

Specific Heat and Volumetric Heat Capacity of Some Saudian Soils as affected by Moisture and Density

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Abstract— The ability to monitor soil heat capacity is an important mean in managing the soil temperature regime, which in turn, affects its ability to store heat. The effect of water content and bulk density on the specific heat and volumetric heat capacity of two Saudian soils (sand and loam) was investigated through laboratory studies. These laboratory experiments used the calorimetric method to determine specific heat of soils. For the type of soils studied, specific heat increased with increased moisture content. Also, volumetric heat capacity increased with increased moisture content and soil density. Volumetric heat capacity ranged from 1.55 to 3.50 for loam and from 1.06 to 3.00 MJ/m³/°C for sand at moisture contents from 0 to 0.20 (kg/kg) and densities from 1200 to 1400 kg/m³. Specific heat ranged from 1140 to 2090 for loam and from 800 to 1530 J/kg/°C for sand at moisture contents from 0.01 to 0.20 (kg/kg) and soil density of 1200 kg/m³. The volumetric heat capacity and specific heat of soils observed in this study under varying moisture content and soil density were compared with independent estimates made using derived theoretical relations. The differences between the observed and predicted results were very small. Loam soil generally had higher specific heat and volumetric heat capacity than sandy soil for the same moisture content and soil density.

Keywords— *Volumetric heat capacity; specific heat; moisture; density*

I. INTRODUCTION

Since the early growth and development of a crop may be determined to a large extent by microclimate, the practical significance of knowing the soil temperature is most important as it plays a significant role in influencing soil microclimate. Changes in soil temperature are governed by its thermal properties. Heat capacity of soil is the one of these properties that controls temperature variations to a larger extent and refers to its ability to store thermal energy. This property is determined by evaluating the amount of energy required to increase the temperature of a unit mass or volume of a material by one degree. Reference [1] defines the specific heat capacity as the material property that determines the amount of energy absorbed or released, or the enthalpy change in a body before its temperature will change.

Heat transfer through geomaterials is encountered in many engineering fields dealing with high level nuclear waste isolation, energy piles, thermal ground improvement techniques, waste containment facilities, etc. ([2],[3]). In recent years, much effort has been made into developing techniques to model heat storage and transfer through soils in order to determine their thermal properties ([4]-[8]). Predicting the transport of water, heat, and solute in soil would help manage soil and water resources in irrigated agriculture. Since the propagation and storage of heat in a soil is governed by its thermal characteristics, thermal properties are necessary for modeling the transport of heat in soil ([9],[10]). The heat capacity of a soil depends 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 to a certain extent. Those factors or properties that are inherent to the soil include the mineralogical composition and the organic component of the soil [11]. Factors influencing soil heat capacity that can be managed externally include water content and soil density ([11]-[13]). Water content plays a major role in soil heat capacity but is the most difficult factor to manage. Soil management affects heat capacity because practices that cause soil compaction will increase the bulk density and decrease the porosity of a soil. This in turn will have a significant effect on heat capacity.

References [10] and [13] developed models that allow estimation of thermal conductivity and volumetric heat capacity of soils from the volume fractions of their constituents and the shape of the soil particles. The dual-probe heat-pulse technique ([14]-[17]) Kluitenberg et al, 1993) has been used to measure soil thermal properties.

For Saudian soils, however, information on thermal properties has been lacking. These data could be useful in constructing models to predict the thermal regime of soils. Such information assumes greater importance with increasing concerns and intentions in developing the agricultural industry in Saudia Arabia. Because the growth and development of a crop may be determined to a large extent by rates of soil warming and cooling, the practical significance of knowing the soil thermal capacity is most important as it is one of the most important factors controlling rates of soil warming and cooling.

In this study, the first objective was to study the effect of moisture content and bulk density on specific heat and volumetric heat capacity of two different soil types; sand and loam. For Saudi Arabia this point is of great concern, since sandy and loam soils are the most common types of soil in the country. The second objective was to compare the predicted and observed specific heat and volumetric heat capacity values under varying water content and soil density.

II. PREDICTION EQUATIONS

Independent estimates of the soil heat capacity and specific heat were obtained using relations derived based on ([9],[10],[18]) for comparison with the laboratory measurements obtained in this study. The following is a summary of the procedure on which the derivation of these relations is based. Heat capacity H of a soil is calculated as the sum of the heat capacities of its different constituents ([9],[10],[18]). Thus if m_s and m_w are masses in kg of soil particles and soil water, respectively, then.

$$H = m_s c_s + m_w c_w \quad (1)$$

where: H is heat capacity of the soil in $J/^\circ C$, c_s and c_w , are the specific heats in $J/kg/^\circ C$ of dry soil particles and soil water, respectively. Usually, the contribution of air can be neglected ($m_a c_a$) because of negligible mass of gaseous phase. Also, the contribution of organic matter ($m_o c_o$) is ignored because the organic matter contents of the soils under test are small [9].

Using (1), the specific heat c of a moist soil can be given by the relation

$$(m_s + m_w) c = m_s c_s + m_w c_w \quad (2)$$

Equation (2), when divided by the total volume of the soil sample V_T , yields

$$\rho c = \rho_d c_s + \rho_d w c_w \quad (3)$$

where: $w = m_w / m_s$ is the gravimetric moisture content in kg/kg ; ρ and ρ_d are the wet bulk density and dry bulk density in kg/m^3 , respectively, and given by:

$$\rho = (m_s + m_w) / V_T \quad (4)$$

$$\rho_d = m_s / V_T \quad (5)$$

Since the volumetric heat capacity C_v of a moist soil is given by $C_v = \rho c$, (3) can be rewritten in the form

$$C_v = \rho_d c_s + \rho_d w c_w$$

or

$$C_v = \rho_d (c_s + w c_w) \quad (6)$$

where: C_v is the volumetric heat capacity of moist soil in $J/m^3/^\circ C$; and $\rho_d c_s$ is the volumetric heat capacity of dry soil in $J/m^3/^\circ C$. Eqn (6) was used to predict the volumetric heat capacity C_v of a moist soil using an average value for c_s of $950 J/kg/^\circ C$ for loam and $870 J/kg/^\circ C$ for sand as measured in this study.

To derive the prediction equation for the specific heat c of a moist soil, (3) can also be rewritten in the following form

$$c = \rho_d (c_s + w c_w) / \rho \quad (7)$$

Since $\rho_d = \rho / (1+w)$, then the specific heat c of a moist soil is given by

$$c = (c_s + w c_w) / (1 + w) \quad (8)$$

Equation (8) was used to predict the specific heat c of a moist soil using the same value for c_s loam and sand as above.

III. SOIL SPECIFIC HEAT AND VOLUMETRIC HEAT CAPACITY

Specific heat is used to calculate the energy change associated with a temperature change. Most reported soil specific heat capacities were determined by the calorimetric method [19]. Briefly, this method consists of heating a substance to a particular temperature and quickly mixing it into a liquid medium of known temperature and known specific heat. From the law of conservation of energy, the heat lost by the substance must equal the heat gained by the liquid. By knowing the masses involved, the changes in temperatures, and the specific heat of the liquid, the unknown specific heat may be easily computed. The specific heat of dry soil particles c_s was determined from the equilibrium temperature when mixing equal quantities of dry soil and water at different initial temperatures according to:

$$c_s = (T_w - T_e) * c_w * W_w / (T_e - T_s) * W_s \quad (9)$$

where: T_w initial temperature of water in calorimeter ($^\circ C$), T_s initial temperature of dry soil ($^\circ C$), T_e equilibrium temperature of mixed water and dry soil in calorimeter ($^\circ C$), c_w specific heat of water $J/kg/^\circ C$, W_w mass of water in calorimeter (kg), and W_s mass of dry soil (kg).

The specific heat of moist soil was similarly measured but by mixing the moist soil with dry soil rather than water. The specific heat of the moist soil c can be calculated from the equilibrium temperature provided the specific heat of the dry soil c_s is known according to:

$$c = (T_s - T_e) * c_s * W_s / (T_e - T_{ds}) * W_{ds} \quad (10)$$

where: T_s initial temperature of dry soil in calorimeter ($^\circ C$), T_{ds} initial temperature of moist soil in calorimeter ($^\circ C$), T_e equilibrium temperature in calorimeter ($^\circ C$), W_s mass of dry soil in calorimeter (kg), W_{ds} mass of moist soil in calorimeter (kg).

Combining (6) and (7) and since $\rho_d = \rho / (1+w)$, C_v the volumetric heat capacity of moist soil can be calculated from the following equation provided the specific heat of the moist soil c is known:

$$C_v = \rho_d (1 + w) c \quad (11)$$

IV. MATERIALS AND METHODS

Measurements of heat capacity were made on two soils: sand (91% sand, 6% silt, and 3% clay) with a soil organic matter content of 1.34% and loam soil (41% sand, 36% silt, 23% clay) with a soil organic matter content of 2.18%. Soils were air-dried and screened through a 2-mm sieve. For the determination of specific heat and volumetric heat capacity of soil at different moisture contents and compaction, the calorimetric method was followed. A small cylindrical capsule

of copper of diameter 10 mm and length 35 mm was prepared. Its one end was closed and there was a removable cap at the other end. The thickness of the wall of the capsule was approximately 1 mm. The capsule was then pushed into the soil with certain moisture content till it was just filled up. By this technique, small soil samples at any desired density could be conveniently obtained. The soil sample was heated in a double-walled steam chamber. The sample could thus be heated without coming in contact with steam. Specific heat of the soil sample was then determined in usual way by the calorimetric method explained in previous section. The temperatures were recorded at an interval of 0.5 s by using a 0.2 mm copper-constantan thermocouple. The samples were weighed prior to each test on a balance reading to 0.001 g. The experiment was repeated with soils at different moisture contents and packed into the container to same density. To investigate the effect of density, the soil of known weight at given moisture content was packed to different known volumes marked on the container. Various levels of moisture contents and bulk density were used for the two soils. The moisture levels used ranged from 0 to 0.2 kg/kg. Moisture contents throughout this study were measured by drying at 105 °C for approximately 24 h. The bulk densities of soils ranged from 1200 to 1400 kg/m³. The experiment was replicated three times for each treatment. Independent estimates of volumetric heat capacity and specific heat and under varying water content and soil density were also made using (6) and (8), respectively.

V. RESULTS AND DISCUSSION

A statistical analysis was performed to test the null hypothesis that “replicate” had no effect on the results obtained. Means were separated by the LSD procedure at alpha level α of 5% to compare means between replicates for each treatment. The analysis indicated that the replicate effect was not significant. Thus, the results were combined over the three replicates for each treatment in this study.

Specific heat of two sieved and repacked Saudian soils as a function of water content is shown in Figs 1 and 2. The two figures show both predicted and observed specific heat of the loam and sandy soils as a function of water content at a given bulk density using (8) and (10), respectively. At various water contents and at a given bulk density, specific heat increased with increasing soil water content for both soils. It is observed that the specific heat of both the soils, exhibit a nearly linear relationship up to certain moisture content. For higher values of moisture content, specific heat increased less rapidly in case of sandy and more rapidly in case of loam soil. In general, the loam soil had higher specific heat than the sandy soil. The differences in mineralogy and sand, silt, and clay fractions could be the primary reasons that loam soils often have a

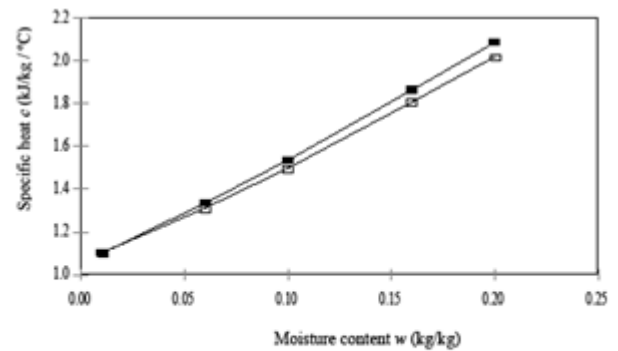


Fig. 1. Measured (■) and predicted (□) specific heat (c : error range 0-0.26 kJ/kg/°C) as a function of moisture content for a loam soil at a bulk density of 1200 kg/m³.

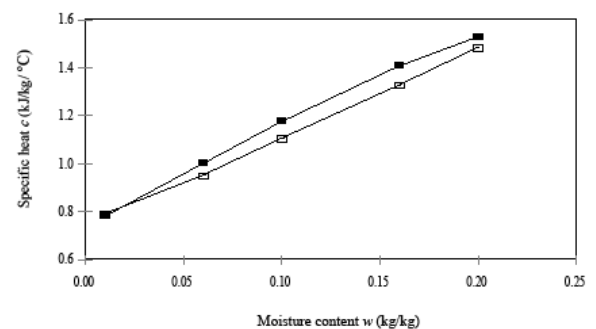


Fig. 2. Measured (■) and predicted (□) specific heat (c : error range 0-0.26 kJ/kg/°C) as a function of moisture content for a sandy soil at a bulk density of 1200 kg/m³.

higher specific heat than sandy soils. The sandy soils often contain more quartz. Similar results were reported by ([12],[20]). Reference [9] reported that the clay soil had higher specific heat than the sandy soil and that for higher values of moisture content, specific heat increased less rapidly in case of sandy and more rapidly in case of clay soil. Rapid increase in the specific heat of loam soil with increasing moisture content is probably due to adsorption of water forming thick hulls around loam particles, which greatly enhanced its effective specific heat compared with sandy soil. It is expected that this type of relation between specific heat and water content holds up to saturation point beyond which specific heat of soil tends to approach the specific heat of water quite rapidly. Comparisons of the specific heat values predicted using (8) with the values measured by the capsule method using (10) are shown in Figs 1 and 2. The differences between the observed and predicted results were small.

Variations of volumetric heat capacity predicted using (6) with the volumetric heat capacity measured by the capsule method using (11) for the two soils are shown in Figs 3 and 4. They show the observed and predicted volumetric heat capacity of the loam and sandy soils as a function of moisture content and bulk density. At various moisture contents and at a given bulk density, measured volumetric heat capacity increased with

increasing soil moisture content for both soils. For sandy soil, measured C_v varies linearly with moisture content (Fig 4) and the linearity was equally good for loam soil (Fig 3). In addition, measured volumetric heat capacity increased with increasing bulk density for the two soils. Measured volumetric heat capacity increased with increasing bulk density for the two soils as a result of particle contact enhancement as porosity is decreased, and because of greater mass of solids per unit volume. For the loam soil, measured volumetric heat capacity did not increase uniformly with increasing bulk density at various water contents (Fig 3). Initially, it increased rapidly with an increase in bulk density for loam soil. However, further increases in bulk density increased the measured volumetric heat capacity only slightly (Fig 5). Such a phenomenon was absent in the sand soil. It appears that higher values of bulk density of sand did improve contact between the relatively larger sand particles, and produced relatively more homogenous soil samples.

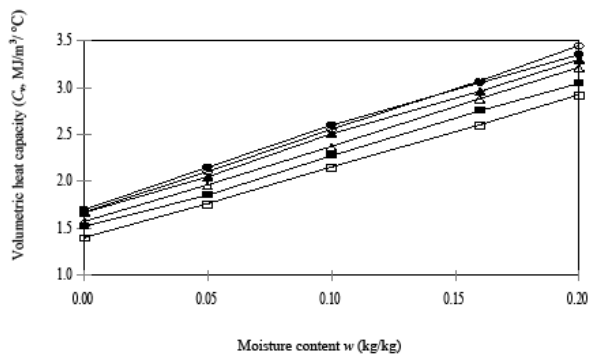


Fig. 3. Measured (■) and predicted (□) volumetric heat capacity (C_v : error range 0-0.38 MJ/m³/°C) as a function of moisture content for a loam soil at the bulk densities: ■ and □, 1200 kg/m³; ▲ and Δ, 1300 kg/m³; ● and ○, 1400 kg/m³.

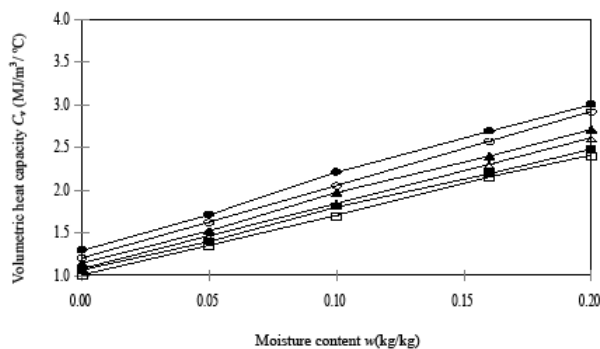


Fig. 4. Measured (■) and predicted (□) volumetric heat capacity (C_v : error range 0-0.38 MJ/m³/°C) as a function of moisture content for a sandy soil at the bulk densities: ■ and □, 1200 kg/m³; ▲ and Δ, 1300 kg/m³; ● and ○, 1400 kg/m³.

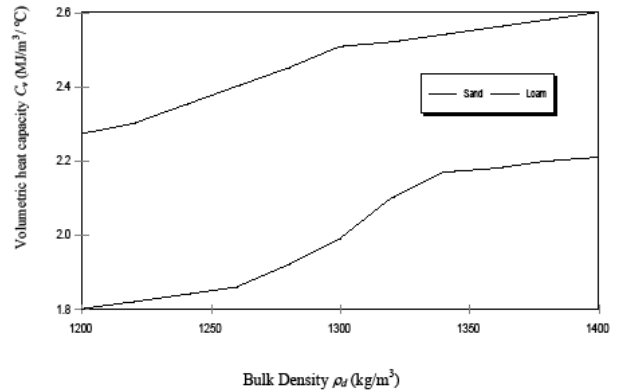


Fig. 5. Measured volumetric heat capacity as a function of bulk density at a moisture content of 0.1 kg/kg for both soils.

Comparisons of the volumetric heat capacity values measured by the capsule method using (11) with the values predicted using (6) for the loam soil (Fig 3) and the sandy soil (Fig 4) show that C_v predicted agreed closely for both soils with C_v measured by the calorimeter method. The differences between the measured and predicted volumetric heat capacity values were small, and were constant over the full moisture content range used in this study. The slopes of the lines for the two soils shown in Figs 3 and 4 are practically the same. The results, therefore, clearly reveal that the calorimeter method yielded C_v values very close to those generated from (6) for both soils. In general, the loam soil had higher volumetric heat capacity than the sandy soil. As shown in Table 1, similar results were reported by other researchers ([9],[12],[18],[21]).

TABLE 1. COMPARISON OF THERMAL PROPERTIES OBTAINED IN THIS STUDY WITH VALUES OBTAINED BY OTHER RESEARCHERS

Source	Specific heat, J/kg °C		Volumetric heat capacity, × 10 ⁶ J/m ³ ·°C	
	Sand	Loam	Sand	Loam
This study	800-1530	1140-2090	1.06-3.01	1.52-3.50
Ghuman and Lal, (1985)	910	1450	1.52	1.54
Yadav and Saxena, (1973)	820-1610	1100-1990	1.14-3.14	1.56-3.55
Bristow, (1998)	— ^a	—	1.10-3.00	—
Abu-Hamdeh (2003)	830-1670	—	1.09-3.04	—

^a Dashes indicate that property was not investigated.

VI. CONCLUSIONS

The effect of water content and bulk density on the specific heat and volumetric heat capacity of some sieved and repacked soils was investigated through laboratory studies. For the type of soils studied, specific heat increased with increased moisture content. Also, volumetric heat capacity increased with increased moisture content and soil density. The differences between the observed and predicted results of the volumetric heat capacity and specific heat were very small. Loam soil generally had higher specific heat and volumetric heat capacity

than sandy soil for the same water content and soil density. Moisture content values and bulk densities were chosen to represent actual values that can be found in natural soils. Additional studies are now needed to test the effect of the above parameters on thermal conductivity of undisturbed Saudian soils.

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