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Article

Calculation of Thermal Conductivity and Heat Capacity from Physical Data for Some Representative Soils of Korea

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The thermal properties including volumetric heat capacity, thermal conductivity, thermal diffusivity, and diurnal and annual damping depths of 10 representative soil series of Korea were calculated using some measurable soil parameters based on the Taxonomical Classification of Korean Soils. The heat capacity of soils demonstrated a linear function of water content and ranged from 0.2 to 0.8 cal cm^{-3} ℃$^{-1}$ for dry and saturated medium-textured soil, respectively. A small increase in water content of the dry soils caused a sharp increase in thermal conductivity. Upon further increases in water content, the conductivity increased ever more gradually and reached to a maximum value at saturation. The transition from low to high thermal conductivity occurred at low water content in the soils with coarse texture, and at high water content in the other textures. Thermal conductivity ranged between 0.37×10^{-3} cal cm^{-1} s^{-1} ℃$^{-1}$ for dry (medium-textured) soil and 4.01×10^{-3} cal cm^{-1} s^{-1} ℃$^{-1}$ for saturated (medium/coarse-textured) soil. The thermal diffusivity initially increased rapidly with small increases in water content of the soils, and then decreased upon further increases in the soil-water content. Even in an extreme soil with the highest diffusivity value (1.1×10^{-2} cm^2 s^{-1}), the daily temperature variation did not penetrate below 70 cm soil depth and the yearly variation not below 13.4 m as four times of damping depths.

Key words: Thermal conductivity, Heat capacity, Damping depth, Korean soils

Introduction

All physical, chemical, and biological processes in the soils are influenced by soil temperature. Soil temperature is determined by the transport processes of heat within the soil and by exchange of heat between the soil and atmosphere. Basically, there are three different modes of heat transfer: conduction, convection and radiation. Heat conduction is governed by the soil thermal properties including the volumetric heat capacity, thermal conductivity, and thermal diffusivity (Campbell, 1985; Aydin, 1993; Hillel, 1998). Soils are complex porous systems, consisting of solids, water, water vapor and air, all in varying proportions. Therefore, measurement of the true thermal conductivity is difficult, time consuming, equipment and labor-intensive, and error-prone. Hence there is a great demand for estimates of thermal conductivity from more readily available soil properties (Tarnawski et al., 2009). The arrangement of soil particles, particle size, mineralogy, solute concentration, and bulk density affects thermal conductivities, which are key properties for estimating soil-energy balance and land-atmosphere interactions (Logsdon et al., 2010). Agricultural practices (for example, mulching) affect soil thermal properties (Dahiya et al., 2007). Salts contained in the soils may result in a lower thermal conductivity (Guo et al., 2007).

In nature, soil temperature varies continuously in response to weather conditions acting on the soil-atmosphere interface (Balland and Arp, 2005; Kim et al., 2005). On the other hand, soil temperature varies differently at different depths in the soil. There is a characteristic depth in the soil, called the damping depth, at which the temperature amplitude is 0.37 (= 1/e) times its value at the soil surface (Hillel, 1998; Scott, 2000). The temperature at 2-3 damping depths is expected to be about the mean temperature for the period of oscillation (Campbell, 1985).

There are several models available (de Vries, Johansen, Gori, Campbell etc.) for predicting thermal conductivity of saturated and unsaturated porous media under variable

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temperature conditions (Markle et al, 2006). De Vries model is one of the most widely used approaches. The model is based on a weighted average of volumetric fractions of soil components, their thermal conductivities, and the ratio of the overall temperature gradients in the continuous (air or water) and dispersed (solids) phases (Tarnawski et al., 2009). De Vries model can predict the effect of water content on soil thermal conductivity (Mochizuki et al., 2008).

The objective of this study was to calculate the thermal properties of representative soil series of Korea using de Vries model, based on some measurable physical properties of the soils.

Materials and Methods

Relevant properties of soils The morphological, mineralogical, physical and chemical characterizations of Korean Soils have been reported by NAAS (1999). In this study, 10 representative soil series of Korea were selected to calculate their thermal properties. Generally, the soils have solid, liquid and gas phases under normal conditions. The solid phase includes various minerals and organic matter. Here, the soil minerals were roughly divided into two groups: quartz and other minerals. So, the soils were assumed to be composed of five components such as water, quartz, other minerals, organic matter and air. In addition to soil components mentioned above, soil porosity and volumetric water content at wilting point (15-bar) were taken into considerations for the calculations.

Accurate predictions of soil thermal conductivity are strongly influenced by the volumetric fraction of quartz, data for which are very scarce (Tarnawski et al., 2009). In the absence of this, predictions need to be guided by assumptions about the general mineral content of gravel and soil (Balland and Arp, 2005). Consequently, the missing quartz fraction is often assumed to be equal to sand fraction (Lu et al., 2007), although this assumption has never been verified by any alternative method of quartz fraction determination. However, for the studied soils, the volumetric fraction of quartz was taken as the sum of sand and one-third of silt fraction, based on gravel and mineral compositions of Korean soils (Zhang et al., 2006).

Mathematical procedure and calculations The volumetric heat capacity of a soil is defined as the change in heat content of a unit soil volume per unit change in temperature. Heat capacity can be calculated by summing the heat capacities of the various components as given by de Vries (1966):

$$Cv = 0.46Vm + 0.60Vo + Vw \qquad (1)$$

where Cv is volumetric heat capacity of soil (cal cm^{-3} ℃$^{-1}$); Vm, Vo and Vw are volumetric fractions (cm^3 cm^{-3}) of soil minerals, organic matter and water, respectively.

Thermal conductivity of soil is influenced by all of soil components and the physical properties of those components, and is expressed as (Campbell, 1985; Aydin and Huwe, 1993):

$$\lambda = \frac{Vw\lambda w + fqVq\lambda q + fsVs\lambda s + foVo\lambda o + faVa\lambda a}{Vw + fqVq + fsVs + foVo + faVa} \qquad (2)$$

in which, λ is thermal conductivity of soil (cal cm^{-1} s^{-1} ℃$^{-1}$); Vq, Vs and Va are volumetric fractions (cm^3 cm^{-3}) of quartz, other minerals and air, respectively. The expressions λw, λq, λs, λo and λa are thermal conductivities (cal cm^{-1} s^{-1} ℃$^{-1}$) of water, quartz, other minerals, organic matter and dry/moist air, respectively. The weighting functions fq, fs, fo and fa depend on the thermal conductivity and geometry of each component. The influence of latent heat transfer by the diffusion of water vapor in the air-filled pores is proportional to the temperature gradient in the pores, and can be taken into account (as vapor enhancement factor) by adding it to the thermal conductivity of air (Hillel, 1998). Cass et al. (1984) separated the contributions of latent heat transfer of vapor and conduction. The latent heat transfer through vapor diffusion is important even at low temperatures. The magnitude of latent heat transfer resulting from thermal vapor diffusion is strongly soil texture-dependent (Lu et al., 2011). A simple 'inter-particle contact heat transfer' model for predicting effective thermal conductivity of soils at moderate temperatures (0-30℃) has been extended up to 90℃, by Leong et al (2005). They reported that the extended model accounted for latent heat transport by water vapor diffusion in soil-air above the permanent wilting point; below that point, the soil thermal conductivity was approximated by linear interpolation without latent heat effect.

The quantity fi is the ratio of the average temperature gradient in the particles to the corresponding quantity in the medium, and is given as (de Vries, 1966; Huwe and van der Ploeg, 1990; Aydin and Huwe, 1993):

$$fi = \frac{1}{3}\sum_{a,b,c}\left[1+\left(\frac{\lambda i}{\lambda med}-1\right)g_a\right]^{-1} \tag{3}$$

where λi and λmed are the thermal conductivities of each component and medium respectively, and g_a is the shape factor ($g_a = g_b = g_c$ for spherical granules, $g_a = g_b$ for ellipsoid particles and $g_a + g_b + g_c$=1). In the wet soils, water can be considered as a continuous medium in which soil particles and air are dispersed (for the continuous medium $fmed$ =1). The value of fi depends not only on the ratio $\lambda i / \lambda med$, but also on the particle sizes, shapes and mode of packing (Hillel, 1998). In the model of de Vries, the soil particles are assumed to be rotated ellipsoids of uniform size and equally distributed in a homogeneous medium. All components with the same shape and conductivity are considered as one type and have common weighting factor and conductivity. However, the ellipsoidal shape factor (the length ratio of the minor and major axes) depends strongly on the soil texture (Markle, et al., 2006; Tarnawski et al., 2009).

The thermal diffusivity is the ratio of the conductivity to volumetric heat capacity and can be calculated using (Yesilsoy and Aydin, 1991; Hillel, 1998):

$$Dt = \lambda / Cv \tag{4}$$

where Dt is the thermal diffusivity (cm^2 s^{-1}). On the other hand, the temperature variations can be used to calculate the vertical component of the Darcy velocity and thermal diffusivity in the soil (Song et al., 1992; Koo et al., 2003; Bendjoudi et al., 2005).

The damping depth can be calculated from the ratio of the thermal diffusivity and radial frequency as (Campbell, 1985; Scott, 2000):

$$d = (2Dt/\omega)^{1/2} \tag{5}$$

where d is the damping depth (cm), and ω is the radial (or angular) frequency which is 2π times the actual frequency (Yesilsoy and Aydin, 1991):

$$\omega = 2\pi / P \tag{6}$$

Here P is the period (measured in seconds). In the case of diurnal variation, the period is 86400 s, so ω=2π/86400=7.27×10^{-5} s^{-1}.

The damping depth for the annual variation is (365)$^{1/2}$ = 19.1 times larger than that for the diurnal variation in the same soil (Yesilsoy and Aydin, 1991; Scott, 2000). It is assumed that daily and yearly temperature variations are practically limited to a layer of four times their damping depths (Aydin, 1993).

Results and Discussion

The thermal properties of three typical soil series were compared in Fig. 1. Comparisons were made for the top horizons of the soils. The maximum damping depths of all the studied series were given in Fig. 2.

The thermal conductivity increased as a power function of soil water content. A small increase in water content of the dry soils caused a sharp increase in thermal conductivity. Thermal conductivity began to increase rapidly from about one-fourth of the water content at wilting point until two-fourths, in the medium-textured soils. Upon further increases in water content, the conductivity increased ever more gradually and reached to a maximum value at saturation (Fig. 1). The transition from low to high thermal conductivity occurred at low water content in the soils with coarse texture, and at high water content in the other-textured soils. Ekwue et al. (2006) emphasized that the clay soil had significantly lower values of thermal conductivities and greater corresponding water contents than the clay loam and the sandy loam soils. As also explained by Hillel (1998), the space-averaged (macroscopic) thermal conductivity of the soils depended on its mineral composition and organic matter content, as well as on the volume fractions of water and air.

Soil thermal conductivity is strongly influenced by soil water content as well as the arrangement of solid particles in soil as reported by Ju et al. (2011). Water content has the greatest impact on soil thermal conductivity, because the water film develops bridges between the soil particles. This “bridging” increases

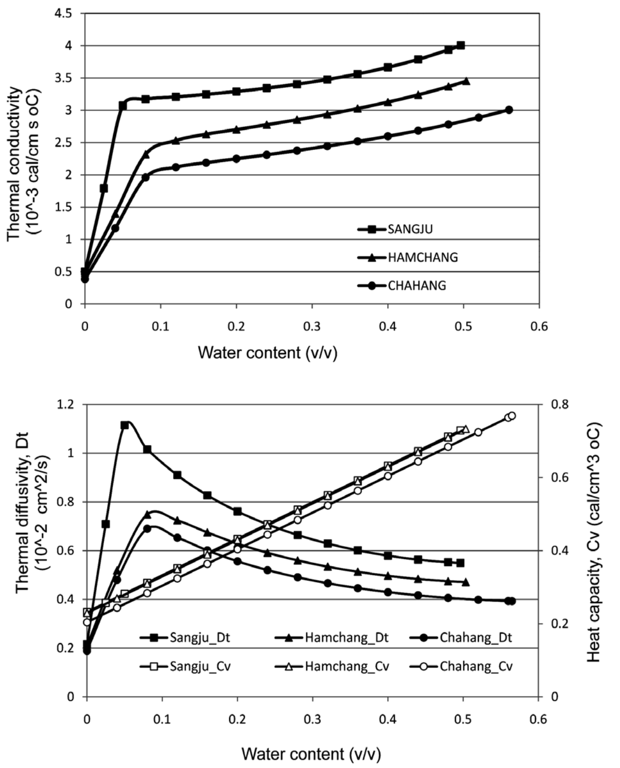

Fig. 1. Thermal properties of the top layers of three selected soil series (Sangju: Upland, Hamchang: Paddy field, Chahang: Forest).

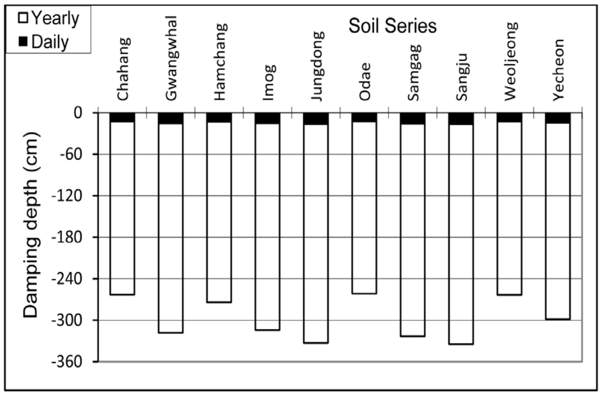

Fig. 2. Comparisons of maximum damping depths of soil series studied.

the effective contact area between the particles, which increases the heat flow and results in higher thermal conductivity. As the voids between the soil particles become completely filled with water, the soil thermal conductivity no longer increases with increasing water content (Becker et al., 1992; Wang et al., 2005; Usowicz et al., 2006; Sakaguchi et al., 2007; Yun and Santamarina, 2008). Changes in thermal conductivity with water content are also related to the changing tortuosity of the solid plus liquid phases. This explanation can contribute toward improved understanding of soil thermal conductivities over a range of soils (Logsdon et al., 2010).

At low water content, air space controls thermal conductivity; while at high water content, the thermal conductivity of solid phase becomes more important (Campbell, 1985). The differences in the thermal conductivities of different soils can be attributed to the differences in their compositions and soil-water characteristics. Conductivity varied between 0.37×10^{-3} cal cm^{-1} s^{-1} $℃^{-1}$ for dry (medium-textured) soil and 4.01×10^{-3} cal cm^{-1} s^{-1} $℃^{-1}$ for saturated (medium/coarse-textured) soil.

The heat capacity of soils was a linear function of water content. It was rather stable over a wide range of soils. The volumetric heat capacity of soils ranged from 0.2 to 0.8 cal cm^{-3} $℃^{-1}$ for dry and saturated medium-textured soil, respectively. Initially thermal diffusivity began to increase rapidly with small increases in water content of the soils. Upon further increases in the soil water content, diffusivity decreased (Fig. 1). Similarly, Liu et al. (2008) explained that the thermal diffusivity increased firstly and then decreased with the increase of water content. Yang and Koike (2005) noted that in most cases the thermal diffusivity was not a monotonic function of soil water content, which could result in multiple solutions of soil water content. In our study, the maximum values of thermal diffusivities in medium-textured soils were obtained at around 50% of water content retained at wilting point (15-bar).

Maximum diurnal damping depths were about 14 to 18 cm for the studied soils, and typical annual damping depths were 2.6-3.3 m. According to Campbell (1985), the temperature at 2-3 damping depths would be expected to be about the mean temperature for the period of oscillation because temperature fluctuations would be only 5-10% of the temperature fluctuation at the surface. In a broad range, however, Yesilsoy and Aydin (1991) emphasized that no change in temperature occurred at 4 damping depth. The temperatures at 55-70 cm depth of studied soils would therefore remain constant over a diurnal period, and 10.5-13.4 m for an annual cycle, approximately (Fig. 2; Tables 1 and 2).

The accuracy of thermal conductivity predictions is strongly influenced by the volume fraction of quartz. Therefore a lack of data for quartz fraction is a critical issue, hindering the successful application of

Table 1. Thermal properties of some soil series with low water content at wilting point (Cv : heat capacity (cal cm^{-3} ℃$^{-1}$); λ : thermal conductivity (10^{-3} cal cm^{-1} s^{-1} ℃$^{-1}$); Dt : thermal diffusivity (10^{-2} cm^{2} s^{-1}); d : daily damping depth (cm)).

Volumetric wetness	Gwangwhal				Sangju	Imog			
	Cv	λ	Dt	$d \times 4$	$d \times 4$	Cv	λ	Dt	$d \times 4$
0	0.236	0.512	0.217	30.9	30.9	0.231	0.492	0.213	30.6
0.025	0.261	1.696	0.651	53.5	55.9	0.256	1.629	0.636	52.9
0.05	0.286	2.880	1.009	66.6	70.0	0.281	2.766	0.984	65.8
0.08	0.316	2.923	0.926	63.8	66.8	0.311	2.808	0.902	63.0
0.12	0.356	2.979	0.838	60.7	63.3	0.351	2.864	0.815	59.9
0.16	0.396	3.037	0.768	58.1	60.3	0.391	2.920	0.746	57.3
0.2	0.436	3.097	0.711	55.9	57.9	0.431	2.980	0.691	55.1
0.24	0.476	3.163	0.665	54.1	55.8	0.471	3.043	0.646	53.3
0.28	0.516	3.235	0.627	52.5	54.1	0.511	3.113	0.609	51.8
0.32	0.556	3.315	0.597	51.2	52.6	0.551	3.191	0.579	50.5
0.36	0.596	3.408	0.572	50.2	51.4	0.591	3.279	0.555	49.4
0.4	0.636	3.515	0.553	49.3	50.5	0.631	3.380	0.535	48.5
0.44	0.676	3.640	0.539	48.7	49.8	0.671	3.498	0.521	47.9
0.48	-	-	-	-	49.3	0.711	3.635	0.511	47.4
0.4888	0.724	3.824	0.528	48.2	-	-	-	-	-
0.4962	-	-	-	-	49.2	-	-	-	-
0.4992	-	-	-	-	-	0.730	3.710	0.508	47.3

Volumetric wetness	Jungdong				Volumetric wetness	Samgag			
	Cv	λ	Dt	$d \times 4$		Cv	λ	Dt	$d \times 4$
0	0.232	0.500	0.216	30.8	0	0.235	0.513	0.218	31.0
0.025	0.257	1.805	0.703	55.6	0.025	0.260	1.739	0.669	54.3
0.05	0.282	3.110	1.104	69.7	0.05	0.285	2.965	1.041	67.7
0.08	0.312	3.135	1.006	66.5	0.08	0.315	3.102	0.985	65.8
0.12	0.352	3.170	0.902	63.0	0.12	0.355	3.146	0.886	62.5
0.16	0.392	3.210	0.820	60.1	0.16	0.395	3.193	0.808	59.6
0.2	0.432	3.255	0.754	57.6	0.2	0.435	3.245	0.746	57.3
0.24	0.472	3.307	0.701	55.5	0.24	0.475	3.303	0.695	55.3
0.28	0.512	3.368	0.658	53.8	0.28	0.515	3.369	0.654	53.7
0.32	0.552	3.440	0.624	52.4	0.32	0.555	3.446	0.621	52.3
0.36	0.592	3.525	0.596	51.2	0.36	0.595	3.536	0.594	51.1
0.4	0.632	3.626	0.574	50.3	0.4	0.635	3.642	0.574	50.2
0.44	0.672	3.747	0.558	49.5	0.44	0.675	3.769	0.558	49.6
0.48	0.712	3.893	0.547	49.1	0.48	0.715	3.921	0.548	49.1
0.4983	0.730	3.970	0.544	48.9	0.4901	0.725	3.964	0.547	49.0

thermal functions. In general, the existing measured conductivity data have not been supported by measurements of quartz fraction (Tarnawski et al., 2009). According to Lu et al. (2007), the use of sand fraction led to large over predictions of thermal conductivity for coarse sands, whereas it was acceptable for the remaining soils. The thermal conductivity of soils with higher organic matter is typically lower than the soils with lower organic material (O'Donnell et al., 2009). In our study, it was found that the coarse-textured soils had higher values of thermal conductivity than the other textures as also reported by Abu-Hamdeh and Reeder (2000). On the other hand, Akinyemi et al. (2004) carried out a study to determine spatial and temporal variability of thermal properties in a 16-ha clay soil, and found an inconsistent spatial pattern of

Table 2. Thermal properties of some soil series with high water content at wilting point (Cv : heat capacity (cal cm^{-3} ℃$^{-1}$); λ : thermal conductivity (10^{-3} cal cm^{-1} s^{-1} ℃$^{-1}$); Dt : thermal diffusivity (10^{-2} cm^{2} s^{-1}); d : daily damping depth (cm)).

Volumetric wetness	Odae				Weoljeong			
	Cv	λ	Dt	$d \times 4$	Cv	λ	Dt	$d \times 4$
0	0.200	0.373	0.187	28.7	0.197	0.366	0.186	28.6
0.04	0.240	1.139	0.475	45.7	0.237	1.141	0.481	46.0
0.08	0.280	1.905	0.681	54.8	0.277	1.915	0.691	55.2
0.12	0.320	2.074	0.649	53.4	0.317	2.105	0.664	54.1
0.16	0.360	2.146	0.597	51.2	0.357	2.183	0.612	51.9
0.2	0.400	2.203	0.551	49.3	0.397	2.234	0.563	49.8
0.24	0.440	2.262	0.515	47.6	0.437	2.289	0.524	48.0
0.28	0.480	2.324	0.485	46.2	0.477	2.347	0.492	46.5
0.32	0.520	2.390	0.460	45.0	0.517	2.409	0.466	45.3
0.36	0.560	2.461	0.440	44.0	0.557	2.477	0.445	44.2
0.4	0.600	2.537	0.423	43.2	0.597	2.551	0.427	43.4
0.44	0.640	2.621	0.410	42.5	0.637	2.632	0.413	42.6
0.48	0.680	2.713	0.399	41.9	0.677	2.722	0.402	42.1
0.52	0.720	2.815	0.391	41.5	0.717	2.822	0.394	41.6
0.56	0.760	2.927	0.385	41.2	0.757	2.931	0.387	41.3
0.5753	0.775	2.978	0.384	41.1	-	-	-	-
0.5813	-	-	-	-	0.778	3.002	0.386	41.2

Volumetric wetness	Yecheon				Chahang	Hamchang
	Cv	λ	Dt	$d \times 4$	$d \times 4$	$d \times 4$
0	0.230	0.490	0.213	30.6	28.8	30.3
0.04	0.270	1.622	0.600	51.4	46.0	47.8
0.08	0.310	2.753	0.887	62.5	55.1	57.4
0.12	0.350	2.929	0.836	60.6	53.6	56.4
0.16	0.390	2.990	0.766	58.1	51.4	54.5
0.2	0.430	3.042	0.707	55.8	49.5	52.6
0.24	0.470	3.102	0.659	53.9	47.8	51.0
0.28	0.510	3.168	0.621	52.3	46.5	49.6
0.32	0.550	3.244	0.589	50.9	45.3	48.5
0.36	0.590	3.330	0.564	49.8	44.3	47.5
0.4	0.630	3.430	0.544	48.9	43.5	46.7
0.44	0.670	3.546	0.529	48.2	42.8	46.1
0.48	0.710	3.684	0.519	47.8	42.3	45.7
0.5012	0.732	3.768	0.515	47.6	-	-
0.5111	-	-	-	-	-	45.5
0.52	-	-	-	-	41.9	-
0.56	-	-	-	-	41.6	-
0.5648	-	-	-	-	41.6	-

thermal conductivities with spatial correlations and fractal characterizations that varied by parameter and depth.

Conclusions

Evaluation of the thermal conductivity of solids poses a serious dilemma, as the volumetric fraction of quartz is usually not known (Tarnawski et al., 2009).

Therefore, estimated quantities with the model should be interpreted cautiously due to the lack of measured data for quartz fraction. Soil-water content showed a great influence on the scatter of soil thermal properties. Increasing the percentage of soil organic matter and clay fraction decreased thermal conductivity. In overall, the predicted quantities were in agreement with the published data available in the literature.

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