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The effect of soil water and temperature on thermal properties of two soils developed from aeolian sands in South Africa

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ABSTRACT

The influence of soil water content and temperature on the three thermal properties, namely volumetric heat capacity (C), thermal conductivity (K_t) and diffusivity (D) were analysed in laboratory using the KD_2 Pro Thermal Analyser. Five water content and temperature levels were investigated in a two-factor factorial experiment. The results showed an interaction effect between water and temperature on all the thermal properties. From the analysis, three important water content and temperature combinations were identified, i.e. wetting of a dry soil with a rising temperature (up to 60 °C), the effect of freezing (0 °C) and thawing (10 °C) with increasing water content, and the excessive wetting of soils beyond 0.16 $mm^3\ mm^{-3}$ with increasing temperature. Wetting of dry soils with little water improved all thermal properties of these aeolian soils. Hence, a 94, 703 and 346% increase in C, K_t and D has been observed between dry and slightly wetted soils. On the other hand, an average 55% decrease in C, 137 and 367% increase in K_t and D, respectively, were observed due to an increase in temperature from 0 to 60 °C in the two water contents. Freezing (0 °C) and thawing (10 °C) temperatures also had a significant influence in the volumetric heat capacity of the soils. As a result, there was an average 8% increase in C as the temperature changed from 0 to 10 °C while a 42% decrease was recorded due to a change in water content from 0 to 0.39 $mm^3\ mm^{-3}$. Though the influence of freezing and thawing temperatures was negligible, K_t decreased by 11% and D increased by 10% due to an increase in water content from 0 to 0.39 $mm^3\ mm^{-3}$. The effect of the excess addition of water with a rising temperature differs for the three thermal properties. Hence, C and K_t increased at a decreasing rate with addition of water up to DUL whereas D increased dramatically with increasing water content up to 0.16 $mm^3\ mm^{-3}$. Throughout all water contents, C increased with temperature. Thermal conductivity and diffusivity also increased with temperature up to DUL and 0.16 $mm^3\ mm^{-3}$, respectively, followed by a decrease with increasing temperature.

1. Introduction

Soils that are developed from aeolian sandy deposits cover a significant area expanse (303 million ha) in the Southern parts of Africa, stretching from the Republic of Congo to north-western South Africa (Harmse and Hattingh, 2012; Thomas and Wiggs, 2008; Thomas et al., 2005). The study of this area has received great attention due to the fact that the area is highly suitable for agriculture (Ehlers et al., 2007; Le Roux et al., 2013). On the other hand, the physical and chemical properties of soils of arid and semi-arid areas are dynamic since these areas are highly influenced by the remobilization of the aeolian process. Even though the Southern African dune system is currently inactive, model simulations (Holmes and Meadows, 2012; Thomas et al., 2005) showed that the region would be disrupted by the dune dynamics, in all likelihood caused by the possible climate changes of the twenty-first century. As a result, information about the thermal properties of aeolian soils of this region will be of cardinal significance.

Thermal properties are physical properties that govern heat flow and retention processes in soils (Hanson et al., 2000; Hillel, 2004). Knowledge about these properties is crucial for understanding and modelling soil thermal regimes and mass-energy exchange processes occurring in the soil-plant-atmosphere system (Usowicz et al., 1996). As soon as the solar energy has reached the soil surface, it is either stored or transmitted down the soil profile or propagated as sensible heat back to the atmosphere in dry soil conditions. However, in wet soil conditions a considerable amount of the energy would be expended as latent heat of vaporization (Hillel, 2004). The amount of energy to be stored/transmitted to soils or propagated back to the atmosphere depends on the thermal properties of soils. Thermal properties are also crucial in various fields of agriculture, environment and engineering applications. In cultivated soils, thermal properties control the transport and exchange of water and heat energy at the soil-atmosphere interface,

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critical for the occurrence of essential chemical reactions and physical and biological processes.

Thermal properties of soils comprise thermal conductivity (K_t), volumetric heat capacity (C) and thermal diffusivity (D). Thermal conductivity (K_t) describes the soil's ability to transfer heat mainly by conduction. Conductivity involves the quantity of heat that flows through a unit area in a unit time under a unit temperature gradient (Bristow, 2002). Similarly, C explains the amount in heat change in a unit volume of soil per unit change in temperature (Hillel, 2004). Measurements concerning D reflect on how quickly a soil can change its temperature and are defined as the ratio of K_t to C (Hanson et al., 2000). These properties depend heavily on soil-physical properties such as bulk density, water content and temperature.

Concerning the effect of water content on thermal properties, literature (Busby, 2015; Misra et al., 1995; Oladunjoye and Sanuade, 2012; Oladunjoye et al., 2013; Smits et al., 2009; Willis and Raney, 1971) suggested that thermal properties are significantly dependent on water content. However, the magnitude of the responses to water content was variable. Some researchers observed a linear increase in all thermal properties with an increase in water content (Różański and Stefaniuk, 2016; Oladunjoye et al., 2013). A curve linear response was also observed by Misra et al. (1995), Rubio (2013), Tarnawski and Leong (2000) and Willis and Raney (1971). The curve linear response gives two types of critical water contents for K_t. One is associated with a water content required for establishing sufficient contacts between solid particles for significant conductance of heat in unsaturated soils. The other critical water content is associated with water contents that give maximum heat conduction (Misra et al., 1995; Rubio (2013). For very dry soils all thermal properties of soils are governed by coordination number and quality of contacts between particles (Santamarina, 2012). On the other hand, literature study revealed that knowledge concerning the effect of soil temperature on thermal properties is very limited. Sawada (1977) indicated that K_t and D increased with decreasing temperature and increasing water content. Willis and Raney (1971) observed that K_t increases non-linearly over a temperature range stretching from 20 °C to 60 °C. They also demonstrated that the effect of temperature on soil thermal properties is insignificant with regard to extremely low and high water contents.

Thermal properties can be determined in various ways. The most popular methods are direct field measurement, laboratory procedures and predictive mathematical models. Direct determination methods are the most reliable but are expensive, time consuming and laborious as well as impracticable for large scale applications (Dashtaki et al., 2010; Guber and Pachepsky, 2010; Tombul et al., 2004 and Vereecken et al., 2010). Therefore, indirect estimation models that relate thermal properties to available or easily measureable soil-physical properties like texture, bulk density, water content, organic matter content, soil temperature, etc. are important alternatives. These predictive empirical models are called pedotransfer functions.

Laboratory methods applied to measure thermal properties consist of a steady and transient state methods (Farouki, 1981; ASTM, 2000; Decagon Devices Inc., 2011). Steady-state methods involve the application of unidirectional and measured heat source to a specimen and measuring the change in temperature difference in the specimen. On the other hand, the transient methods involve the application of heat to the specimen, and monitoring the change in temperature through time. Generally, steady-state methods take a longer time to measure thermal properties than the transient ones since in steady state, extra time is needed until the specimen reaches steady state condition (Łydżba et al., 2014).

This study was conducted to determine the influence of soil water and temperature on thermal properties (K_t, C and D) of two important aeolian soils in South Africa, namely Clovelly and Hutton soil forms. Hot and dry climates prevalent in areas dominated by aeolian soils make responses of soil thermal properties to moisture and temperature regimes essential for optimum soil-water management. The interactive effects of different soil-water and temperature levels were analysed in laboratory.

Fig. 1. Measurement of thermal properties in laboratory: (a) Set up of the measurement process (b) the dual SH-1 sensor for measuring thermal properties.

2. Theory of dual needle probe

In transient-line heat-source measurement, a probe consists of a needle with a heater in which a temperature sensor has been inserted. A current passes through the heater and the system monitors the temperature of the sensor over time. Specifically, in the dual-needle probe developed by Decagon Devices Inc., the heater and temperature sensor have been placed in separate needles (Decagon Devices Inc., 2011) as shown in Fig. 1b. The analysis of temperature-versus-time relationships for the separated needle probes generates information for the three thermal properties (Decagon Devices Inc., 2011: Low et al., 2014).

In the process of measurement, a measured amount of heat is applied to the heated needle for a certain heating time, t_h, and the temperature is measured by the monitoring needle, at a distance of 6 mm from the heating needle, during heating and cooling times. The resulting temperature is found by subtracting the ambient temperature at time 0, multiplying by 4π and dividing by the heat-per-unit length (Decagon Devices Inc., 2011). The resulting data are expressed by the following equations through Marquardt (1963) non-linear-least-squares procedures:

$$T^* = b_o t + Ei\left(\frac{b_2}{t}\right) \tag{1}$$

$$T^* = b_o t + b_1\left\{Ei\left(\frac{b_2}{t}\right) - Ei\left[\frac{b_2}{t - t_h}\right]\right\} \tag{2}$$

$$T^* = \frac{4\pi(T - T_o)}{q} \tag{3}$$

where Ei is the exponential integral function, b_o, b_1 and b_2 are the parameters to be fit, T_o is the initial temperature during the start of measurement and q is the amount of heat input. In the above equations, Eq. (1) applies in the first t_h seconds when the heat is on, while Eq. (2) applies when the heat is off.

Finally, the thermal conductivity (K_t) and diffusivity (D) can be calculated as follows (Decagon Devices Inc., 2011):