.60

Table 2
Chemical composition of quartzite sand.

Chemical composition (wt%)	SiO_2	Al_2O_3	Fe_2O_3	K_2O	TiO_2	CaO	MgO	Ig-loss	Total
Quartzite sand	99.6	0.1	0.03	–	0.02	Trace	Trace	0.1	99.85