



Effects of aggregate size on soil thermal conductivity: Comparison of measured and model-predicted data

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ABSTRACT

Soil thermal conductivity is largely influenced by soil water content and state of aggregation. The aim of this study was to compare measured and model-predicted thermal conductivity as a function water content for both non-aggregated soil (<0.25 mm) and five aggregate fractions (0.25–0.5, 0.5–1, 1–3, 3–5 and 5–10 mm). The measured thermal conductivity (λ) was derived from the equation $k \times C_v$ where k is the thermal diffusivity as determined from measurements of temperature change due to the temperature gradient and C_v is the volumetric heat capacity as determined from measurements of the specific heat using calorimetric method and the dry bulk density of the soil and aggregate fractions. All the measurements were performed for 13 selected water contents in the range of 0.15–0.53 kg kg⁻¹ obtained using standard Richards tension chambers and drying at room temperature. Measured thermal conductivities were then compared with those predicted using statistical-physical model. The model requires readily available soil characteristics such as soil texture, soil bulk density and water content. The results showed that λ were highest in non-aggregated soil and successively decreased in 0.25–3 mm and 3–10 mm aggregates due to likely reduced contact area between heat-conductive solids and water films. We found a satisfactory agreement between measured and model-predicted thermal conductivities for whole range of water contents with the highest accuracy for the non-aggregated soil. The root mean square error (RMSE) and maximum relative error (MRE) of the model (for all treatments) were 0.104 W m⁻¹ K⁻¹ and 64.2%, respectively. The model used showed a reasonable sensitivity of the thermal conductivity on the aggregate fraction size. The modelled values tended to underestimate the thermal conductivity in the range of low thermal conductivity values (mostly for the 3–10 mm aggregate beds) and to overestimate for medium conductivity values in the region of intermediate conductivities (mostly for the 0.25–3 mm aggregates). The results revealed that investigation of thermal conductivity of structural soils and other similar media must take into account the aggregate size and associated arrangement of solid, air and water.

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1. Introduction

Soil thermal conductivity has a significant effect on the surface-energy partitioning and resulting temperature distribution [11] and moisture flow within soil and near ground atmosphere system [17,38]. Knowledge on the thermal conductivity of soils is required in numerous agricultural, meteorological and industrial applications [9,50] as well as under space conditions where soils are used as analogues of extra-terrestrial porous media [14,48,52]. The thermal conductivity of a given soil is significantly influenced by variable soil water status, bulk density and less variable organic matter

content [1,25,45,53]. Some studies [40,52] showed that the thermal conductivity is more strongly correlated with air-filled porosity (difference of saturated and current volumetric water content) than with volume fractions of water.

In fine-textured soils the thermal conductivity can be highly influenced by aggregate structure that forms pore network with relatively large continuous and interconnected inter-aggregate pore spaces (from μ m to mm) and very small intra-aggregate pore spaces between the textural grains (from nm to μ m) [8,20,32,33,35,49,57]. The intra-aggregate porosities store substantial organic substrates on mineral surfaces within micro-pores of aggregate interior regions [42,47], that can further affect the thermal properties of soil.

Most of studies on the effects of soil aggregation were related to hydraulic properties of soil and gas exchange. They showed that

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Nomenclature			
a	linear regression coefficient	z	depth (m)
B	coefficient that is related to the shape and size of the body	<i>Greek symbols</i>	
c	specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)	θ	water content ($\text{m}^3 \text{m}^{-3}$)
C_V	volumetric heat capacity ($\text{J m}^{-3} \text{K}^{-1}$)	ϕ	porosity ($\text{m}^3 \text{m}^{-3}$)
f_w	content of liquid ($\text{m}^3 \text{m}^{-3}$)	λ	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
f_g	content of air ($\text{m}^3 \text{m}^{-3}$)	λ_m	thermal conductivity, measured ($\text{W m}^{-1} \text{K}^{-1}$)
f_s	content of minerals and organic matter ($\text{m}^3 \text{m}^{-3}$)	λ_o	thermal conductivity, predicted ($\text{W m}^{-1} \text{K}^{-1}$)
k	thermal diffusivity ($\text{m}^2 \text{s}^{-1}$)	$\lambda_1, \lambda_2, \dots, \lambda_k$	thermal conductivity of particles ($\text{W m}^{-1} \text{K}^{-1}$)
L	number of all combinations of particles	λ_q	thermal conductivity of quartz
m	the rate of equalizing temperature	λ_{mi}	thermal conductivity of other minerals
MRE	maximum relative error (%)	λ_{om}	thermal conductivity of organic matter
r_1, r_2, \dots, r_k	radii of particles (m)	λ_w	thermal conductivity of water
R^2	determination coefficient	λ_g	thermal conductivity of air
RMSE	root mean square error ($\text{W m}^{-1} \text{K}^{-1}$)	ρ	dry bulk density of the aggregate beds (kg m^{-3})
t	time (s)	<i>Subscripts</i>	
T	temperature ($^{\circ}\text{C}$)	g	air
u	number of parallel connections of thermal resistors	s	solid
x_1, x_2, \dots, x_k	number of particles	w	water
W	mass water content (kg kg^{-1})		

potential to accelerate the flux, i.e. preferential flow of water and solutes under ponded conditions [13,34] and affect unsaturated water conductivity and diffusivity [49] and greenhouse gas exchange between soil and atmosphere [29]. An important factor affecting water storage and hydraulic conductivity in aggregated soil is that the large inter-aggregate pores are dewatered first and the transport of water is influenced by the properties of the individual aggregates [4,20,43,49] and contacts between them [8]. Accordingly, Sławiński et al. [49] reported that saturated hydraulic conductivity was substantially lower in non-aggregated (<0.25 mm) than aggregated soil and the inverse was true for unsaturated hydraulic conductivity. Soil aggregation and associated pore structure have also the potential to greatly influence water vapour adsorption and evaporation [27,58].

The hydraulic properties of soil are influenced by aggregate size. It was shown that the relative saturation in aggregates <1 mm compared with aggregates >1 mm was greater at most pressure heads [36]. Moreover, aggregate size influences significantly crop emergence and establishment through the effect on water supply and temperature [35]. In general seedbed soil structures with large aggregates lead to reduced crop establishment due to mostly poor soil - seed contact and lack of water and nutrient capture [3] whereas the fine seedbed structures (<5 mm size) produce the greatest establishment [3,16].

The foregoing indicates that the aggregate size largely affect the hydraulic properties of soil and heat transfer since water moving through the soil system always carries with it heat [18,19]. However, understanding of the relations in aggregated soil remains challenging due to lack of measurement techniques to determine λ and θ simultaneously and continuously. Consequently, efforts have been undertaken to develop $\lambda(\theta)$ models based on easily measurable soil parameters as soil texture and bulk density without consideration of soil aggregation [7,9,10,23,25,46]. Recently, Ju et al. (2010) [24] using thermo-TDR technique revealed that λ values of the non-aggregated (<0.1 mm) soils were significantly higher than those of the aggregated (<2 mm) soils at intermediate water contents. To our knowledge no comprehensive studies have been performed to predict soil thermal conductivity in a wide range of aggregate sizes and water content.

Therefore, the aim of this study was to compare measured and model-predicted thermal conductivity as a function of water

content in non-aggregated soil (<0.25 mm) and five variously sized aggregate beds (within the range 0.25–10 mm). A better description of thermal conductivity depending on aggregate size and water status is critical in selecting management practices to obtain most suitable aggregation depending on the soil function involved. We used the statistical-physical model that allows predicting the thermal conductivity based on soil texture bulk density and water content. The model was useful in assessing thermal conductivity of various soils as well as space bodies [52,55].

2. Materials and methods

2.1. Soil and measurements of soil properties

Soil samples were taken from Haplic Phaeozem situated respectively in Werbkowice, SE Poland ($23^{\circ}41'$, $50^{\circ}45'$). Some characteristics of the soils are given in Table 1 [44,58]. Following drying of the soil in the laboratory to the air-dry state, the soil was sieved through a set of sieves (10, 5, 3, 1, 0.5 and 0.25 mm apertures) to obtain non-aggregated sample (<0.25 mm) and five aggregate size fractions: 0.25–0.5; 0.5–1; 1–3; 3–5 and 5–10 mm. Then soil samples were loosely packed in the cylinders of 100 cm³ volume, 5 cm diameter in five replicates.

The measured thermal conductivities were taken from Sikora [44]. The conductivities were determined from the equation $\lambda_m = k \times C_V$, where k is the thermal diffusivity obtained from the equation $k = \frac{\partial T}{\partial t} \left(\frac{\partial}{\partial z} \left(\frac{\partial T}{\partial z} \right) \right)^{-1}$; where $\frac{\partial T}{\partial t}$ is the rate of temperature change induced by changes of temperature unity gradient $\frac{\partial}{\partial z} \left(\frac{\partial T}{\partial z} \right)$ where $\frac{\partial T}{\partial z}$ is the temperature gradient, C_V is the volumetric heat capacity.

The thermal diffusivity k was measured in the cylinders according to the theory describing the process of the so-called ordered heat exchange [44]. The measurement procedure was as follows: during the process of warming up or cooling down there takes place an ordered heat exchange between the body and its surroundings when the rate of equalizing temperature levels in the points of the body with the temperature of the medium is constant and does not change in time, i.e.

$$m = \frac{\partial(\ln \partial T)}{\partial t} \quad (1)$$

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