METER
ENVIRONMENT

UNDERSTANDING HOW RHO CHANGES WITH CHANGING DENSITY, TEMPERATURE, COMPOSITION, AND WATER CONTENT OF BACKFILL

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METER's TEMPOS measures the thermal resistivity of materials. These measurements are fast, and accurate when interpreted correctly. The purpose of this note is to describe factors that affect thermal resistivity of porous materials and to provide typical resistivity values, so that the measurements made with the TEMPOS can be as useful, representative, and accurate as possible.

Soils and other porous materials vary in density, water content, temperature, and composition. All of these parameters affect the thermal resistivity of the porous material. Table 1 shows thermal properties of typical soil constituents. 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 Figures 1, 2, and 3.

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 (Figure 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 (Figure 1).

Material	Density (M gm-3)	Specific Heat (J g-1K-1)	Thermal Cond. (W m-1K-1)	Thermal Resistivity (°C cm/W)
Soil Materials	2.65	0.87	2.5	40
Granite	2.64	0.82	3.0	33
Quartz	2.66	0.80	8.8	11
Glass	2.71	0.84	1.0	100
Organic Matter	1.30	1.92	0.25	400
Water	1.00	4.18	0.56+0.0018T	165 @ 25 °C
Ice	0.92	2.1+0.0073T	2.22-0.011T	45 @ 0 °C
Air (101 kPa)	(1.29-0.0041T * 10-3)	1.01	0.024+0.00007T	3880 @ 25 °C

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

As the water content of porous materials decreases below saturation, a threshold is reached where resistivity increases rapidly with decreasing water content; an effect that is evident in all three figures. This threshold is more closely related to hydraulic than it is to thermal properties of the material. Water molecules inside the pores vaporize on the warmer side of the pore, and then condense on the cooler side. This movement of latent heat contributes significantly to thermal conduction in the material. The threshold mentioned previously is defined by the water content at which liquid water can no longer flow across particle surfaces to re-evaporate and repeat the cycle of transporting latent heat across pores in the medium.

Effectively, the pores in the soil in aggregate act 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 takes place as latent heat within the pores. Latent heat proportion of the total 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, increasing the water content of the material above the threshold does not affect its resistivity. In Figure 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.

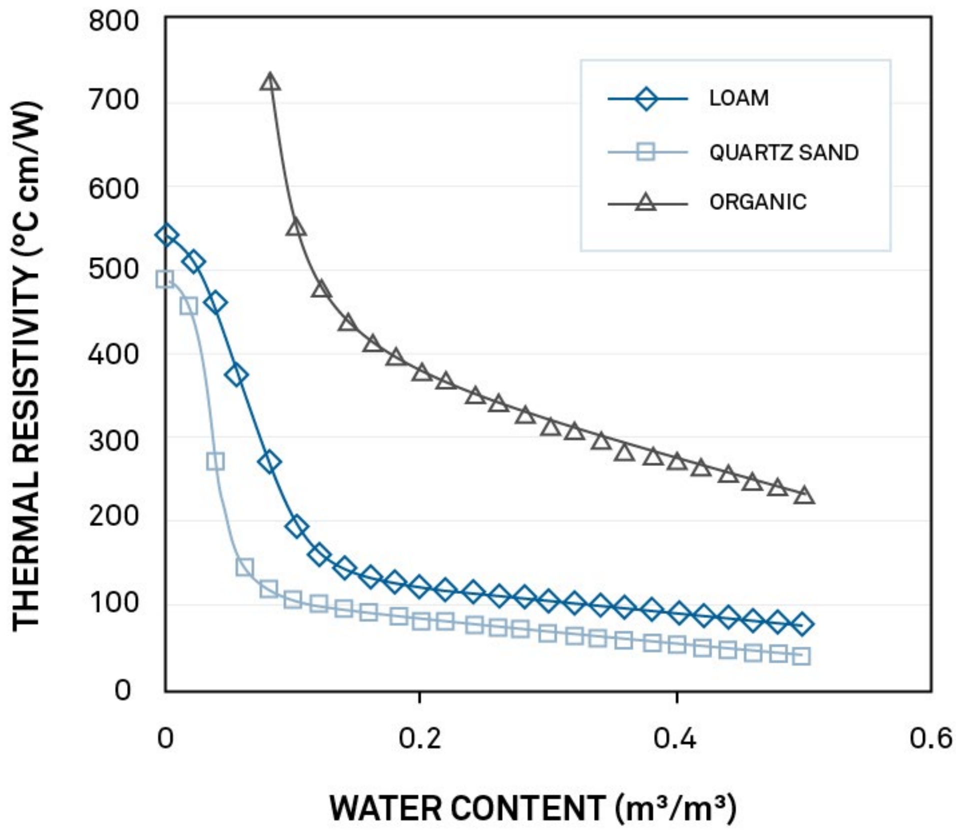

Figure 1. The thermal resistivity of 3 soil materials as a function of water content. The solid fraction in each was 0.5.

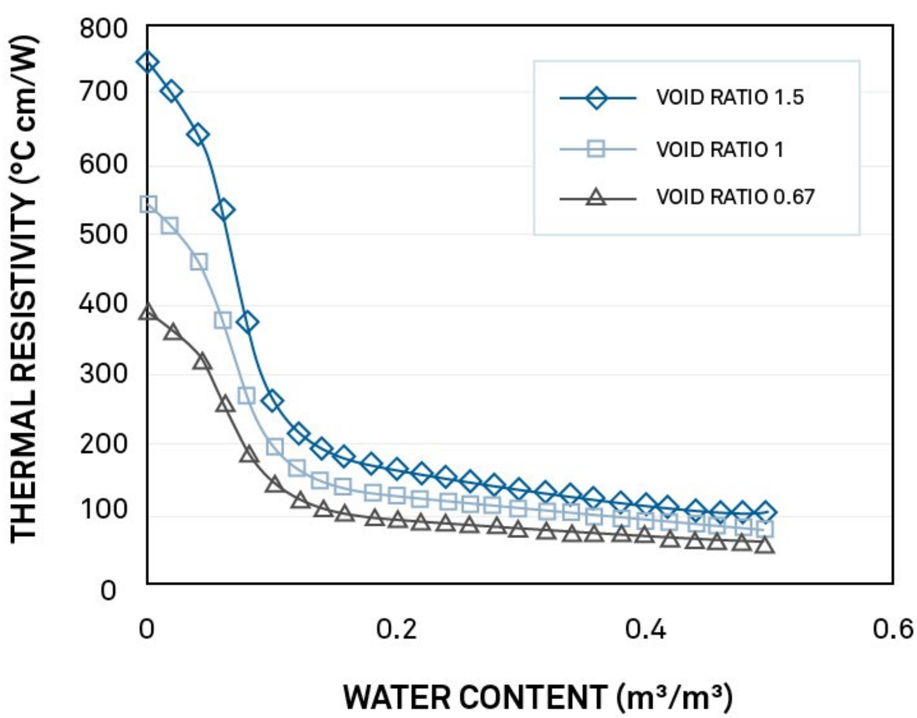

Figure 2. Effect of density and water content on thermal resistivity of a loam soil. The void ratio 1 curve is the same as in Figure 1. The bulk densities are 1.06 Mg/m3 for void ratio of 1.5, 1.33 Mg/m3 for void ratio 1, and 1.59 Mg/3 for void ratio of 0.67.

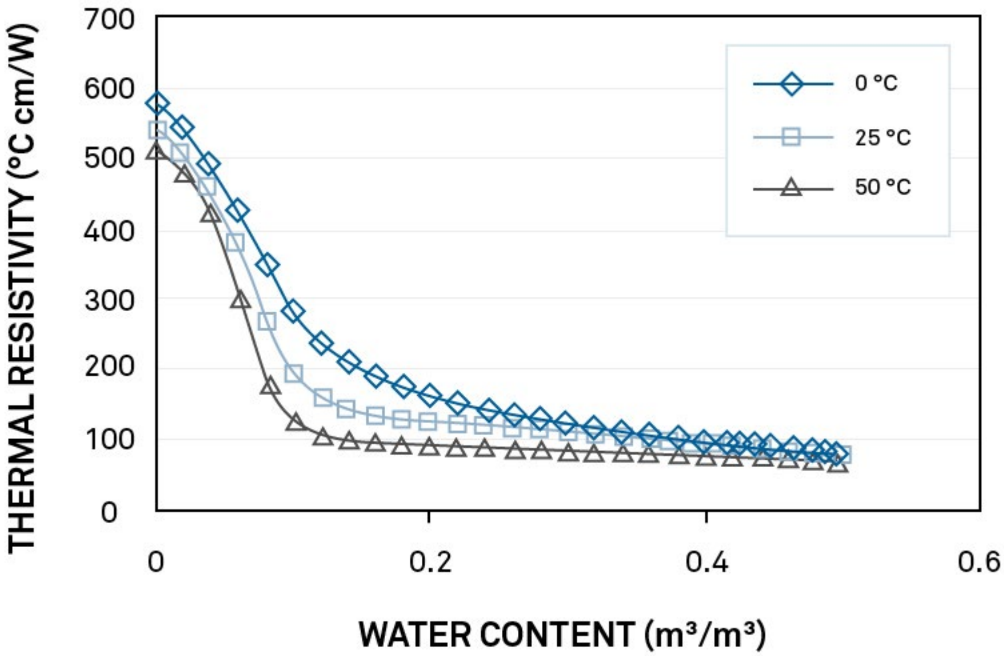

Figure 3. Effect of temperature and water content on thermal resistivity of a loam soil. The 25 °C curve is the same as in Figure 1

REFERENCES

1. Campbell, Gaylon S., and John M. Norman. *An Introduction to Environmental Biophysics*, pp. 167-184. Springer New York, 1998. Book link.

2. Campbell, G. S., J. D. Jungbauer Jr, W. R. Bidlake, and R. D. Hungerford. “Predicting the effect of temperature on soil thermal conductivity.” *Soil Science* 158, no. 5 (1994): 307-313. Article link

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