A soil temperature demonstration

K. A. Barbarick

ABSTRACT

An exhibit was constructed to demonstrate the effects of soil moisture on the heat capacity and thermal conductivity of two different soils. Four soil columns were fitted with thermistors at depths of 0 to 1, 5, and 10 cm below the soil surface. Half the columns were saturated with water and the other half were left air-dry. A heat source was applied to the top of the columns, and the temperatures in the columns were measured periodically. For a sand and a silt clay soil, the surface of the dry soils warmed up faster and to a higher temperature than the saturated soils while the subsoil generally warmed up at an equal or faster rate in the saturated soils. Based on this information, a number of questions were posed to students concerning the effects of soil moisture on the thermal properties of soils.

Additional index words: Thermal conductivity, Heat capacity, Thermistors.

EXPLAINING the influence of soil moisture on the thermal properties of soils in an introductory soil science course is a challenge. Students are often confused about the effects of moisture on the heat capacity and thermal conductivity of soils. Patterson and Cook (1974), suggested using thermometers to measure daily temperature changes between a moist and a dry soil. The objective of this article is to describe a demonstration used in the introductory soil science course at Colorado State University to illustrate the effects of soil moisture content on the heat capacity and thermal conductivity of soils.

THEORY

Soil moisture influences the heat capacity of a soil. Since the specific heat for water is higher than for soil materials, increasing the moisture content increases the soil’s heat capacity.

Soil moisture also affects the thermal conductivity of a soil. A fundamental equation for calculating heat conduction is (Baver et al., 1972; Rose, 1966):

$$\frac{dT}{dt} = \frac{K}{C_v} \left( \frac{d^2T}{dz^2} \right)$$

where,

- $K = \text{thermal conductivity in calories cm}^{-1}\text{sec}^{-1}\text{C}^{-1}$,
- $C_v = \text{volumetric heat capacity in calories cm}^{-3}$,
- $T = \text{temperature in } \text{C}$,
- $t = \text{time in seconds}$,
- $z = \text{soil depth in cm}$.
\[
\frac{dT}{dt} = \text{the change in temperature at a given point with time},
\]
\[
\frac{d^2T}{dz^2} = \text{the rate of change of the temperature gradient with depth}.
\]

Also, \(K/Cv\) is called the thermal diffusivity. As shown in Eq. [1], \(dT/dt\) is directly related to the thermal diffusivity. Equation [1] essentially states that the rate of temperature change \((dT/dt)\) in a soil is influenced by the thermal diffusivity \((K/Cv)\), which is a property of the soil, and by the acceleration of the temperature fluctuation with respect to soil depth \((d^2T/dz^2)\). Finally, as the moisture content of a soil increases, \(K\) increases since water is a better conductor of heat than air (Baver et al., 1972).

**MATERIALS AND METHODS**

Four plexiglass columns of 5.7 cm o.d. and 22 cm long were constructed. Three 1.0-cm holes were drilled at a distance 5, 10, and 15 cm from one end. The bottom of each column was sealed with a plexiglass plate of 6.5 by 6.5 cm. Thermistors were inserted into 00 stoppers which were placed in the holes of each column. In two columns, four 0.2-cm drain holes were drilled just above the plexiglass bottom plate. Two columns (one with and one without drain holes) were filled with a crushed, air-dried sand soil (88% sand, 8% silt, 4% clay) and the other two columns were filled with a crushed, air-dried silty clay soil (5% sand, 52% silt, 43% clay). Soil was added to each column until the top thermistor was covered with about 0.5 to 1 cm of soil. The columns were then tapped on a bench top. Uniform packing was not insured in each column; therefore, a comparison of the results for columns of different soil textures would be difficult. The depths of the thermistors were at 0 to 1, 5, and 10 cm below the soil surface. The columns with the drain holes allowed air to escape during the wetting process. Once water flowed through these holes, they were sealed and water was added to a height of almost 0.5 cm above the soil surface.

The thermistors of the two columns of the same soil texture were connected to a Yellow Springs Instrument (YSI)\(^1\) Switch Box (model 4002) which was connected to a YSI Telethermometer (model 43TC). Properly positioned short-stem thermometers could possibly be used in place of the thermistors and corresponding instrumentation. A heat lamp (Sylvania Infrared heat lamp) was positioned about 30 cm above the soil surface.

Once the heat lamp was turned on, temperatures at each location of the dry and saturated soil columns and the air temperatures were recorded. The temperature fluctuations for all four columns could not be completed with one set-up, since the heat lamp was only large enough to uniformly heat two columns simultaneously. Consequently, a separate determination was completed on the other two columns.

This experiment was set up for the introductory soil science auto-tutorial (A-T) lab dealing with soil moisture. Students were allowed to read and record temperatures in the columns. The temperatures at a given time for all depths in all four columns and graphs of the rate of temperature change \((\Delta T/\Delta t)\) with respect to cumulative time \((t)\) were plotted. Students were asked questions concerning the influence of soil moisture on the thermal properties of soils. Two exam questions relative to the thermal properties of soils were given in two different semesters.

**RESULTS AND DISCUSSION**

The temperatures recorded for the sand and silty clay soils at various times after the heat source was applied are presented in Tables 1 and 2, respectively. In most cases, temperatures increased rapidly at first and then leveled-off.

The temperature at the surface of the dry soils was higher than at the surface of the saturated soils. The rate of temperature rise \((\Delta T/\Delta t)\) vs. time was also greater for the dry soils (Fig. 1 and 2). The heat capacity and thermal conductivity of the saturated soils was greater than the dry soils. Consequently, when a uniform amount of heat was added, the surface of the dry soils reached a higher temperature than the surface of the saturated soil. The saturated soil did not heat as rapidly since it takes more heat to raise its temperature, and it rapidly conducts heat from the soil surface.

For the 5 and 10 cm depths, the temperature changed at an equal or greater rate in the saturated soils than in the dry soils (Fig. 3 through 6). Heat added to the saturated soils was conducted to 5 and 10 cm more rapidly than in the dry soils since water is a better conductor of heat than air. Figures 3 through 6 indicate that the thermal conductivity was probably greater for the saturated soil.

The students were provided with Tables 1 and 2 and Fig. 1 through 6. The following questions were posed when the soil temperature demonstration was set-up.

| Table 1. Soil temperature data for columns of the sand soil. |
| --- | --- | --- |
| Time after the addition of heat | Air temp. 6-cm above the soil surface | 0-1 cm Saturation | 5 cm Dry Saturated | 10 cm Dry Saturated |
| Minutes | C | | | | |
| 0 | 21 | 18.5 | 17 | 18.5 | 17.5 | 18.5 | 17.5 |
| 10 | 26 | 24 | 20.5 | 19.5 | 18.5 | 19 | 18.5 |
| 24 | 28 | 28.5 | 23 | 21.5 | 20.5 | 20.5 | 20 |
| 30 | 28 | 30 | 24 | 22 | 21.5 | 21 | 21 |
| 106 | 34.5 | 40 | 32 | 28.5 | 27.5 | 28 | 27 |
| 121 | 35 | 41 | 32.5 | 29 | 28.5 | 28 | 28 |
| 202 | 35.5 | 43 | 33 | 31 | 30.5 | 30.5 | 30.5 |

| Table 2. Soil temperature data for columns of the silty clay soil. |
| --- | --- | --- |
| Time after the addition of heat | Air temp. 6-cm above the soil surface | 0-1 cm Dry Saturated | 5 cm Dry Saturated | 10 cm Dry Saturated |
| Minutes | C | | | | |
| 0 | 21.5 | 21 | 20.5 | 21 | 21 | 21 |
| 15 | 28 | 33.5 | 25.5 | 21.5 | 22.5 | 21.5 |
| 25 | 35 | 35.5 | 27 | 22 | 22.5 | 22.5 |
| 50 | 36 | 37 | 29.5 | 22.5 | 23.5 | 22 |
| 78 | 36 | 38 | 31 | 23 | 25 | 22.5 |
| 106 | 36 | 38.5 | 31.5 | 23.5 | 25.5 | 23.5 |
| 121 | 36 | 40 | 32.5 | 25 | 27.5 | 25.5 |
| 178 | 38 | 40.5 | 33 | 26 | 28 | 26.5 |
| 212 | 38 | 40.5 | 33 | 26 | 28 | 26.5 |

\(^1\)Trade names are included for the benefit of the reader and do not imply an endorsement or preferential treatment of the named products by Colorado State University.
during an auto-tutorial session on "Soil Moisture":

1. Why does the surface of the dry soil warm-up at a faster rate and to a higher temperature than the saturated soil?

2. At the 5 and 10 cm depth, the temperature changed at a faster or equal rate in the saturated soil as compared to the dry soil. What soil thermal property did the moisture increase in the saturated soil to cause this change?

3. An increase in soil moisture increases what two soil thermal properties?

4. Which soil will warm-up faster in the spring at planting time?

Exam questions relative to the influence of soil moisture on the thermal properties of the soil were posed to the students. On an hour exam in the introductory soil science course in the 1979 fall semester, the following multiple choice questions on soil temperature were asked:

1. Which one of the following statements is true?
   - A) the heat capacity increases and the heat conductance decreases.
   - B) both the heat capacity and heat conductance increase.
   - C) the heat capacity decreases and the heat conductance increases.
   - D) both the heat capacity and heat conductance decrease.

2. Assume that in the spring you plant some corn seeds at 2 cm below the surface of the soil. The seeds would germinate faster in
   - A) a soil at field capacity.
   - B) a saturated soil.

Of 302 students, 61% responded correctly to the first question and 87% to the second. The average for the entire exam was about 82%.

**CONCLUSIONS**

A demonstration was constructed to show the influence of soil moisture on the soil temperatures measured at 0 to 1, 5, and 10 cm below the soil surface when heat was supplied to the surface. Information concerning the results of the temperature change in columns of dry and saturated sand and silty clay soils were provided to the
students of an introductory soil science course. Two objective exam questions were given to the students in the 1979 fall semester. About 61% of the class responded correctly to a question about the influence of moisture on the heat capacity and thermal conductivity of the soil while 87% responded correctly to a question about the influence of soil moisture on the temperature of a soil at planting time. In the 1980 spring semester, the students averaged 66% for the correct response on two short answer questions dealing with the influence of moisture on thermal properties of soils.

The demonstration is believed to be an effective tool for teaching students about the influence of moisture on the thermal properties of soils. It also gives the students some exposure to soil temperature instrumentation.
LITERATURE CITED

