Thermal Resisitivity of Porous Materials (Soils) Change with Changes in Density, Water Content, Temperature and Composition

Decagon's KD2 measures the thermal resistivity of materials. These measurements are fast and accurate, but there is a limit to the number of samples that can be tested, and the sampling and testing procedure itself may affect the reading obtained. The purpose of this note is to give insight into the factors that affect thermal resistivity of porous materials so that the measurements made with the KD2 can be as useful, representative and as accurate as possible. It will also provide information on typical values of resistivity for these materials.

Soils and other porous materials vary in density, water content, temperature and composition. All of these affect the thermal resistivity of the porous material. Table 1 shows thermal properties of typical soil constituents.

Table 1. Thermal properties of soil materials (T is Celsius temperature) [modified from Campbell and Norman, 1998]

Material	Density ($Mg\ m^{-3}$)	Specific Heat ($J\ g^{-1}\ K^{-1}$)	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	Thermal Resistivity ($mK\ W^{-1}$)
Soil minerals	2.65	0.87	2.5	0.40
Granite	2.64	0.82	3.0	0.33
Quartz	2.66	0.80	8.8	0.11
Glass	2.71	0.84	1.0	1.00
Organic matter	1.30	1.92	0.25	4.00
Water	1.00	4.18	0.56+0.0018T	1.65 @ 25C
Ice	0.92	2.1+0.0073T	2.22-0.011T	0.45 @ 0C
Air (101 kPa)	$(1.29-0.0041T) \times 10^{-3}$	1.01	0.024+0.00007T	38.8 @ 25C

These constituents occur as mixtures in typical porous materials. The thermal resistivity of the mixture is quite difficult to compute, since it depends, not only on the thermal resistivities of the components, but also on their geometric arrangement. Methods for making this computation are given by Campbell and Norman (1998) and deVries (1963). These methods were used to compute the thermal resistivity of soils as they vary with water content, composition, density and temperature. The results of these computations are shown in the following three figures:

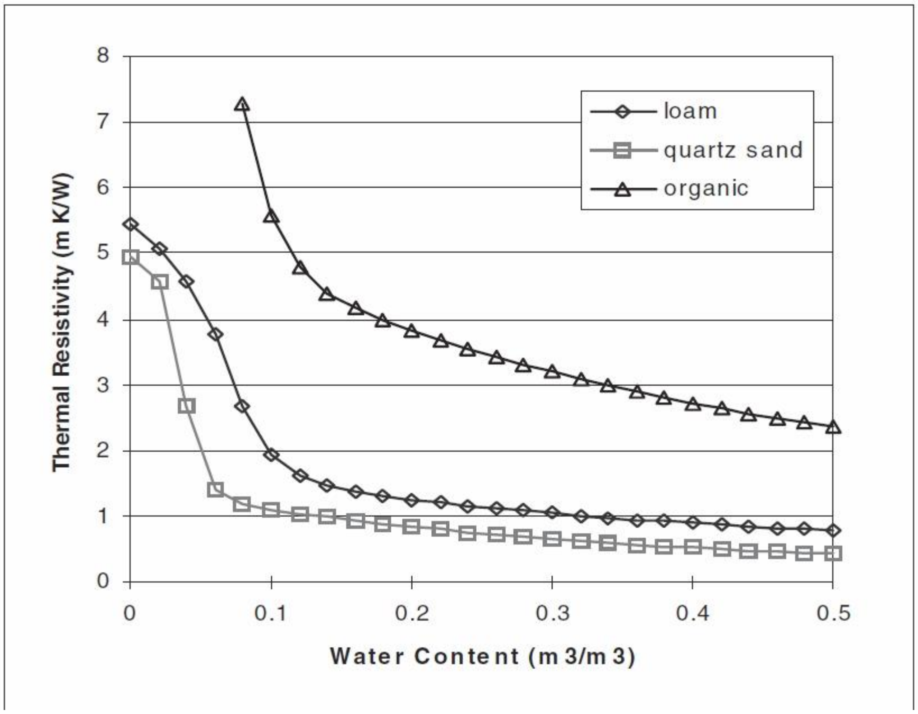

Figure 1. Thermal resistivity of three soil materials as a function of water content. The solid fraction in each was 0.5.

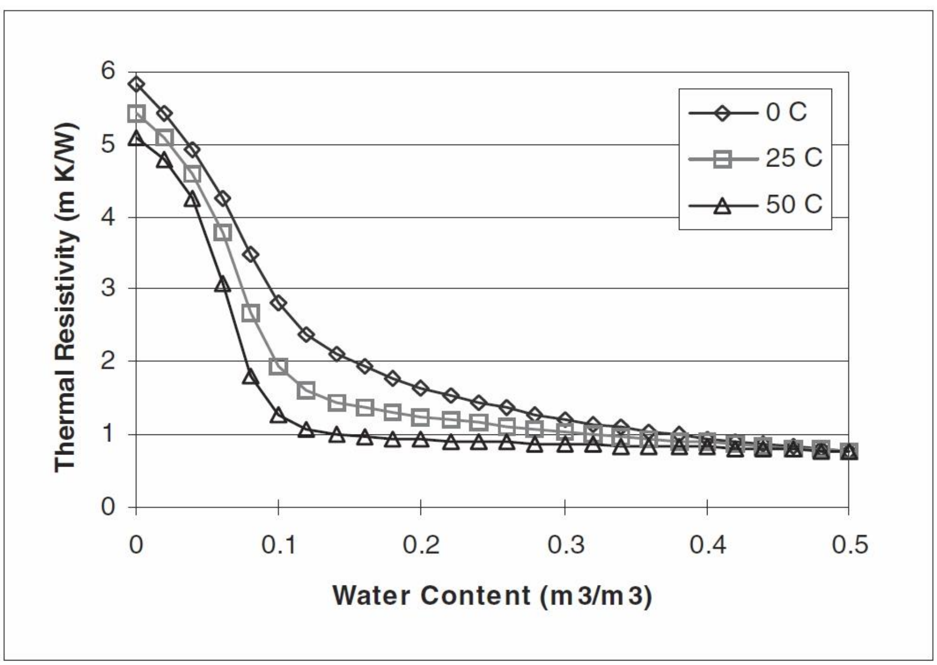

Figure 2. Effect of density and water content on thermal resistivity of a loam soil. The void ratio 1 curve is the same as in Fig. 1. The bulk densities are 1.06 Mg/m³ for void ratio of 1.5, 1.33 Mg/m³ for void ratio 1, and 1.59 Mg/m³ for void ratio of 0.67.

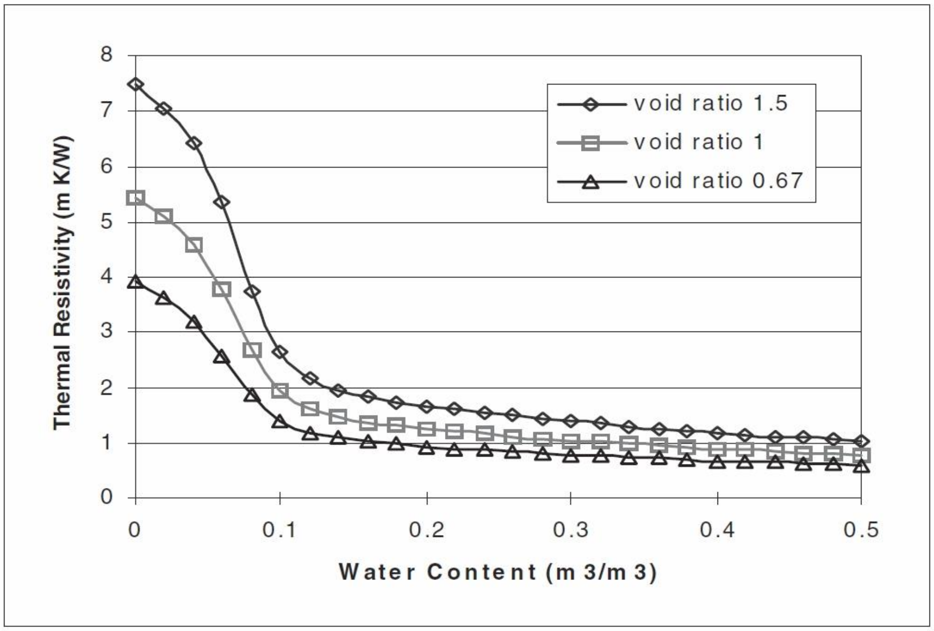

Figure 3. Effect of temperature and water content on thermal resistivity of a loam soil. The 25°C curve is the same as in Fig. 1.

In general, the thermal resistivity of a mixture is strongly influenced by the component with the highest resistivity. Dry quartz sand and dry loam soil have about the same resistivity, even though the resistivity of the minerals differs by a factor of 3 (Fig. 1 and Table 1). As the limiting resistivity becomes larger, differences in the resistivities of the other components have a larger effect. For example, dry quartz and loam differ in resistivity by about 10%, while water saturated quartz sand has about half the resistivity of saturated loam (Fig. 1).

As the water content of unsaturated porous materials increases, a threshold is reached where resistivity decreases rapidly with increasing water content. This is evident in all three figures. This threshold is more closely related to hydraulic than thermal properties of the material. It is the water content at which liquid water can flow across particle surfaces to re-evaporate and transport latent heat across pores in the medium. In other words, the soil is acting like a “heat pipe”, an engineering device which makes use of latent heat transport for rapid and effective heat transfer. In a moist soil at room temperature 10 to 20% of the total heat transport is as latent heat through the pores. This portion of the heat transport is strongly temperature dependent, roughly doubling for each 10°C temperature rise. The effective thermal resistivity of moist, air-filled pores is about the same as the thermal resistivity of water at 60°C, so, at this temperature, changing the water content of the material does not affect its resistivity. In Fig. 3, the 50°C curve shows almost no change in resistivity with increasing water content once the water content is high enough to sustain the liquid return flow within the pores.

References

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Campbell, G. S., J. D. Jungbauer, Jr., W. R. Bidlake and R. D. Hungerford. 1994. Predicting the effect of temperature on soil thermal conductivity. Soil Sci. 158:307-313

De Vries, D. A. 1963. Thermal properties of soil. In Physics of Plant Environment. W. R. van Wijk (ed.) North Holland Pub. Co. Amsterdam pp. 210-235.