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Thermo- and Fluid Dynamics

Measurement of Thermal Conductivities of Soils*

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Abstract. Energy conservation in buildings, in particular in underground constructions, is strongly affected by the thermal properties of the soil surrounding such buildings.

Experimental results of thermal conductivity studies of different soils are reported based on a quasi-steady method [1]. The soil sample is placed in the annular space between two concentric tubes and is heated uniformly on the inside wall keeping the outside wall insulated.

Four different types of soils (Moon Valley, River Sand, In-situ, and Ridgedale), are studied over a temperature range from -5°C to 30°C for three different densities and moisture contents ranging from 0.5 to approximately 12% (by weight). The results indicate that the moisture content is by far the most important parameter. The thermal conductivity may increase by almost an order of magnitude as the moisture content increases. In addition, there may be a strong variation of the thermal conductivity in the phase transition region from unfrozen to frozen soils.

Messung der Bodenwärmeleitfähigkeit

Zusammenfassung. Die Energieeinsparung in Gebäuden wird besonders bei unterirdischen Bauwerken stark von den thermischen Eigenschaften des Bodenmaterials bestimmt.

Es werden in der vorliegenden Arbeit experimentelle Ergebnisse aus Wärmeleitfähigkeitsmessungen an verschiedenen Bodenarten nach einem quasistationären Verfahren [1] dargestellt.

Das Probenmaterial befindet sich dabei zwischen zwei konzentrischen Rohren, wobei das innere gleichmäßig beheizt und das äußere isoliert ist.

Bei Untersuchungen vier verschiedener Bodenproben in einem Temperaturintervall von -5°C bis 30°C, drei verschiedenen Dichtewerten und Feuchtigkeitsgehalten von 0,5 bis annäherend 12 Gew.-% erweist sich der Feuchtigkeitsgehalt als der bestimmende Parameter. Die Wärmeleitfähigkeit nimmt etwa mit derselben Größenordnung wie die Feuchtigkeit zu. Außerdem tritt eine starke Änderung der Wärmeleitfähigkeit beim Phasenübergang von ungefrorenem zu gefrorenem Boden auf.

Nomenclature

k	thermal conductivity
q	heat flux per unit area
r	radius
t	time
T	temperature
ΔT	$T_i - T_0$
α	thermal diffusivity

Subscripts

i	at the inside surface
0	at the outside surface

Introduction

In an attempt to reduce heat losses and gains in a building, underground construction is considered as a viable option. In order to implement this option, accurate data of the thermal properties of soils are required as a function of soil composition, moisture content, density, and temperature.

An extensive study of soil properties has been initiated in the Mechanical Engineering Department of the University of Minnesota in conjuction with a large underground construction on the Minneapolis campus (Williamson Hall). This building has a floor area of 7,710 m^2, all except five percent of which is below ground level. In addition to the soil at the building site (In-situ), three different backfill materials (Moon Valley, River Sand and Ridgedale) are used in order to embrace a wide variety of soils which are found in the United States.

Steady state heat transfer through soils is, in general, controlled by the apparent soil thermal conductivity and the temperature gradients. Since the thermal conductivities of soils depend on composi-

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tion, moisture, texture, bulk density, and temperature, a wide variation of these parameters is desirable for laboratory studies.

Heat flow in soils occurs by conduction through the soil particles, through the water present as continuous films around the contact points between particles, through the air in the soil pure spaces, and by a mass transfer process associated with the vapor phase (evaporation and condensation of moisture).

Water has a thermal conductivity thirty times as high as that of air but considerably lower than that of mineral soil particles. As a consequence, the geometric arrangement and the thickness of the water layer around the particles that conduct the heat from one soil grain to the next should have a strong effect on the thermal conductivity of the system.

The effect of composition on the thermal conductivity of dry soils is well-known. It increases in the sequence clay-loam-sand-gravel [2-4].

The observed increase of the thermal conductivity of soils with increasing water content is associated with the previously mentioned presence of water films at the points of contact between soil particles. An increase of this film thickness improves the thermal contact between soil grains.

The relationship between thermal properties and soil water potential reveals a similar behavior for soils with different textures [4]. The similarity of extremely different soils indicates that the thickness and the geometry of the water films around the particles actually determines the thermal conductivity of the soil-air-water system.

Although the thermal conductivity of soils increases with increasing dry density, this dependence is minor compared to the effect of moisture variations.

The thermal conductivity increases with temperature in moist soils [3], but it is essentially constant for dry soils. There is, however, a discontinuity at the freezing point of water which must be associated with the phase change.

In the following sections the underlying principle of the method will be discussed which has been chosen for generating thermal conductivity data, followed by a description of the apparatus and the experimental procedure. The last section will be devoted to the presentation and discussion of the results.

Theoretical Model

The theoretical model is based on a one-dimensional heat transfer situation in cylindrical coordinates (Fig. 1). Assuming that the thermal conductivity is independent of temperature, the governing equation may be written as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

subjected to the boundary conditions:

$$\text{at } r = r_i \quad -k\frac{\partial T}{\partial r} = q$$

$$\text{at } r = r_0 \quad \frac{\partial T}{\partial r} = 0 \, .$$

The solution of Eq. (1) is given by [1]:

$$T(r,t) = \frac{q}{\frac{k}{r_i}\left[\left(\frac{r_0}{r_i}\right)^2 - 1\right]}\left[\frac{1}{2}\left(\frac{r}{r_i}\right)^2 + \frac{2\alpha t}{r_i^2} - \left(\frac{r_0}{r_i}\right)^2 \ln\frac{r}{r_i}\right] + F(r,t) \, . \qquad (2)$$

The first term in this equation represents the quasi-steady part of the solution describing a temperature profile which maintains its shape while shifting to higher temperatures with increasing time. The second term, $F(r,t)$, represents the transient part of the solution which vanishes for $t \to \infty$. From Eq. (2) follows:

$$k = \frac{q}{\Delta T} f_1(r_i, r_0) \qquad (3)$$

and

$$\alpha = \frac{k\frac{\partial T}{\partial t}}{q} f_2(r_i, r_0) \qquad (4)$$

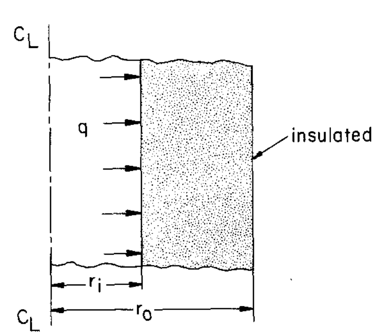

Fig. 1. Schematic diagram for the model

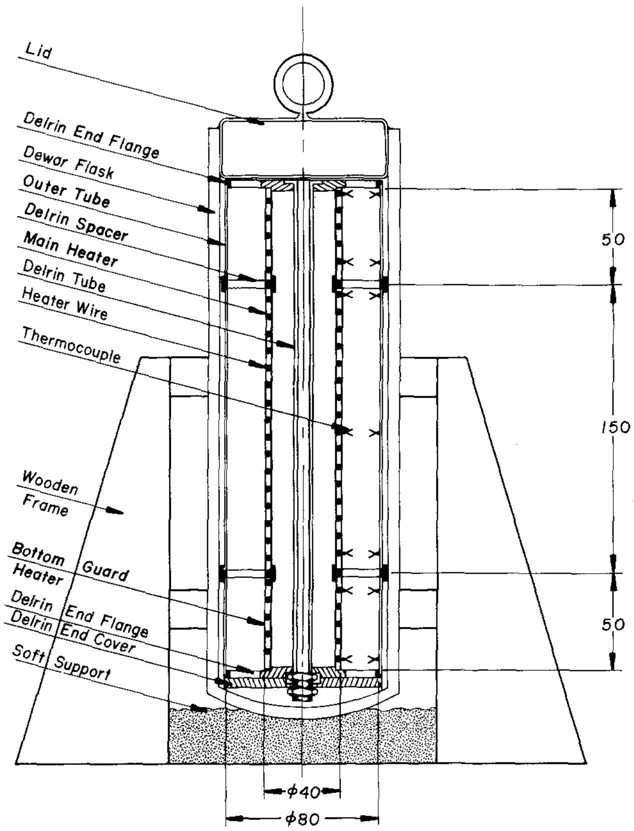

Fig.2. Sketch of the test apparatus (dimensions in mm)

where

$$f_1(r_i, r_0) = \frac{r_i}{\left[\left(\frac{r_0}{r_i}\right)^2 - 1\right]} \left[\left(\frac{r_0}{r_i}\right)^2 \ln\frac{r_0}{r_i} - \frac{1}{2}\left[\left(\frac{r_0}{r_i}\right)^2 - 1\right]\right]$$

and

$$f_2(r_i, r_0) = \frac{r_i}{2}\left[\left(\frac{r_0}{r_i}\right)^2 - 1\right].$$

Since f_1 is only a function of the geometry, the thermal conductivity may be obtained by measuring the heat flux, q, and the temperature difference, ΔT, between inside and outside tube after quasi-steady conditions are established. In a similar way the thermal diffusivity may be derived from the geometry factor f_2, the measured heat flux, q, the already determined thermal doncutivity, k, and the temperature gradient with respect to time after quasi-steady conditions are reached. As will be discussed in the last section of this paper, the latter requirement has not been met in these experiments.

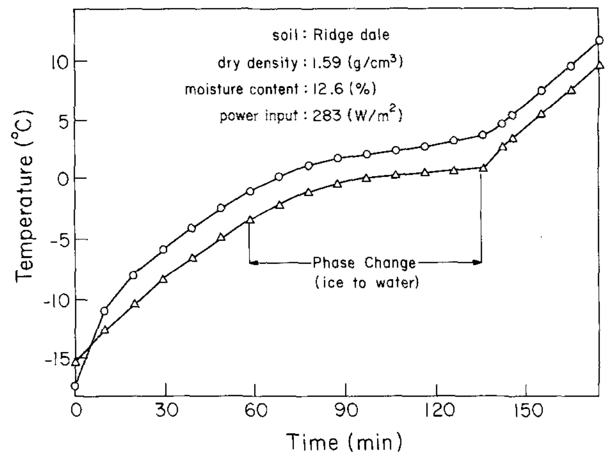

Fig.3. Temperature - time history for a typical test

Description of the Test Assembly and Experimental Procedure

The design of the test apparatus [1] which is shown in Fig.2 has been guided by three major requirements:

1) In order to insure solely radial heat fluxes, guard heaters have to be employed at both ends of the main heater section.

2) The time required for running a test shall be relatively short (in general, less than one hour).

3) The temperature difference between inside and outside surface is to be kept $\leq 10°C$.

Since the thermal conductivity of soil is affected by the dry density, compaction of the soil must be done with great care. Before compaction, the desired dry density and moisture content are selected. After the proper amount of water is mixed with the soil, the mixture is compacted in small increments by successively compacting relatively thin layers to assure the desired uniformity of the density in the apparatus. After compaction, the apparatus is sealed to prevent any loss of moisture. The measurement commences by placing the apparatus in a thermostat at -20°C for approximately five hours. After a uniform temperature exists throughout the apparatus, it is removed from the thermostat and placed in the Dewar flask (Fig.2). Power to the main heater and to the guard heaters is turned on and the experiment monitored. The inside and outside temperature changes with time are continuously recorded with a Doric recorder at intervals of approximately three minutes (Fig.3). The voltage applied to the main heater, as

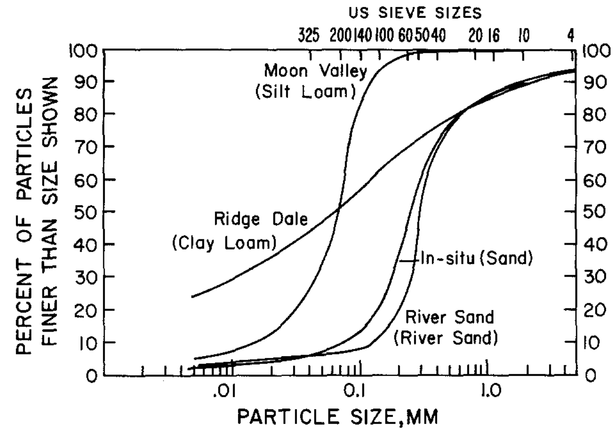

Fig. 4. Grain size accumulation for the solids tested

well as the current, is also monitored at the same time intervals.

Small deviations from the ideal behavior predicted by the analysis are to be expected because of minor heat losses. The heat capacities of the containing tubes and of the Dewar flask require the following corrections for the evaluation of the thermal data of a soil sample (1):

a) The thermal inertia of the outside copper tube and of the inner wall of the Dewar flask changes the boundary condition at the outer radius of the sample. The modified boundary condition is:

$$\text{at } r = r_i \qquad q = q_i$$

$$\text{at } r = r_0 \qquad q = q_0 \;.$$

b) The net heat input to the soil sample cannot be equated with the heat dissipated in the heater coil because a fraction of this heat is used for raising the inside tube and heat coil itself to the desired temperature level. By taking the heat capacity of the inside tube and of the heating coil into account, the necessary corrections can be calculated. These corrections have been included in the evaluation of the data which will be discussed in the last section of this paper.

Four types of soils are included in the test program; namely, Moon Valley soil (silty loam), In-situ soil (mainly sand), River sand (sand), and Ridgedale soil (clay-loam). Details of the composition are shown in Fig. 4. Because of the dimensions of the test apparatus, it is desirable to remove coarse ingredients larger than 0.84 mm (sieve No. 20) from the soil. This, however, should have little influence on the results because even in the worst case this coarse material is less than 18 percent by weight.

Results and Discussion

Under dry conditions, the thermal conductivity of soils shows little variation and is practically inde-

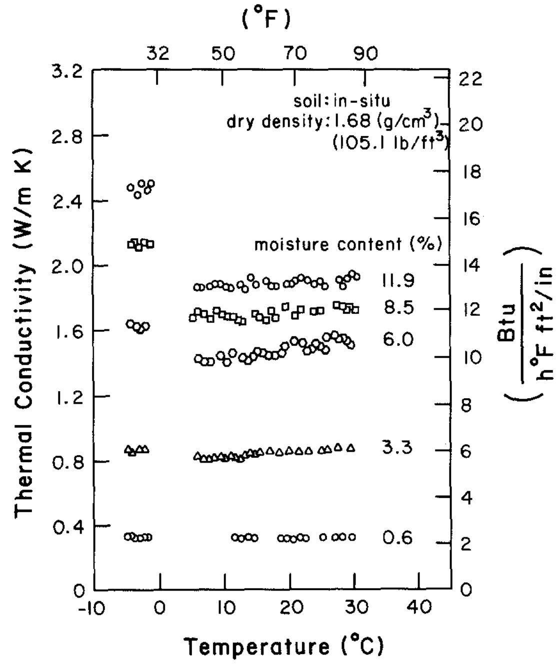

Fig. 5. Typical thermal conductivity results for in-situ soil as a function of temperature

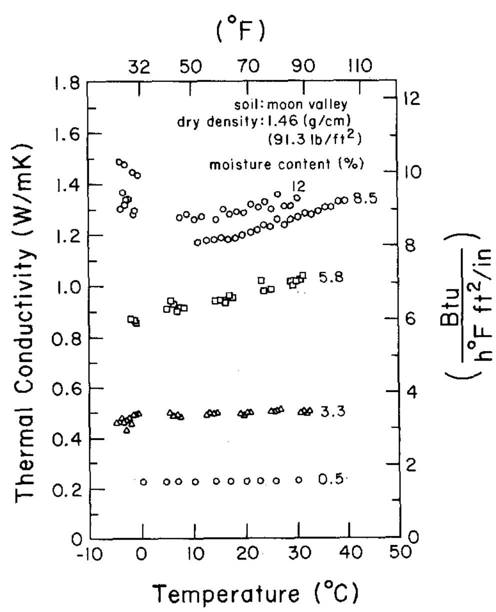

Fig. 6. Typical thermal conductivity results for moon valley soil as a function of temperature

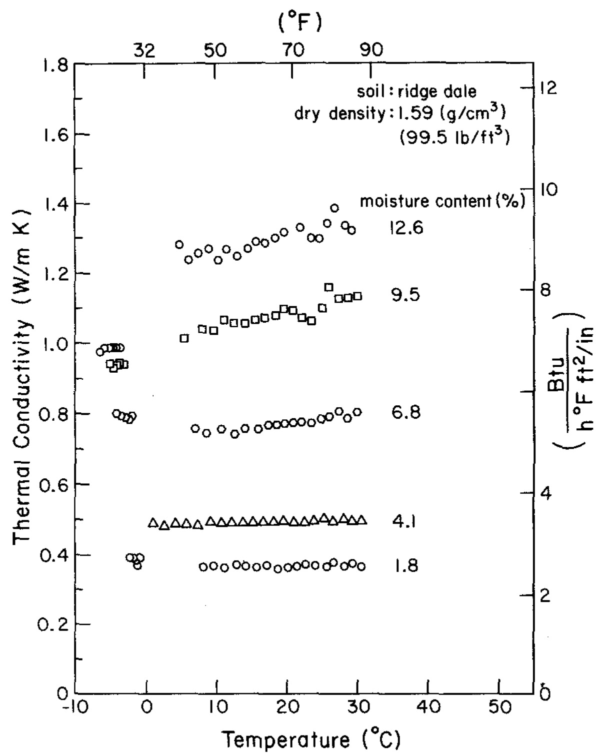

Fig.7. Typical thermal conductivity results for ridgedale soil as a function of temperature

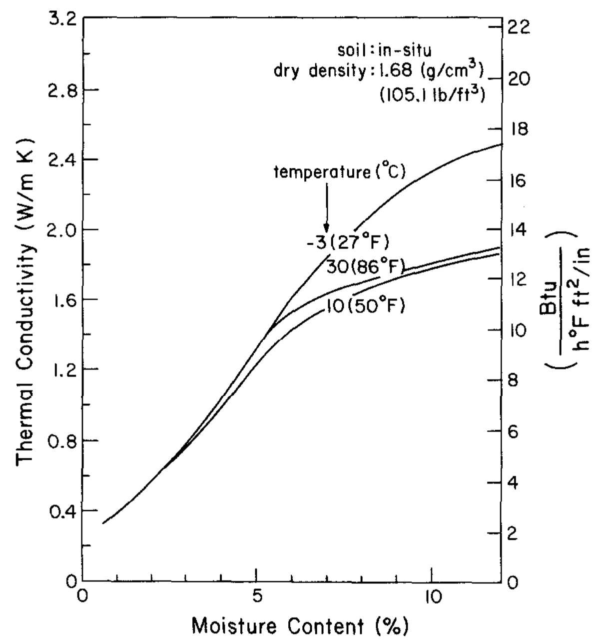

Fig.8. Typical thermal conductivity results for in-situ soil as a function of moisture content ($\% \frac{\text{kg of water}}{\text{kg of dry soil}}$)

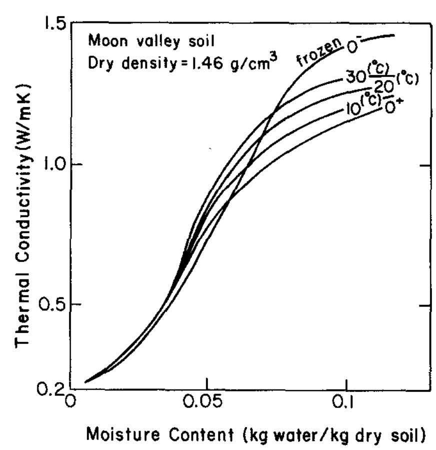

Fig.9. Typical thermal conductivity results for moon valley soil as a function of moisture content ($\% \frac{\text{kg of water}}{\text{kg of dry soil}}$)

pendent of temperature. As the moisture content in the soil increases, moisture migration due to temperature gradients may distort the results. The apparatus has been designed such that the effect of moisture migration on the thermal conductivity will be minimal [5].

The temperature-time history of a particular test is shown in Fig.3. The test begins at temperatures of about -15°C, and, after the initial transient period, it reaches a quasi-steady state at about -5°C. At this point, temperature variations with time become linear. When the temperature reaches 0°C, the phase change from ice to water takes place and after the phase change is completed, the system becomes again quasi-steady. Since the phase change regime is included in the particular test, it requires substantially more time compared with tests above the freezing point.

Figures 5-7 show the effect of temperature on the thermal conductivity of three soil samples. River sand is excluded because the results are very similar to in-situ soil which is to be expected because of almost identical compositions (Fig.4). The thermal conductivity depends little on temperature; in fact, for dry soil, as pointed out earlier, it is essentially independent of temperature. However, as the moisture content increases, the rate of increase of the thermal conductivity with temperature seems also to increase.

Although the effect of temperature on the thermal conductivity is small, the results reveal a discontinuity at the freezing point of water. In general, the thermal conductivity of moist soils may be consider-

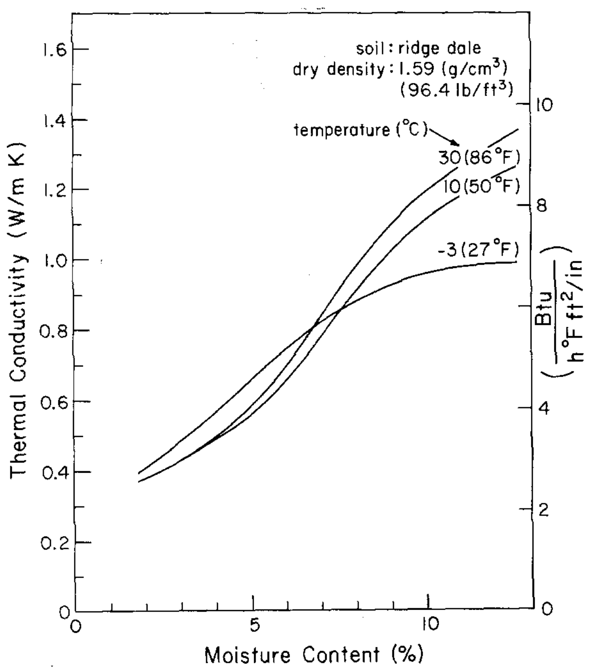

Fig. 10. Typical thermal conductivity results for ridgedale soil as a function of moisture content ($\%\ \frac{\text{kg of water}}{\text{kg of dry soil}}$)

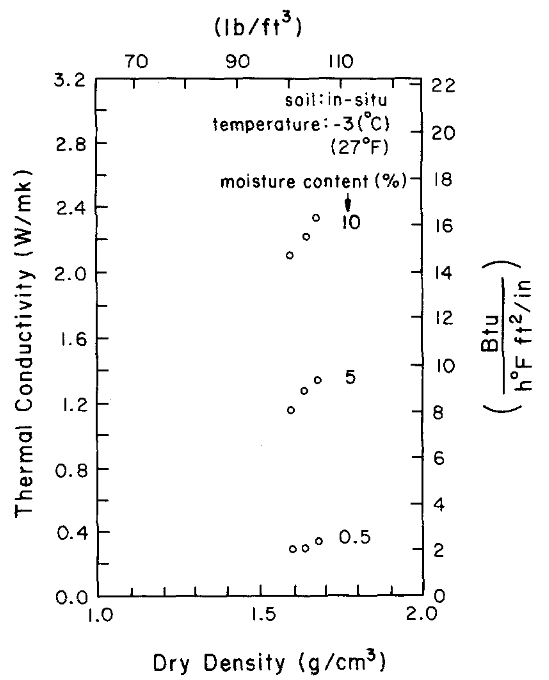

Fig. 11. Typical thermal conductivity results as a function of dry density

ably different when comparing frozen and unfrozen soil. For sandy soils (Fig. 5), the thermal conductivity of frozen soil is always higher than that of unfrozen soil and this difference increases with increasing moisture content. This finding is mainly due to the fact that the thermal conductivity of ice is more than three times higher than that of water. For Moon Valley soil (Fig. 6), which is silty loam, the thermal conductivity in the unfrozen state is higher than that of the frozen state at low moisture contents; but, as the moisture content increases, the situation becomes similar to that of sandy soils. The reason is that Moon Valley soil has a larger number of fine particles compared to sandy soils and also a higher porosity. At low moisture contents, all the moisture appears in the form of thin (molecular dimension) absorbed layers, i.e. no continuous liquid rings between the soil particles exist. Therefore, the previously discussed effect of the moisture rings does no longer prevail and the usual trend for temperatures above 0°C persists now for temperatures below 0°C.

Ridgedale soil (Fig. 7) behaves opposite to that of sandy soils which is true for moisture contents up to 12 %, i.e. for the entire range of the tests. This phenomenon has not been fully understood. It is suspected that the structure of the clay may play an important role. However, it is expected that with further increase in moisture content, the thermal conductivity of frozen clay will eventually become larger than that of unfrozen clay.

Figures 8-10 show the typical effect of moisture content on the thermal conductivity of these samples. The results indicate that the thermal conductivity of the dry samples is almost the same. An increase of the moisture content in coarse-textured soils, such as sands, results in a higher thermal conductivity per unit water added than in the case of finely-textured soils such as clays. As the moisture content is increased, the rate at which the thermal conductivity reaches its maximum when the soil becomes saturated. The curves labeled 0^- and 0^+ in Fig. 9 reflect the previously discussed sudden change of the thermal conductivity by passing from the solid (0^-) into the liquid (0^+) state.

The effect of dry variations is shown in Fig. 11. An increase of the dry density will also increase

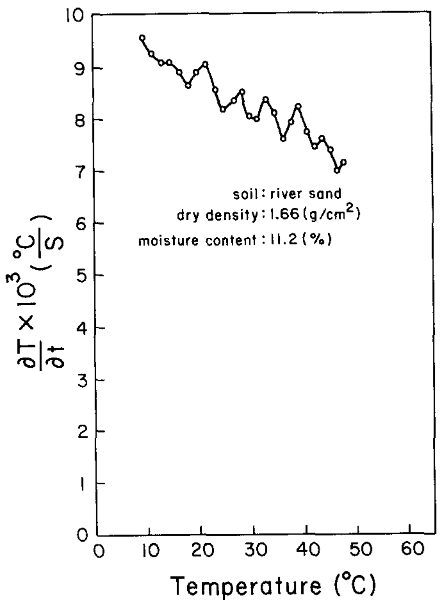

Fig. 12. Variations of $\partial T/\partial t$ for a typical test

the thermal conductivity, a result which is to be expected. Unfortunately, the small range of dry densities covered by these experiments does not allow to draw general conclusions about density effects.

Thermal Diffusivity Measurements

Thermal diffusivity measurements are not reliable with this method [5]. From Eq. (4) follows for the thermal diffusivity:

$$\alpha \sim \frac{\partial T}{\partial t} .$$

This temperature gradient should assume a constant value in a quasi-steady state situation. The results, however, show a substantial decrease during the experiment (Fig. 12). It appears that the time required for $\frac{\partial T}{\partial t}$ to reach a constant value is substantially longer than the time required for the temperature difference, ΔT, to reach an asymptotic value. Extending the experiment to several hours, however, defeats the purpose of the quasi-steady approach.

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