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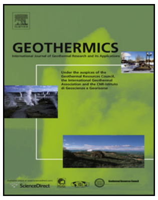

Full Length Article

Evaluation of effective thermal conductivity of unsaturated granular materials using random network model

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ABSTRACT

The effective thermal conductivity of granular materials is widely used in numerous geothermal engineering applications, such as the ground source heat pump (GSHP) system. However, for unsaturated granular materials, it is difficult to predict the thermal conductivity because of the interaction between solid and fluid in media. In this study, the effective thermal conductivity of unsaturated granular materials was measured, reviewed and analysed using a macroscopic pore structure network model with a randomly packed particles. The network model was verified by measured data (soil water characteristics curve, thermal conductivity and etc.) of three different glass beads and also Jumunjin sand (standard sand of South Korea). Upon the series of laboratory experiments, some modification to the existing network model were introduced, such as the use of soil water characteristic curve (SWCC) applied to modelling the thermal conductivity of granular materials. In addition, an empirical correlation between the fraction of the mean radius (χ) and the thermal conductivity at a given saturated condition was developed through comparison with the test results. In the range of lower degree of saturation (5%–20%), the modified network model shows relatively higher thermal conductivity than the laboratory measurements. However, for the higher degree of saturation (>40%), it shows a similar tendency to the laboratory measurements.

1. Introduction

A knowledge of heat conduction in granular materials or particulate composites can be widely used in numerous engineering applications such as geothermal, geomechanics, civil, chemical and electronic engineering. Numerous efforts have been made to obtain the effective thermal conductivity of the porous medium using a particulate relationship of granular materials. A prior objective of these studies was to establish fundamental physical principles for predicting the effects of particle volume fraction and their arrangements within the medium (Kanuparthi et al., 2008). The analytical approximations (Kanuparthi et al., 2008; Torquato, 2002) of the effective thermal conductivity for particulate composites can be broadly classified models based on the Maxwell's approximation (Maxwell, 1873; Hasselman and Johnson, 1987; Benvensite, 1987; Nan et al., 1997), self-consistent model (Rayleigh, 1892; Bruggeman, 1935; Landauer, 1952; Garland and Tannera, 1978), and models of differential effective medium (Bruggeman's asymmetric model (BAM)) (Bruggeman, 1935; Every et al., 1992; Tarnawski et al., 2002). These models use known thermal properties of particles to predict the thermal conductivity of composite materials. In addition, numerical methods (finite element method, discrete element method, and boundary element method) have also been suggested to evaluate the effective thermal conductivity of the porous medium (Kuipers et al., 1992; Tsuji et al., 1993; Cheng et al., 1999; Kanuparthi et al., 2006; Feng et al., 2008). Although numerical methods have been well established for various types of problems, they are prone to a computational challenge when coupled with other physical phases such as solid and fluid media (Kanuparthi et al., 2006). An attempt to predict thermal conductivity of granular media using an artificial neural network (ANN) model (Grabarczyk and Furmanski, 2013; Go et al., 2016) was recently suggested but the ANN model basically needs the sufficient data set to increase an accuracy.

For unsaturated granular materials, it is more difficult to predict the thermal conductivity of composite materials because of the interaction between solid and fluid in media as water and air. Especially, in the case of unsaturated soil, the thermal conductivity is dependent on various conditions such as grain size and shape of soil, mineralogy, pore volume or porosity, pore fluid, overburden stress, drainage condition and conductivity each particle (Crane and Vachon, 1977; Cheng et al., 1999; Gangadhara et al., 1999; Singh and

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Devid, 2000; Weidenfeld et al., 2004; Yun and Evans, 2010). Therefore, the relationship between solid and fluid and also the complex configuration of particle skeleton including the pore volume characteristics need to be determined. In practical case, to predict the thermal conductivity of composite material at the unsaturated condition, empirical methods (Kersten, 1949; Johansen, 1975; Côté and Konrad, 2005; Gori and Corasaniti, 2012) that calculate the thermal conductivity at the unsaturated condition from dry and saturated condition were often used. Moreover, there is a fundamental problem in measuring the thermal conductivity of unsaturated soils on evaporation of pore water in soil (Bovesecchi and Coppa, 2013).

It is generally known that inter-particle contacts are the most effective way for heat transfer in the particle system (Carslaw and Jaeger, 1959; Vargas and McCarthy, 2001; Kanuparthi et al., 2006; Yun and Evans, 2010). A number of studies have been carried out, in which the interaction between particles was included by a simplified model (Feng et al., 2008). In the network model where the void spaces of a porous medium are represented by a grid of connected spots (Fatt, 1956a; Fatt, 1956b; Fatt, 1956c; Batchelor and O'Brien, 1977; Yun and Evans, 2010), each particle is represented as an isothermal disk for the two-dimensional (2D) domain or sphere for the three-dimensional (3D) domain, and each pair of contacting particles has an equivalent thermal resistance bar (2D) or cylinder (3D). In addition, the network model is based on some assumptions that oversimplify a real structure of void space. For example, at each network, a particular value is assigned to the number of bonds or throats are assumed to have the same length (Fatt, 1956a; Fatt, 1956b; Fatt, 1956c; Bryant et al., 1993; Askari et al., 2015). Consequently, the thermal conductivity of granular media can be modelled in terms of the corresponding thermal resistance or conduction network of the entire system (Kanuparthi et al., 2006). Because of these concepts, the particle size distribution of certain granular materials can be reflected in the network model.

In this study, the effective thermal conductivity of unsaturated granular materials has been estimated using a network model with a random packed system at a particle scale. Numerical assemblies are generated using DEM software PFC^{3D} (PFC, 2006). According to a theoretical derivation of heat conductance between particles (Batchelor and O'Brien, 1977), the local conductance was determined using the contact conditions such as distance between particles, contact area, particle size, and the state of unsaturated condition. Then overall conductance was made up for using steady-state heat conduction through particles and porosity with a boundary condition at constant temperature in a 3D random packed particle system. The suggested network model for the unsaturated soil was verified using reference materials (three types of glass beads and Jumunjin sand (South Korea standard sand)). By carrying out the laboratory tests, experimental values of thermal conductivity for the reference materials at various unsaturated conditions were obtained. In addition, the pressure plate extractor (PPE) test has been performed to obtain the soil-water characteristic curve (SWCC) of the reference materials.

In the suggested network model, the SWCC is required to adjust an equivalent radius of a thermal cylinder in the contact area between particles at the unsaturated condition. The cut-off range parameter that defines the effective zone between particles, was also adjusted according to the SWCC at given conditions. By combining the obtained experimental data and the proposed network model, the modified network model was developed. The purpose of the modification to the network model as stated above is to practically estimate the thermal conductivity of granular materials at various unsaturated conditions dispensing with direct measurement. The conventional empirical correlation between the fraction of the mean particle radius (χ) and the thermal conductivity at given unsaturated conditions was provided after thorough verification by comparing with the test results.

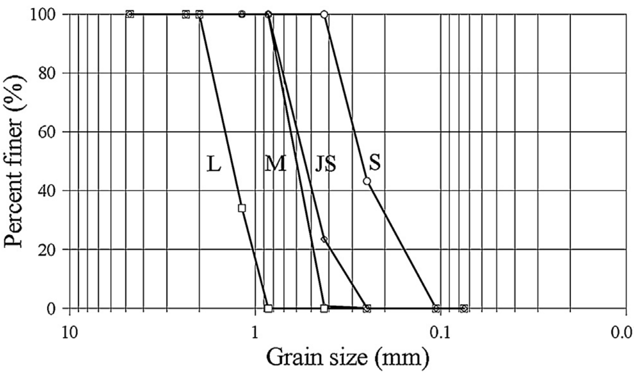

Fig. 1. Grain size distribution of three types of glass beads and Jumunjin sand (L: large size, M: medium size, S: small size, JS: Jumunjin sand).

Table 1
Material properties of specimens.

Materials		D (mm)	G_s (t/m^3)	C_u	C_c	k (W/m·K)
Glass beads	Large	1.0–1.4	2.47	1.52	0.96	1.13
	Medium	0.4–0.6		1.44	0.96	
	Small	0.18–0.3		2.30	1.03	
Jumunjin sand		0.35–0.5	2.63	1.88	1.10	3.00

D: diameter, Gs: specific gravity, C_u: uniformity coefficient, C_c: coefficient of gradation, k: thermal conductivity of grain.

2. Laboratory test

2.1. Materials

In this study, three types of glass beads (large, medium and small size) and Jumunjin sand were used as reference granular materials. Jumunjin sand is a well-known standard silica sand used in various research areas in Korea. The gradation of this standard sand is poorly-graded with a uniform grain size (Oh et al., 2007; Lee et al., 2008; Lee et al., 2011). The glass beads and Jumunjin sand are chosen because they are relatively uniform materials and do not show any reactions with water, such as a swelling phenomenon. To obtain a grain size distribution of reference materials, the sieve analysis (ASTM D6913-04) was performed. The grain size distribution was then used to generate the spherical particles in the network model of each tested material (Fig. 1). Table 1 shows physical properties of the glass beads and Jumunjin sand from the laboratory tests. The thermal conductivity of grains was adopted from the previous studies (Clauser and Hugenges, 1995; Incropera and Dewitt, 1996; Sundberg et al., 2009; Yun and Evans, 2010). As shown in Fig. 1, the grain size distribution of Jumunjin sand is between the medium size and small size glass beads.

2.2. Pressure plate extractor test and thermal conductivity measurement

To obtain the unsaturated characteristics of each specimen, the pressure plate extractor (PPE) test (ASTM D2325-68) was performed according to drying hysteresis. From the PPE test, the SWCC, which shows a relationship between the degree of saturation and matric suction, was obtained. The pressure of the PPE test was controlled from 5 to 100 kPa. A special bronze case (as shown in Fig. 2) was devised to contain the unsaturated specimen during measuring the thermal conductivity with the QTM-500 (Kyoto Electronics) device equipped with the PD-13 probe, which uses the transient