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THE THERMAL GRADIENT AND COMPACTION EFFECTS ON HEAT AND WATER MOVEMENT IN SOME SOILS OF EGYPT

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ABSTRACT

Two laboratory experiments were conducted at the Soil Lab., Fac. of Agric., Al-Azhar Univ. The first experiment was conducted to evaluate the effect of thermal gradient for different soil samples varied in their texture and moisture content on heat energy and water movement. The second experiment was conducted to evaluate the effect of compaction on heat transfer in sandy clay loam soil. To achieve these purposes, different soil columns were prepared to measure soil temperature and moisture content for the abovementioned treatments.The obtained results of the first experiment showed that the increase in total heat energy (H_t) and heat content (H_s) of soil was a proportional value to the increase in thermal gradient. The higher values of H_t and H_s were noticed for sandy clay loam. The net movement of moisture increase by about 110 % by increasing thermal gradient from dt_1 to dt_2. The heat energy consumed in moisture movement (H_c) has been saved with increasing both heat gradient and moisture content values. In other words, the results of the second experiment showed that heat transfer was affected by compaction, where the thermal conductivity of soil increased due to bulk density increasing.

INTRODUCTION

The simultaneous of liquid water, water vapor and heat in the soils plays a critical role in the overall water and energy balance of the near surface environment of arid or semiarid regions in many agricultural and engineering applications. Moisture near the soil surface is influenced by evaporation, precipitation, liquid water flow and water vapor flow, most of which are strongly coupled. In arid regions, vapor movement is often an important part of the total water flux since soil moisture contents near the soil surface usually are very low (Hirotaka et al., 2006). Knowledge of simultaneous transfer of heat and moisture in soils near the soil surface is of great important to meteorologists, soil scientists and ecologists. Parlange et al. (1998) studied evaporative losses of soil water and its thermal regime. They concluded that effective thermal conductivity of porous materials depends greatly on moisture content due to its very high value of heat capacity compared to other two phases of soil constituents; namely, solid and air. Qualitatively, the rate of water transfer is a function of the magnitude of the motivating forces responsible for moisture movement include gravity, particularly in saturated flow, moisture tension gradient, vapor or osmotic pressure whose separate effects are additive. In agricultural applications, spatial and temporal changes in surface soil moisture need to be well understood to achieve efficient and optimum water management. Vapor transport is also important since the actual contact area between liquid water and seeds are often very small such that seeds to imbibe water from vapor to germinate (Wuest et al., 1999).

Horton and Wierenga (1984) found that thermal conductivity for sandy loam increases rapidly with water content from 6.05×10^{-4} cal sec^{-1} $\circ c^{-1}$ when air dried to 26.0×10^{-4} cal sec^{-1} $\circ c^{-1}$ at 30 % saturation. Thereafter, it increases less rapidly (in proportion to the increase of volumetric heat capacity) to a value of 59.5×10^{-4} cal sec^{-1} $\circ c^{-1}$ at complete saturation. Similar results were found by El-Nawawy (1986); who indicated that there is an increase in soil heat content with water content.

Sepaskhah and Boersma (1979) mentioned that the heat flow through soils is controlled by its apparent thermal conductivity and by temperature gradient. Heat flow occurs by conduction through the soil particles, through the water present as continuous films on the particles, or as annulet at the points of contact between particles, and through the air in soil pores. Heat transfer in moist soil also occurs as a result of vapor diffusion. Water vapor molecules diffuse from warm regions, where evaporation occurs to cold regions where condensation occurs as a result of vapor pressure gradient caused by temperature differences. Water movement in the liquid phase may occur as a result of surface tension differences between warm and cold regions. Surface tension decreases with increasing temperature resulting in water potential gradients between points with different temperature.

Ghuman and Lal (1985) stated that clay soil have low thermal conductivity due to its low bulk density and this suggests that they would exhibit larger surface temperature amplitude compared with loamy or sandy loam soils under equal heat flux densities. Also, Jury et al. (1991) found that clay soils had lower thermal conductivity values than sandy soils at all levels of water content. Moreover, conductivity increased with increasing soil water content.

Semmel et al. (1990) stated that the magnitude of soil heat storage or release can be significant over a few hours, but is usually small from day to day. It was also interestingly noticed for both soil particle size fractions that partial or total heat gain or loss generally increased as particles diameter decreased.

The thermal conductivity of a soil depended on several factors. These factors can be arranged into two broad groups; those which are inherent to the soil itself, and those which can be managed or controlled, at least to a certain extent, by human management. Those factors or properties that are inherent to the soil itself include the texture and mineralogical composition of the soil (Campbell, 1985). Factors influencing a soil's thermal conductivity that can be managed externally include water content and soil management, (Tavman, 1996).

Marshall and Holmes (1979) postulated that the conduction of heat through a solid body is described by the Fourier equation:

$$Q = \lambda \, d T/d z$$

Whereas; Q is the flux density of heat which is the rate of heat transfer per unit area ($J\ m^{-2}\ S^{-1}$), d T/d z is the gradient of temperature ($K\ m^{-1}$) and λ is the thermal conductivity ($J\ m^{-1} S^{-1}\ K^{-1}$).

Baver et al (1972) stated that the thermal conductivity increase as soil moisture increase from the oven dry condition to pF 3.8. They stated that the thermal conductivity of different soils follow the order of sand < loam < clay < peat. Thermal conductivity diminishes with decreasing particle size due to reduced surface contact between the particles through which heat will readily flow. Sepaskhah and Boersma (1979) found that the apparent thermal conductivity was independent of water content at very low water contents. They also found that the differences between the apparent thermal conductivity of the three soils were more pronounced at the higher water content. This is due to differences between the thermal conductivities of individual particles.

Heat transport and water flow are coupled by the movement of water vapor, which can account for significant transfer of latent energy of vaporization. Soil temperatures may be significantly underestimated when the movement of energy associated with vapor transport is not considered. Cahill and Parlange (1998) reported that 40 to 60 % of the heat flux in the top 2 cm of a bare field soil of Yolo silt loam was due to water vapor flow. Fourier's law describing heat transport due to conduction (Campbell, 1985) thus needs to be extended to include heat transport by liquid water and water vapor flow. The general heat transport model then considers movement of soil heat by conduction, convection of sensible heat by liquid water flow, transfer of latent and sensible heat by diffusion of water vapor (Nassar and Horton, 1992).

The aim of this investigation is study the effect of thermal gradient with different textures and moisture content on heat energy and water movement, and also, the effect of compaction on heat transfer in soil.

MATERIALS AND METHODS

The current investigation was carried out to study the effect of thermal gradient with different textures and moisture content on heat energy and water movement and the effect of compaction on heat transfer in soil. Some physical properties were determined according to Klute, (1986) and are presented in Table 1. PVC cylinders were used to hold the soil each cylinder 300 mm long and 100 mm diameter and 16 mm wall thickness. The top was tightly sealed with aluminum metal which is one of the best heat conductors. Seven holes were pored in the cylinder's side to insert thermocouples at distance of 0, 3, 6, 9, 15, 20, and 30 cm from the top for the first experiment and 3, 9 and 15 cm for the second experiment. The cylinders were placed vertically and heated by infrared lamp (net density 57.44 cal/min) away from the top of the cylinders by a constant distance of 25 cm. The set was coated with aluminum foil to prevent heat reflection. Two temperature gradients were used in heating process, equal to 0.33 (dt1) and 0.66 (dt2) ◦c/cm. Heating process was intermittently carried out to maintain the surface temperature at the constant degree experiment lasted for 3 hours after reaching the required thermal gradient. The temperature was recorded every 30 minutes at all depths. Three moisture levels were chosen 25 % (W_1), 50 % (W_2) and 100 % from available moisture (W_3). In the second experiment, the sandy clay loam soil of known weight was packed to different volumes to bring the soil sample to the desired bulk density (i.e. 1.25, 1.45 and 1.65 g cm^{-3}).

Table 1: Some soil physical properties of the investigated soils.

Soil property	Sandy clay loam	Loamy sand
Coarse sand %	6.0	39.0
Fine sand %	51.0	45.0
Silt %	17.0	5.0
Clay %	26.0	11.0
Bulk density g cm^{-3}	1.25	1.35
Particle density g cm^{-3}	2.55	2.50
Total porosity %	5٠.98	46.0
Heat capacity cal $g^{-1}c^{-1}$	0.266	0.215
Moisture content at suction 0.10 bar. 0.33 bar. 15 bar.	 32.30 24.70 10.55	 16.40 11.50 4.30
Saturation percentage %	38.0	23.0
Hygroscopic moisture %	2.3	1.0

RESULTS AND DISCUSSION

The First Experiment

Effect of thermal gradient on total heat, soil heat and moisture movement.

Total heat

The effect of thermal gradient change from dt1 to dt_2 is calculated as a percentage difference of dt1 level. The data in Table 2 indicate a general positive response of Ht with increasing heat gradient. The sandy clay loam soil gives higher response of Ht than the sandy loam ones. This may be attributed to the highest heat capacity of the fine-textured soil. The increase in moisture content leads to a gradual increase in H_t values . The results show an equal response for the two samples under dt_2, while completely different values were obtained for the sandy clay loam soil relative to sandy loam ones under dt1. Meanwhile, the response is more pronounced in the coarse-textured soil relative to the fine-textured ones. It was also found that most of the differences in Ht are strictly associated with the two higher moisture levels especially under dt_2. These findings agree well with those obtained by Tavman (1996). Data presented in Table 2 show also the values of heat consumption in water movement (Hc). It is expected that increasing the heat intensity generally decrease the viscosity and surface tension of soil solution (Baver et al., 1972). Therefore, water movement under dt_2 will be easier than that under dt1. Practically, the data presented in Table 2 show that the values of Hc decrease generally by about 20 % under dt_2 compared to dt1 either in sandy clay loam and sandy loam soils.

Table 2. Component of heat contents of the investigated soils as affected by tested treatments.

	Sandy clay loam						Sandy loam soil					
Depth cm	dt_1			dt_2			dt_1			dt_2		
	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
0-3	537	566	580	1202	1188	1287	487	512	525	1024	1088	1165
3—6	467	523	552	1061	1089	1231	435	461	487	922	999	1088
6—9	382	509	509	847	914	1103	397	410	448	832	871	973
9—15	594	764	934	1245	1414	1810	615	717	845	1408	1460	1716
15-20	377	495	613	731	849	1108	427	512	619	811	960	1152
20-30	566	707	849	990	1273	1556	683	811	982	1024	1451	1707
H_s	2923	3564	4037	6076	6747	8095	3044	3423	3906	6021	6829	7801
H_t	7113	7530	8234	13300	14108	15910	5944	6565	7256	11519	12220	14598
H_c	76.08	63.16	18.19	65.51	52.26	6.16	43.36	37.97	10.77	35.49	26.49	5.00

Soil heat

When a soil is heated up, the total heat content of such soil will be conditioned by its specific heat. The heat content of each soil was calculated for each layer and the corresponding values for each treatment are presented in Table 2. The obtained results revealed that increasing of heat gradient leads to a marked increase in soil heat content (H_s) by about 96% in mean. This was true for all treatments. However, the increase of heat content was about 100 % and 93 % for sandy clay loam and loamy sand, respectively. Also, the data showed that a gradual increase in soil heat content (H_s) with increasing in moisture content levels in both soils. In this concern, Semmel et al. (1990) stated that heat conduction and diffusivity should increase rapidly as soon as the dry soil particles are surrounded by water films enlarging their contact area.

Concerning the effect of thermal gradient, soil moisture content and texture on soil heat content, data presented in Table 2 show that sandy clay loam soil does not exhibit any considerable variations in its heat content due to increasing moisture level. But, in sandy loam soil, it is evident that soil heat content (H_s) values display different magnitude of increase upon increasing thermal gradient. The gradual increase in moisture level gave an almost similar positive response in soil heat content (H_s) values for two samples either under dt1 or dt_2. This behavior is expected as the occurrence of moisture around soil particles will surely increase both thermal capacity and conductivity. Meanwhile, water has a profound effect in this field as it has the highest heat capacity and moderate thermal conductivity value. Therefore, its effect is superior for other parameters under consideration. Generally, the results indicated that the differences in soil heat content (H_s) values between fine and coarse-textured soil fluctuated around 5% either under dt1 or dt_2. This means that soil texture has a minute effect on heat absorption by soils.

Moisture movement

Moisture movement is one of the processes which involves many mechanisms and numerous factors affecting these mechanisms, e. g., heat gradient, initial moisture content, texture…..etc. In this investigation two major factors, namely, heat gradient and texture variation are taken into consideration. The moisture content in each layer at the end of heating runs is presented in Table 3. It seen that the rising in heat gradient from dt1to dt_2 leads to an increases in soil moisture movement by about 113 %, as a general mean value which is closely correlated with the increase in (H_t). The interrelated effect of moisture level and heat gradient on moisture movement was more pronounced in case of sandy clay loam soil particularly under W_2 level. This indicates that moisture movement was more sensitive to increase of heat gradient. On the other hand, water movement in the loamy sand soil under W_1 level exhibits the maximum response to doubling heat gradient. This may be attributed to the effect of temperature on viscosity, flow velocity and surface tension, thereby on soil water movement. Theses results are in agreement with those of Ghali and Mohamed (2002).

Table 3. Moisture content in the soil layers as affected by treatments

Soil	Sandy clay loam						Sandy loam					
	dt_1			dt_2			Dt_1			dt_2		
Depth	W1	W2	W3	W1	W2	W3	W1	W2	W3	W1	W2	W3
0-3	12.91	16.88	24.03	12.05	16.22	23.58	5.99	9.16	15.50	4.69	8.73	8.23
3-6	13.66	17.23	24.49	13.48	16.90	24.07	6.90	9.80	15.89	6.43	9.52	9.52
6-9	14.80	17.86	24.62	13.90	17.26	24.53	7.42	10.50	16.63	6.72	10.99	10.73
9-12	14.41	17.88	25.18	14.69	18.39	24.94	7.63	10.61	16.67	7.71	10.94	10.96
12-15	14.36	18.11	25.17	15.38	18.72	25.53	7.95	10.96	16.68	8.98	11.69	11.34
15-20	14.33	17.90	24.97	14.59	18.17	25.49	7.73	10.66	16.83	8.59	11.24	11.10
20-30	14.23	17.71	24.86	14.61	18.02	25.17	7.64	10.60	16.74	8.05	10.93	16.92

The Second Experiment

Effect of compaction on heat transfer in soil

Soil temperature reading during heating cycle under different bulk density is presented in Table 4. The obtained data reveal that the soil temperature increased with increasing the values of soil bulk density. In general, these increases were found with increasing time of heating. At 300 min time from heating, the increase of soil bulk density from 1.25 to 1.65 g cm $^{-3}$ led to increase of soil temperature values from 56.4 to 62.2, 52.0 to 56.8 and 37.3 to 46.7 ◦c at 2, 7 and 12 cm depth, respectively. This may be explained by the fact that an increase in temperature is accompanied by an increase in heat conduction of the soil. Several researchers have measured the relationship between soil water content, bulk density and soil thermal properties. The conclusion of these investigations provides valuable information, particularly about the change of thermal conductivity as a function of water content and bulk density (Tyson et al., 2001). Abu-Hamdeh (2003) found that the soil thermal properties increased with increasing of moisture content and soil bulk density.

Table 4. Soil temperature profile during heating cycle for soil

Depth Cm	Time of readings (minutes)										
	0.00	30	60	90	120	150	180	210	240	270	300
1- soil bulk density at 1.25											
2	24.7	28.6	32.3	39.2	43.5	46.9	50.5	52.3	53.5	54.9	56.4
7	24.0	26.3	31.6	36.5	40.8	42.1	45.5	49.2	50.6	51.5	52.0
12	23.5	25.7	28.4	29.7	31.0	31.9	33.4	35.6	36.2	36.9	37.3
2- soil bulk density at 1.45											
2	24.3	28.8	33.6	40.1	44.0	47.5	51.7	54.2	56.1	58.1	60.0
7	24.1	26.7	31.8	37.0	14.3	43.4	46.2	49.9	51.4	52.6	55.0
12	24.0	25.9	30.9	32.3	35.5	36.9	37.7	39.2	41.2	43.4	45.2
3- soil bulk density at 1.65											
2	24.0	29.1	34.7	42.5	45.6	49.0	53.1	56.0	58.3	60.4	62.2
7	23.8	27.0	32.6	39.3	42.8	45.1	48.3	50.5	53.1	55.0	56.8
12	23.7	27.5	31.3	35.5	37.4	38.7	39.3	40.7	42.1	44.5	46.7

Thermal conductivity of soil as a function of soil bulk density is shown in Table 5 and on Figs 1, 2 and 3. The results showed that the thermal conductivity expressed as the slop of thermal gradient curve increased with increasing of soil bulk density. This may be a result of particle contact enhancement as porosity was decreased. Baver et al (1972) found that increasing the bulk density of the dry soil increased from 1.1 to 1.5 $Mg.m^{-3}$, porosity decreased from about 59 to 43 %, the thermal conductivity increased from 1.0 to 2.1 × 10^{-3} cal sec^{-1} $◦c^{-1}$. Hopmans and Done (1986) reported that the thermal conductivity is not only a function of water content and temperature but also of bulk density.

Table 5. Thermal gradient dT / dx at different soil bulk density

Depth Cm	Time of readings (minutes)										
	0.00	30	60	90	120	150	180	210	240	270	300
1- soil bulk density at 1.25											
2	00	1.95	3.80	7.30	9.40	11.10	12.90	13.80	14.40	15.00	15.85
7	00	0.33	0.97	1.78	2.40	2.58	3.07	3.60	3.80	3.93	4.00
12	00	0.16	0.41	0.52	0.62	0.70	0.82	1.01	1.06	1.12	1.15
2- soil bulk density at 1.45											
2	00	2.25	4.65	7.90	9.85	11.60	13.70	14.95	15.90	16.90	17.85
7	00	0.37	1.10	1.84	2.46	2.76	3.16	3.68	3.90	4.07	4.41
12	00	0.18	0.57	0.69	0.96	1.07	1.14	1.27	1.43	1.62	1.77
3- soil bulk density at 1.65											
2	00	2.55	5.35	9.25	10.80	12.50	14.55	16.00	17.15	18.20	19.10
7	00	0.46	1.26	2.21	2.71	3.04	3.50	3.81	4.18	4.46	4.71
12	00	0.32	0.64	0.98	1.14	1.25	1.30	1.42	1.53	1.73	1.92

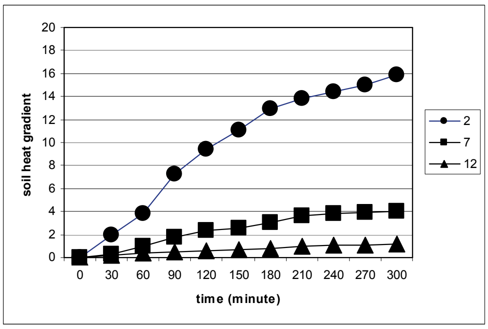

Fig 1: Thermal conductivity as a function of bulk density (1.25 g cm^{-3})

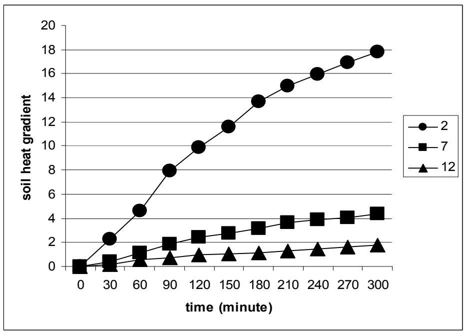

Fig 2: Thermal conductivity as a function of bulk density (1.45 g cm^{-3})

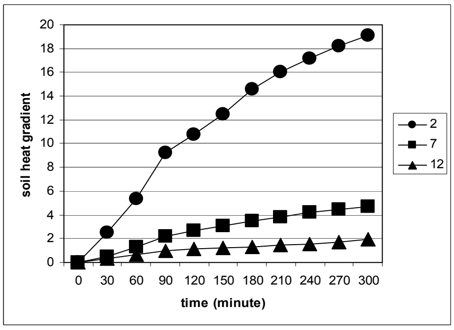

Fig 3: Thermal conductivity as a function of bulk density (1.65 g cm^{-3})

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تأثير التدرج الحراري واندماج التربة على حركة الرطوبة والحرارة في بعض الأراضي المصرية

على محمد عبد الوهاب مشهور و محمد عيسى عليوه الشوبكى

تهدف هذه الدراسة إلى معرفة تأثير التدرج الحراري والمحتوى الرطوبي في أراضى ذات قوام مختلف على المحتوى الحراري وحركة الرطوبة. أيضا دراسة تأثير اندماج التربة على انتقال الحرارة. لذا أجريت تجربتين معمليتين فى معمل قسم الأراضى والمياه – كلية الزراعة – جامعة الأزهر. ولتنفيذ هذه الأهداف تم تجهيز أعمدة تربة مختلفة لقياس حرارة التربة والمحتوى الرطوبي تحت تأثير العوامل سابقة الذكر، إذ اختير تدرجين حراريين هما (٠,٣٣ م°/ سم ، ٠,٦٦ م°/ سم) وذلك على أرضين مختلفتين فى القوام (رملية طينية طميية , طميية رملية) وذلك عند محتوى رطوبي مختلف (١٠٠, ٥٠ , ٢٥ ٪ من الرطوبة الميسرة) وبالنسبة لاندماج التربة (التجربة الثانية) والتى أجريت على تربة رملية طينية طميية حيث كانت قيم الكثافة الظاهرية ١,٢٥ , ١,٤٥ , ١,٦٥ جرام . سم-٣). وكانت أهم نتائج التجربة الأولى ما يلي: - تضاعفت الطاقة الحرارية الكلية والمحتوى الحرارى للتربة بزيادة التدرج الحرارى وكان معدل الزيادة أكثر وضوحا فى الأراضى ناعمة القوام منها فى الأراضى خشنة القوام.تزداد حركة رطوبة التربة بصفة عامة حوالي ١١٠ ٪ بزيادة التدرج الحراري.تقل الطاقة الحرارية المستهلكة فى حركة الماء بصفة عامة بزيادة كلا من التدرج الحرارى ومستوى الرطوبة.وبالنسبة لنتائج التجربة الثانية:- أوضحت النتائج أن انتقال الحرارة تأثر باندماج التربة حيث أن قيم التوصيل الحرارى زادت بزيادة كثافة التربة الظاهرية.