Atatürk Üniv. Ziraat Fak. Derg., 49 (2): 157-163, 2018
Atatürk Univ., J. of the Agricultural Faculty, 49 (2): 157-162, 2018
ISSN : 1300-9036 Araştırma Makalesi/Research Article

Assessment of Multiple Interactions between Soil Texture, Aggregate Size and Soil Thermal Properties

Leila IMANPARAST[*] **Mustafa Y. CANBOLAT**
Ataturk University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Erzurum, Turkey
(*Corresponding author email: Leila.Imanparast13@ogr.atauni.edu.tr)

DOI: 10.17097/ataunizfd.335531
Geliş Tarihi: 21.08.2017 **Kabul Tarihi: 15.12.2017**

ABSTRACT: Soil thermal properties are highly dynamics and is influenced by a multitude of factors. Soil thermal properties affect soil temperature and its thermal regime. Soil water content, soil contribution and state of aggregation affect significantly soil thermal properties. The aim of this study was to determine and evaluate the effects of soil texture and aggregate size on soil thermal properties using the de Vries model. Soil samples with different textures, separated into different aggregate size groups (<4 mm, <2 mm and <1 mm), were used. Thermal properties of soil samples including thermal conductivity, volumetric heat capacity and thermal diffusivity were estimated at field capacity. The results showed that the maximum values for the thermal conductivity, volumetric heat capacity, and thermal diffusivity occurred medium (MTS)>fine, (FTS)>coarse, (CTS) textured soils. In all textural groups thermal conductivity and thermal diffusivity were the smallest in aggregate size <1 mm. Results indicated that soil texture and aggregate size distribution have great effect on the soil thermal properties.

Keywords: Soil texture, thermal properties, field capacity, de Vries model.

Toprak Termal Özellileri, Toprak Tekstürü ve Agregat Büyüklüğü Arasındaki Çoklu Etkileşimlerin Değerlendirilmesi

ÖZ: Toprakların termal özellikleri oldukça değişken olup, birçok faktör tarafından etkilenir. Ayrıca toprak termal özellikleri, toprak sıcaklığı ve sıcaklık rejimleri üzerinde de etkilidir. Toprağın termal özellikleri toprak su içeriği, toprağın yapısal bileşenleri ve agregasyon durumu tarafından önemli ölçüde etkilenir. Bu çalışmanın amacı, toprak tekstürüve agregat büyüklüğünün toprak ısısal özellikleri üzerindeki etkilerinin de Vries modeli ile değerlendirmektir. Bu çalışmada kaba, orta, ince tekstürlü ve farklı agregat büyüklüğüne (<4 mm, <2 mm ve <1 mm) sahip toprak örnekleri kullanılmıştır. Bu özelliklere sahip toprak örneklerinin, tarla kapasitesi koşullarında, termal iletkenlik, hacımsal ısı ve termal difüzivite gibi termal özellikleri hesaplanmıştır. Elde edilen sonuçlara göre, ısısal iletkenlik, hacımsal ısı ve ısısal yayınım açısından en yüksek değerler, toprak tekstürleri arasında, sırasıyla orta, ince ve kaba bünyeli topraklarda ortaya çıkmıştır. Termal iletkenlik ve termal difüzivite için en düşük değerler ise ince bünyeli toprakta tespit edilmiştir. Ayrıca, her bir toprak için en küçük agregatların (<1 mm) oluşturduğu örneklerde en düşük termal iletkenlik ve ısısal yayınım değerleri belirlenmiştir. Elde edilen sonuçlara göre, toprak tekstürü ve agregat büyüklüğünün toprağın ısısal özellikleri üzerinde önemli bir etkiye sahip olduğu belirlenmiştir.

Anahtar kelimeler: Toprak tekstürü, termal özellikler, tarla kapasitesi, de Vries modeli

INTRODUCTION

Prediction of soil thermal properties needs use of information on soil parameters and factors. Many researchers measured soil thermal properties (Clarke *et al.,* 2008) and some researchers used models to predict them (Busby, 2015).Agricultural, meteorological and industrial applications needs information on soil thermal conductivity (Cote and Konrad, 2005).Soil thermal conductivity is affected by some variables such as soil water content, bulk density and organic matter content (Abu-Hamdeh and Reeder, 2000).Soil aggregate structure and size can influence the soil thermal conductivity considerably, especially in fine-textured soils (Lipiec *et al.,* 2012; Sławinski *et al.,* 2011). Organic substances stored on mineral surfaces and in micro-pores of aggregates (Park *et al.,* 2007) can affect the soil thermal properties. Many studies on the soil aggregation showed the correlations between hydraulic properties and gas exchange of soils (Kimura *et al.,* 2012). Studies showed that aggregate size exerts multiple effects on heat transferring, influencing heat transfer due to water content and flow of heated water through pathways (Heitman *et al.,* 2008).

deVries model (1963) is a theoretical model to predict thermal conductivity that assumed soil solid particles were uniformly distributed in continuous pore spaces (fluid) in soils. deVries (1964) developed a method for estimating soil thermal conductivity (λ) by using soil texture, bulk density (ρb) and volumetric water content (θ). Heat transfer in soils occurs by conduction, convection, by vapor movement, which is significant only in soils with very low saturation, and radiation that is negligible (Alrtimi *et al.,* 2016). deVries (1963) proposed a method that applies the every soil layer thermal conductivity value. The de Vries equation is based on the assumption of no contact between the soil particles and the values of the shape factor (g) assume that the soil particles have ellipsoidal shapes (Kersten, 1949; Nusier and Abu-Hamdeh, 2003).The thermal resistance according to the Luikov et al., (1968) is used to calculate the effective thermal conductivity of porous materials. The effect of solid thermal conductivity and particle-particle contact on thermo-diffusion processes was showed by Davarzani and Marcoux (2011). Empirical and semi-empirical models of thermal conductivity have been used to describe the effective thermal conductivity of soil under different soil moisture conditions (de Vries, 1963; Campbell, 1985; Cote and Konrad, 2005). These models evaluated the individual soil properties contribution (porosity, aggregate size, soil texture and organic content) (Smiths *et al.,* 2016). The aim of this study was to compare de-Vries theoretical model calculated values of thermal conductivity, specific heat content, and thermal diffusivity at different soil aggregate sizes of distinct soil textures.

MATERIALS AND METHODS

Experiments were performed on soil samples with different textures (fine (FTS), medium (MTS) and coarse (CTS)), taken from the Daphan plain (40° 10′ 12″ N and 41° 42′ 16″ E), Yarimca village (39° 59′ 32″ N and 41° 28′ 53″ E), and the region of north west of Atatürk University Agricultural Faculty (39° 58′ 26″ N and 41° 29′ 02″ E). Soil samples were air dried, sieved and separated in three sub-groups (<4mm, <2mm and <1mm) and analyzed for soil texture by Day method (Gee and Bauder, 1986); soil reaction (pH) using pH meter by preparing the suspension with 1:2.5 ratio (McLean 1982); electrical conductivity (EC) by preparing the saturation mud and reading by the EC meter (Rhoades,1982); organic matter (OM) with Smith-Weldon method (Nelson and Sommers 1982); lime content (mineral CO_2) with the Scheibler calsimeter and cation exchangeable capacity (CEC) by using of ammonium acetate method (Rhoades 1982a). The soil moisture percent of different soils aggregate sizes under field capacity condition determined by pressure plate (Cresswell *et al.,* 2008).

Correlations between the factors were calculated such as aggregate size classes of different soil textures and gravimetric water content and soil thermal properties such as thermal conductivity, heat capacity and thermal diffusivity.

Thermal conductivity (λ) was calculated by de Vries model **(**Campbell *et al.,* 1994).

$$\lambda = \frac{KwXw\lambda w + KaXa\lambda a + KsXs\lambda s}{KwXw + KaXa + KsXs}$$

where; λ_w, λ_a, and λ_s are the thermal conductivity of water, air and soil particles, respectively, x_w; x_a and x_s are the volume fraction of water, air and soil particles, respectively, and K_w, K_s and K_a are weighting factors depending on the shape and orientation of water, soil particles and air-pores, respectively. The properties are calculated as follows:

$$K_w = \frac{1}{3}\left(\frac{2}{1+\left(\frac{\lambda w}{\lambda f-1}\right)ga} + \frac{1}{1+\left(\frac{\lambda w}{\lambda f-1}\right)gc}\right)$$

$$K_s = \frac{1}{3}\left(\frac{2}{1+\left(\frac{\lambda s}{\lambda f-1}\right)ga} + \frac{1}{1+\left(\frac{\lambda s}{\lambda f-1}\right)gc}\right)$$

$$K_a = \frac{1}{3}\left(\frac{2}{1+\left(\frac{\lambda a}{\lambda f-1}\right)ga} + \frac{1}{1+\left(\frac{\lambda a}{\lambda f-1}\right)gc}\right)$$

Where g_a and g_c are shape factors defined by:

$g_a=0.333-x_w(0.333-0.035)$ for $0.09\leq x_w\leq n$

$g_a=0.013+0.94x_w$ for $0\leq x_w\leq 0.09$

and $g_c=1-2g_a$

where, n is the porosity, λ_f is fluid thermal conductivity and f_w is an empirical weighting function that are calculates as follows.

$\lambda_f = \lambda_a + f_w(\lambda_w - \lambda_a)$

$f_w = 1/(1+(x_w/x_{w0}))^{-q}{}_1$

$q_1 = q_0 (T_k/303)^2$

x_{w0} and q_1 are soil properties that relate to the water content, at which water starts to affect thermal conductivity and rapidity of the transition from air to water dominated conductivity; q_0 is a constant and T_k is the kelvin temperature of the soil (Campbell *et al.,* 1994).

Volumetric heat capacity was calculated by following equation (van Wijk and de Vries, 1963).

$C_v = \rho_b (C_s + \theta_w C_w)$

C_v is volumetric heat capacity (kJ kg^{-1} K^{-1}).

ρ_b is soil bulk density (Mg m^{-3}), θ_w is gravimetric water content and C_s and C_w are soil minerals and water specific heat (kJ kg^{-1} K^{-1}) that are given in Table 1.

Thermal diffusivity (α) was determined using the following equation (Horton *et al.,* 1983).

$\alpha = \frac{\lambda}{Cv}$ (m^2 s^{-1})

Table 1. Density and specific heat of common soil constituents (soil minerals, water and air) at 20°C and 0.101 MPa (1 atmosphere) (after van Wijk and de Vries, 1963).

Soil Constituent	Density (Mg m^{-3})	Specific heat (kJ kg^{-1} K^{-1})
Soil minerals (average)	2.65	0.73
Water	1.00	4.18
Air	0.0012	1.00

RESULTS AND DISCUSSION

Selected physical and chemical properties of the soils studied are given in Table 2.

The clay or fine textured soil (FTS) contains 33% sand, 23% silt and 44% clay, and 1.60% organic matter and 2.1% $CaCO_3$. The loam or medium textured soil (MTS) contains 42% sand, 35% silt and 23% clay, and 1.48% organic matter and 19.3% $CaCO_3$. The sandy loam or coarse textured soil (CTS) contains 55% sand, 31% silt and 14% clay, and 1.82% organic matter and 0.9% $CaCO_3$. The cation exchangeable capacity (CEC) of FTS, MTS and CTS soils are 51.4, 33.8 and 26.8 cmol/kg, respectively.

Table 2. Selected properties of studied soils.

Soils	Clay (%)	Silt (%)	Sand (%)	Soil Texture	pH	EC (dS/m)	OM (%)	$CaCO_3$ (%)	CEC (cmol/kg)
FTS	44	23	33	Clay	7.40	0.60	1.60	2.1	51.4
MTS	23	35	42	Loam	7.46	0.44	1.48	19.3	33.8
CTS	14	31	55	Sandy Loam	7.11	0.30	1.82	0.9	26.8

The soil reaction (pH) and electrical conductivity (EC) of FTS are 7.40 and 0.60 dS/m, of MTS are 7.46 and 0.44 dS/m and of CTS are 7.11 and 0.30 dS/m, respectively (Table 2).

The moisture percent of aggregate size groups of FTS, MTS and CTS are shown under field capacity condition in Table 3.

Table 3. The water content of different soils aggregate sizes under field capacity (pF 2.54) condition.

Soils	<4 mm	<2 mm	<1 mm
FTS	52.4	49.8	51.2
MTS	26.3	30.3	29.4
CTS	23.8	23.7	27.3

CTS (Coarse texture soil), MTS (Medium texture soil) and FTS (Fine texture soil)

It is evident from the data that the moisture percent of aggregate size groups of FTS increased, compared to MTS and CTS.

Thermal conductivity of different soils and different aggregate sizes was calculated by de Vries model at field capacity. The results indicated that thermal conductivity decreased by decreasing aggregate size and the smaller aggregates (<1 mm) had less thermal conductivity as compared to the others such as <4 mm and <2 mm in all soil textures (Figure 1). Also, FTS soil had lower thermal conductivity as compared to the CTS and MTS. Although, the greatest thermal conductivity belonged to the MTS soil<4 mm aggregate size, there was no significant difference between MTS and CTS soils below 4 mm aggregate size. The FTS soil with <1 mm aggregate size had the lowest thermal conductivity (Figure 1). The results showed that FTS with clay texture had the highest volumetric heat capacity compared with the CTS and MTS with sandy and silty texture, respectively. The results indicated no significant difference between CTS and MTS for specific heat. The greatest volumetric heat capacity occurred for the FTS with <2 mm and <1 mm aggregate size and no consistent relationship occurred between aggregate size and volumetric heat capacity across the study soils (Figure 2).

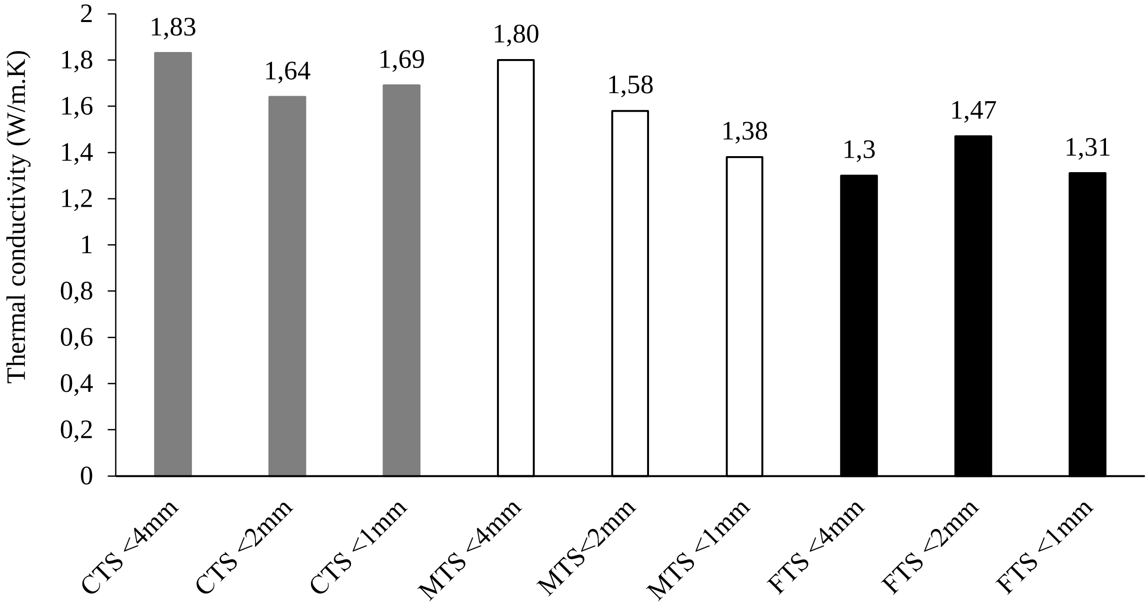

Figure 1. Thermal conductivity of soils with different aggregate sizes,
CTS (coarse texture), MTS (medium texture) and FTS (fine texture).

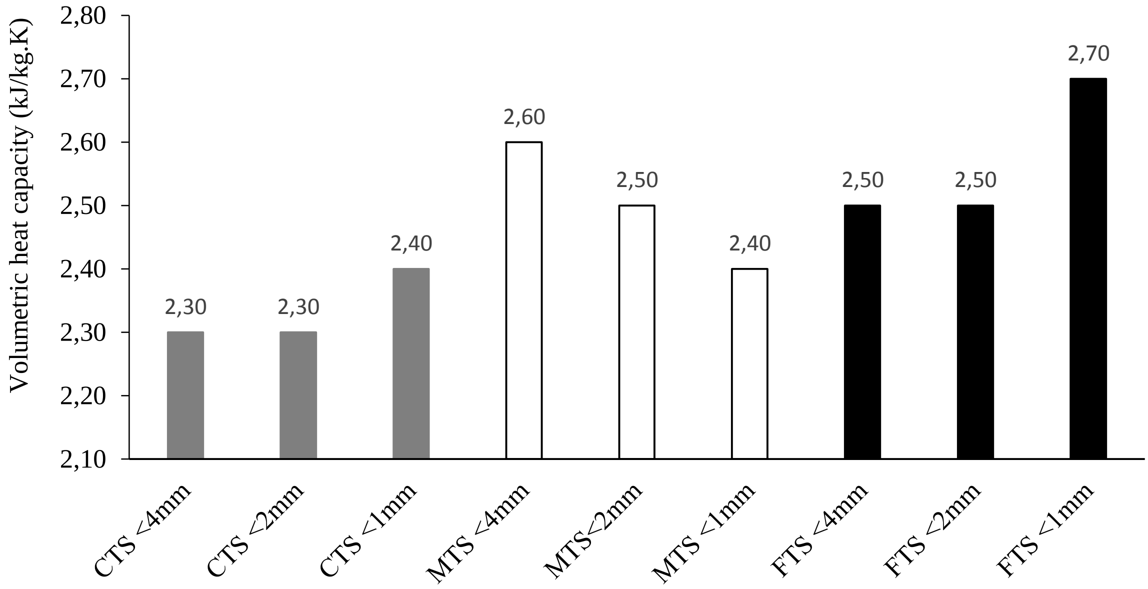

Figure 2. Volumetric heat capacity of soils with different aggregate sizes,
CTS (coarse texture), MTS (medium texture) and FTS (fine texture).

CTS showed the greatest thermal diffusivity compared to the MTS and FTS. Also, FTS had the low thermal diffusivity. The smallest aggregate size (<1 mm) had the lowest thermal diffusivity and the largest aggregate size (<4 mm) had the greatest thermal diffusivity. In general, CTS soil between 4 and 2 mm aggregate size had the greatest thermal diffusivity and the FTS<1 mm aggregate size had the lowest thermal diffusivity (Figure 3).

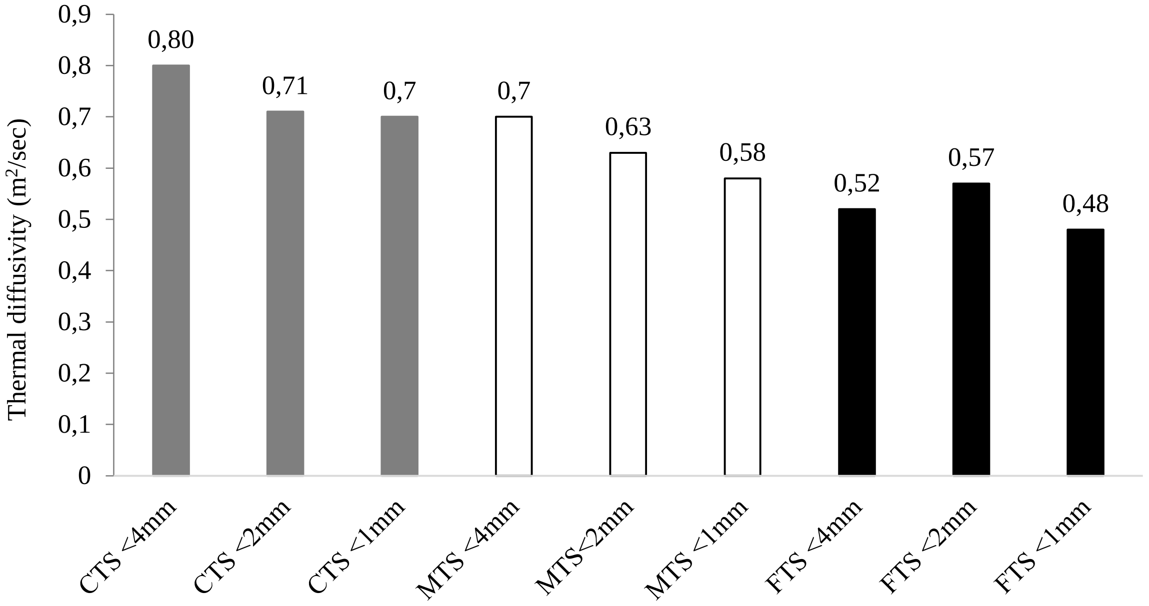

Figure 3. Thermal diffusivity of soils with different aggregate sizes, CTS (coarse texture), MTS (medium texture) and FTS (fine texture).

Ju et al. (2011) showed that thermal conductivity was significantly higher in the non-aggregated soils compared to the aggregated soils at intermediate water contents and Smits et al. (2010) showed that the aggregate size effect on the thermal conductivity was not significant. The sandy loam soil had higher thermal conductivity compared to the clay loam. Thermal conductivity increased with increasing bulk density for the soils as a result of increased particle contact, while porosity decreased. At a specified bulk density, thermal conductivity raised by increasing soil water content. It is indicated that outside a certain bulk density range, higher values of moisture content caused thermal conductivity to increase more rapidly in sandy loam soil than in clay loam soil. Clay loam soil had lower thermal conductivity, measured by both of single and dual probe methods, compared to sandy loam soil at all water contents and bulk densities we studied. Clay loam soils thermal conductivity changes with low thermal conductivities is as surface temperature changes in compare to the sandy loam thermal conductivity changes under equal heat flux densities (Abu-Hamdeh, 2001).

Volumetric heat capacity increased with low speed at sandy and high speed at clay soil. In general, the clay soil showed higher volumetric heat capacity compared tosandy soil (Yadav and Sabena 1973). Yadav and Saxena (1973) and Ghuman and Lal (1985) reported similar results. The highest thermal diffusivity belonged to the sandy soil. Differences in mineralogy, sand, silt and clay fractions could be the primary reasons for sandy soils to have higher thermal conductivity and diffusivity than the clay soils. The sandy soils often comprise more quartz.

Soil thermal diffusivity is a property calculated by soil thermal conductivity divided by volumetric heat capacity. Therefore, higher moisture content in clay soils results in greater specific volumetric heat capacity that decreases the thermal diffusivity. As a result, sandy soil showed higher thermal diffusivity compared to the clay soil. Thermal diffusivity of sandy soil was lower under lower moisture content and increased by moisture content rising to a maximum value and then decreased as moisture content continues raising towards saturation. Clay soil did not followed this trend. The relative changes in thermal conductivity and volumetric heat capacity of soils might have influenced the diffusivity peak in sandy soil (Abu-Hamdeh, 2003). Shein and Mady (2016) reported that greatest values of thermal diffusivity and thermal conductivity occurred when soil bulk density was greatest, and vice versa.

CONCLUSIONS

The results of this study clearly indicated that fine textured soil showed lower thermal conductivity and thermal diffusivity. Smaller the aggregate size lower the value of the soil thermal properties. A reverse relationship of thermal conductivity-volumetric heat capacity and thermal diffusivity-volumetric heat capacity occurred for the fine textured soil.

ACKNOWLEDGEMENT

We thank Ataturk University BAP Coordination Unit for the financial support given to this study under grant PRJ 2015/175.

REFERENCES

Abu-Hamdeh, N.H., Reeder, R.C., 2000. Soil thermal conductivity: effects of density, moisture, salt concentration, and organic matter, Soil Sci. Soc. Amer. J., 64: 1285–1290.

Abu-Hamdeh, N.H., 2001. Measurement of the thermal conductivity of sandy loam and clay loam soils using single and dual probes. J. agric. Eng. Res., 80 (2): 209-216.

Abu-Hamdeh, N.H., 2003. Thermal properties of soils as affected by density and water content. Biosystems Engineering, 86 (1): 97–102.

Alrtimi, A., Rouaini, M., Haigh, S., 2016.Thermal conductivity of a sandy soil. Appl. Therm. Eng., 106: 551-560.

Busby, J., 2015. Determination of thermal properties for horizontal ground collector loops. Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April.

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

Clarke, B.G., Agab, A., Nicholson, D., 2008. Model specification to determine thermal conductivity of soils. Proceedings of the Institution of Civil Engineers Geotechnical Engineering, 161: 161-168.

Cote, J., Konrad, J.M., 2005. Thermal conductivity of base-course materials.Can. Geotech. J., 42: 61-78.

Cresswell, H.P., Green, T.W., McKenzie, N.J., 2008.The adequency of pressure plate apparatus for determining soil water retention. Soil Sci. Soc. Am. J., 72: 41-49.

Davarzani, H., Marcoux, M., Quintard, M., 2011.Effect of solid thermal conductivity and particle-particle contact on effective thermo-diffusion coefficient in porous media. Int. J. Therm. Sci., 50:b 2328-39.

deVries, D.A., 1963. Thermal properties of soils. In: Van Wijk WR, editor. Physics of the plant environment. New York: John Wiley & Sons, 210-235.

deVries, D.A., 1964. Thermal properties of soils. In: van Wijk WR, editor. Physics of plant environment. Amsterdam: North-Holland Publishing Co., 210–35.

Demiralay, İ., 1993. Toprak Fiziksel Analizleri.Atatürk University Agriculture Faculty Publication, No 143.

Farouki, O.T., 1986. Thermal Properties of Soil, Series on Rock and Soil Mechanics. Trans. Tech. Publication., Germany.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. p. 383-411. In A Klute (ed.) Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Agronomy Monograph No. 9 (2ed). American Society of Agronomy, Soil Science Society of America, Madison, WI.

Ghuman, B.S., Lal, R., 1985. Thermal conductivity, thermal diffusivity, and thermal capacity of some Nigerian soils. Soil Science, 139: 74–80.

Heitman, J.L., Horton, R., Ren, T., Nassar, I.N., Davis, D., 2008.Test of coupled soil heat and water transfer prediction under transient boundary conditions. Soil Sci. Soc. Am. J., 72:1197–1207.

Horton, R., Weirenga, P.J., Nielsen, D.R., 1983. Evaluation of methods for determining the apparent thermal diffusivity of soil near the soil surface. Soil Sci. Soc. Am. J., 47: 25-32.

Ju, Z., Ren, T., Hu, C., 2011. Soil thermal conductivity as influenced by aggregation at intermediate water contents, Soil Sci. Soc. Am. J., 75: 26-29.

Kersten, M.S., 1949. Laboratory Research for the Determination of the Thermal Properties of Soils, Bulletin 28, Engineering Experiment Station, University of Minnesota, Minneapoli.

Kimura, S.D., Melling, L., Goh, K.J., 2012. Influence of soil aggregate size on greenhouse gas emission and uptake rate from tropical peat soil in forest and different oil palm development years, Geoderma, (185-186): 1–5.

Lipiec, J., Hajnos, M., wieboda, R.S., 2012. Estimating effects of compaction on pore size distribution of soil aggregates by mercury porosimeter. Geoderma, (179–180): 20–27.

Luikov, A.V., Shashkov, A.G., Vasiliev, L.L., Fraiman, Y.U.E., 1968. Thermal conductivity of porous systems. Int. J. Heat Mass Transf., 11:117- 40.

McLean, E.O., 1982. Soil pH and lime requirement. p.199-224. In A.L. Page et al.(ed.) Methods of soil analysis. Part2.2nd ed. Agron.Monogr.9.ASA, Madison, WI.

M. Smiths. K., Kirby, E.J., Massman, W., Baggett, L.S., 2016. Experimental and modeling study of forest fire effect on soil thermal conductivity. Pedosphere, 26(4): 462-473.

Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter: *In*: A.L. Page, R.H. Miller and D.R. Keeney) Methods of soil analysis. Part 2 Chemical and Microbiological Properties, pp: 539-579.

Nusier, O.K., Abu-Hamdeh, N.H., 2003.Laboratory techniques to evaluate thermal conductivity for some soils. Heat Mass Transf., 39 (2): 119–123.

Park, E.J., Sul, W.J., Smucker, A.J.M., 2007. Glucose additions to aggregates subjected to drying and wetting cycles promote carbon sequestration and aggregate stability, Soil Biol. Biochem. J., 39: 2758–2768.

Rhoades, J.D., 1982a. Reclamation and management of salt-affected soils after drainage. Pages 125-197 in Proc.First Ann. Western Provincial Conf., Soil Salinity, Lethbridge, Alberta. 29 Nov. - 2 Dec. 1982.

Rhoades, J.D., 1982. Soluble Salts. Methods of Soil Analysis. Part 2.Chemicaland MicrobiologicalProperties.2nd Edition. Agronomy No: 9, 167-179, 1159 p, Wisconsin USA.

Shein, E.V., Mady, A.Y., 2016. Soil thermal parameters assessment by direct method and mathematical models. J. Soil Sci. Environ. Manage., 7(10): 166-172.

Slawin ski, C., Witkowska-Walczak, B., Lipiec, J., Nosalewicz, A., 2001.Effect of aggregate size on water movement in soils, Int. Agrophys., 25: 53–58.

Smits, K.M., Sakaki, T., Limsuwat, A., Illangasekare, T.H., 2010.Thermal conductivity of sands under varying moisture and porosity in drainage–wetting cycles. Vadose Zone J., 9: 1–9.

vanWijk, W.R., de Vries, D.A., 1963. Periodic temperature variation in a homogeneous soil. P. 102-143. In: van Wijk, W.R., (ed.). Physics of plant environment. North-Holland Publ. Co., Amesterdam, the Netherlands.

Wiermann, C., Horn, R., 2000. Effect of different tillage systems on the recovery of soil structure following a single compaction event, In: Horn, R., van den Akker, J.J.H., Arvidsson, J., (Eds.), Subsoil Compaction - Distribution, Processes and Consequences. Advances in GeoEcology, Catena, Reiskirchen, vol. 32, Germany, 2000, pp. 339–350.

Yadav, M.R., Saxena, G.S., 1973. Effect of compaction and moisture content on specific heat and thermal capacity of soils. Journal Indian Society of Soil Science, 21: 129–132.