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Assessment of structure effects on the thermal conductivity of two-phase porous geomaterials

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ABSTRACT

The effect of structure on the thermal conductivity of geomaterials is studied for solid–fluid combinations representing a wide variety of two-phase porous geomaterials. Nearly 200 thermal conductivity data sets from the literature were analyzed for geomaterials made of natural soil particles, crushed rock particles and sedimentary rock. Two analog models are studied to quantify the effect of structure. It appears that the effect of structure increases with decreasing fluid/solid thermal conductivity ratio and structure effects are negligible from a ratio of approximately 1/15 and higher. A new simplified model is proposed to compute the effective thermal conductivity as a function of the fluid/solid thermal conductivity ratio and the structure of geomaterials. The model applies well to independent data of homogeneous and heterogeneous materials including industrial cement concrete.

1. Introduction

Thermal analyses of civil engineering infrastructures require the knowledge of the effective thermal conductivity of geomaterials that include natural soil, natural rock, crushed rock, cement concrete and bitumen concrete among others. The thermal conductivity of soils is governed by many parameters such as porosity, water content, mineral content and grain size distribution. Several studies have also recognized the structure effects owed to cementation [1,2] and to particle shape [3–6] especially in dry conditions (saturated with air). However, studies on the quantitative assessment of structure effects generally only cover idealized (or hypothetical or theoretical) soils.

The objective of this paper is thus to develop new semi-empirical modeling approaches to assess the effect of structure on the effective thermal conductivity of two-phase porous geomaterials. The paper first describes the structure of porous geomaterials and its effect on the effective thermal conductivity. Following is a background on the thermal conductivity bounds for two-phase materials and on different modeling approaches. The paper uses two analog models to assess the effect of structure on the effective thermal conductivity of two-phase porous geomaterials: Fricke's model [7] based on theoretical geometrical assumptions and the Côté and Konrad model [6] based on the relative thermal conductivity concept and the empirical assessment of structure effects. The analysis results of nearly 200 thermal conductivity data sets are discussed in terms of structure effects and a new simplified model is proposed and validated.

2. Structure of two-phase porous geomaterials

Geomaterials used in civil engineering infrastructures are mostly made of mineral particles of various shapes and size distributions. Inter-particle pores are generally filled with water and/or air. When the pores are saturated with either water or air, the materials are considered as two-phase porous geomaterials. The particles of geomaterials can also be bound together as a result of natural or industrial processes. The porous geomaterials are thus highly heterogeneous and may even be anisotropic depending on shape and orientation of particles. According to Johansen [4], particle and pore size distributions of most geomaterials allow heat transfer by conduction only. Convection and radiation effects are thus neglected in this study.

Heat conduction through two-phase porous media depends on the thermal conductivity of each phase and on the structure of the solid matrix. In terms of thermal behavior, the structure of the solid matrix characterizes the contact resistance and the continuity of the solid phase [8]. In geotechnical engineering the structure of geomaterials is generally associated with the combined effect of fabric, soil composition and interparticle forces. The term fabric refers to the arrangements of particles, particle groups and pore space [9]. It is recognized that the fabric and the structure

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Nomenclature

a, b, c	axis of spheroids
d	particle diameter
F	weighting factor
g	shape factor
HSL	Hashin/Shtrikman lower bound
HSU	Hashin/Shtrikman upper bound
K	effective thermal conductivity
k_{dry}	thermal conductivity of dry soil (air saturated)
k_f	thermal conductivity of fluids
k_r	relative thermal conductivity
k_s	thermal conductivity of solids
k_{sat}	thermal conductivity of water saturated soil
n	porosity = v_v/v_t
S_r	degree of saturation = v_w/v_v
v_v	volume fraction of voids
v_w	volume fraction of water
v_t	total volume
WL	Weiner lower bound
WU	Weiner upper bound
Z	c/a

Greek symbols

β	empirical parameter
κ	weighting factor (moist soils)
κ_{2P}	weighting factor (two-phase porous geomaterials)

of geomaterials are influenced by the size and shape of particles and the aggregation of particles with or without cement/bounding agents, which can be of natural origin (calcite, silicates, iron oxides, phosphate, etc.) or of industrial origin (bitumen, lime, Portland cement).

The particle shapes and the presence of bounding agents will thus influence the degree of contact resistance and the continuity of the solid phase of the porous geomaterials, which in turn, influence its effective thermal conductivity. Rounded and sub-rounded particles are found in natural soil deposits while angular and sub-angular particles are generally obtained from the rock crushing operations. Sedimentary rocks are naturally cemented geomaterials, while cement or bitumen concretes are industrially cemented geomaterials. Therefore, in terms of thermal characteristics, the structure of porous geomaterials can be divided in three categories: (a) unbound rounded/sub-rounded particles, (b) unbound angular/sub-angular particle and (c) bound/cemented particles as shown in Fig. 1. The solid-to-solid contact area of the unbound angular particles is greater than that of the unbound rounded particles, while the solid-to-solid contact area is further increased when bounding agents are present. The bound/cemented particles category includes round/sub-rounded and angular/sub-angular particles as it is expected that the effect of angularity of particles decreases substantially in the presence of cement.

Studies of the effect of structure on heat flow and effective thermal conductivity (k) of two-phase porous geomaterials have shown that k is generally higher in cemented materials than in loose particle packs [1,2,4]. Furthermore, it was observed that the influence of structure on the effective thermal conductivity of two-phase porous media increases with decreasing solid/fluid thermal conductivity ratios [2]. Hamilton and Crosser [10] also showed theoretically that the k values of particle packs decreases with increasing sphericity of particles. This was observed by Johansen [4] and by Côté and Konrad [6] in air-saturated porous geomaterials where the k values of natural particle packs (rounded/sub-rounded) were systematically lower than those of crushed particle packs (angular/sub-angular). Recently, the fast growing performances of desktop computers enabled the study of structure effects on the effective thermal conductivity of various porous media also showing the importance of particle contact density [11,12].

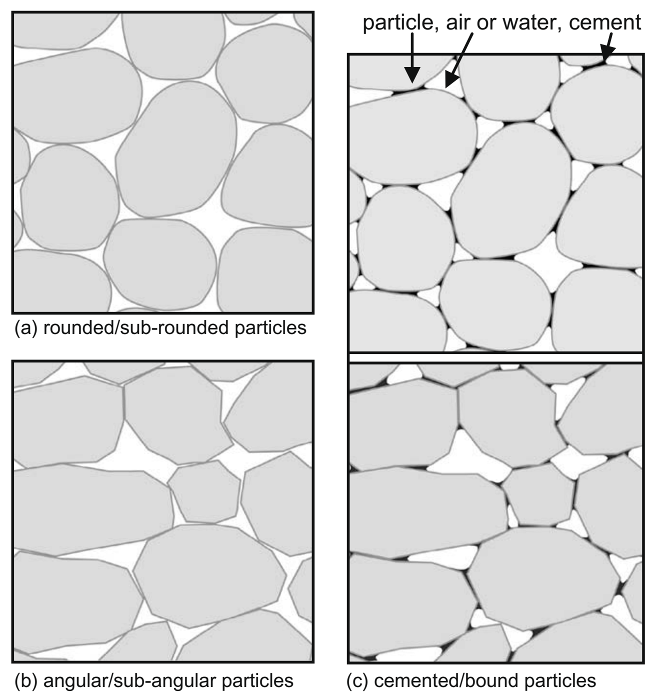

Fig. 1. Schematic structures of porous geomaterials.

3. Thermal conductivity bounds and modeling approaches

3.1. Thermal conductivity bounds

Independently of structure effects, the series and parallel flow models are universally accepted as yielding the widest bounds, also known as the Weiner bounds, in between which the effective thermal conductivity of two-phase materials should stand. The parallel flow model (Eq. (1)) is the upper bound (WU) while the series flow model (Eq. (2)) provides the lower bound (WL):

$$k = (1-n)k_s + nk_f \tag{1}$$

$$k = \frac{k_s k_f}{(1-n)k_f + nk_s} \tag{2}$$

Hashin and Shtrikman [13] proposed narrower bounds for homogeneous isotropic two-phase materials. Their upper bound (HSU) applies to a continuous solid phase including uniformly dispersed fluid filled cavities (Eq. (3)) and their lower bound (HSL) applies to a continuous fluid phase including uniformly dispersed solid spheres (Eq. (4)). The HSU and HSL bounds are mathematically equivalent to the well known Maxwell model [14] and thus represent the internal and external porosity cases [15]: