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Heat and Moisture Transfer Characteristics of Compacted MacKenzie Silt

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RÉSUMÉ

Les caractéristiques de transfert de chaleur et d'humidité dans un silt provenant de la vallée du fleuve Mackenzie ont été déterminées en laboratoire. Avec un appareil de balayage à rayons gamma double, on a mesuré les changements de densité et de teneur en humidité volumétrique dans des échantillons de sol. Les coefficients de diffusivité sol-eau dans des conditions isothermiques et dans certains gradients de température ont été établis. La mise au point d'une courbe d'étalonnage pour l'analyse des enregistrements des rayons gamma est décrite. Les points faibles des procédés utilisés pour déterminer les coefficients de transport sont traités.

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ABSTRACT: The heat and moisture transfer characteristics of a silt from the Mackenzie River Valley have been determined in a laboratory investigation. A dual gamma-ray scanner was used to measure the changes in density and volumetric moisture content along the soil samples. The coefficients of soil-water diffusivity under isothermal conditions and under temperature gradients have been obtained. The development of a calibration curve for the analysis of gamma-ray readings has been described. The shortcomings of the procedures used for the measurement of transport coefficients have been discussed.

KEYWORDS: moisture transfer, heat, silts, gamma-rays, evaporation, thermal conductivity

Consideration of heat and mass transfer in geological materials is an important element in the design of many engineering structures such as pipelines, buried transmission lines, and underground radioactive waste disposal facilities. All heat generating structures (for example, boiler houses, furnace buildings, storage tanks for hot fluids, and some oil refining facilities) transfer heat to the underlying soils for a long period of time. As a result of temperature rise, thermal expansion takes place and the ground heaves. On the other hand, the temperature increase in the ground may result in settlement if a significant amount of moisture is lost under the influence of the temperature gradient. The heat stored in the ground causes moisture migration from high- to low-temperature regions. Subsequently, a gradient of moisture content develops, and this causes moisture movement in the opposite direction from that caused by the thermal gradient. The effects of the two simultaneous driving forces are combined to produce the net effect. Therefore, reliable predictions of the performance of structures generating heat require information on the heat and moisture transfer characteristics of soils.

The subject of soil moisture movement caused by hydraulic and temperature gradients has been investigated experimentally and theoretically by many researchers in soil sciences and engineering. Studies reported in Refs *1* through *3* are a few among many other contributions. The soil characteristics measured in the present study are based on the constitutive relation developed by Philip and de Vries [*4*]. Research [*5-8*] confirms in general the validity of the Philip and de Vries model. Experiments show that the model is capable of qualitatively representing the heat and moisture transfer phenomena; but, it is not accurate quantitatively [*11*] if the transport coefficients are calculated using the physical arguments given by Philip and de Vries [*4*]. The limitations of the model in geotechnical engineering practice are given in Ref *9*.

The evaluation of the procedures was as important a part of this investigation as obtaining the transport coefficients for a specific soil. A silty soil from the Norman Wells area along the Mackenzie River Valley was used in the experiments. The grain size distribution is given in Fig. 1.

Constitutive Relation

Philip and de Vries proposed Eq 1 for total moisture flux q in unsaturated soils under the combined effects of volumetric moisture content and temperature gradients, $\nabla\Theta$ and ∇T, respectively

$$\frac{q}{\rho_l} = -D_\Theta \nabla\Theta - D_T \nabla T \qquad (1)$$

where

D_Θ = isothermal moisture diffusivity,
D_T = moisture diffusivity under temperature gradient, and
ρ_l = density of liquid water.

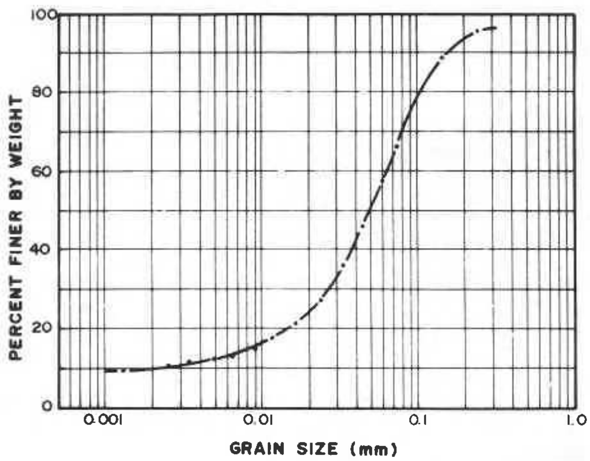

FIG. 1—*Grain size distribution.*

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A term related to the gravity is omitted from Eq 1 because its effect is not considered in the present study. The moisture flow takes place in vapor and liquid phases as a function of the gradients of temperature and moisture content. The following equations give separately the vapor flux q_v and liquid flux q_l

$$\frac{q_v}{\rho_l} = -D_{Tv}\nabla T - D_{\Theta v}\nabla\Theta \quad (2)$$

$$\frac{q_l}{\rho_l} = -D_{Tl}\nabla T - D_{\Theta l}\nabla\Theta \quad (3)$$

where D_{Tv}, D_{Tl}, $D_{\Theta l}$, and $D_{\Theta v}$ are components of transport coefficients.

The total moisture flux is obtained by adding Eqs 2 and 3. Accordingly, the coefficients can be written as

$$D_\Theta = D_{\Theta v} + D_{\Theta l} \quad (4)$$

$$D_T = D_{Tv} + D_{Tl} \quad (5)$$

which are nonlinear functions of the volumetric moisture content and vary over several orders of magnitude for dry and saturated soils.

Test Procedures

Two types of tests were carried out to determine the transport coefficients. The first one was an isothermal, one-dimensional evaporation experiment to obtain D_Θ. In the second type of test a temperature gradient was generated between the ends of the soil specimen to determine D_T. Thermocouples were used to measure temperatures. Moisture content measurements were taken either by the gravimetric method or the dual gamma-ray attenuation technique.

Evaluation of D_Θ

The test procedure followed in the present study to determine D_Θ was proposed by Gardner and Miklich [*10*] and Shapiro and Hsi [*11*]. Soil with uniform moisture content was compacted in the containers shown in Fig. 2. The specimen was kept horizontal during evaporation from the open end to eliminate the effect of gravity in moisture flow. The weight of moisture loss was recorded as a function of time. At the end of the test, the moisture profile was determined either gravimetrically for the soil column in the split tube or using the dual gamma-ray scanner for the soil in the aluminum box. For a horizontal, one-dimensional soil specimen under isothermal conditions, Eq 1 reduces to

$$\frac{q}{\rho_l} = -D_\Theta \frac{d\Theta}{dx} \quad (6)$$

where $d\Theta/dx$ is the volumetric moisture content gradient at any point x along the specimen. The diffusivity coefficient D_Θ can be obtained from

$$D_\Theta = \frac{E}{A\rho_l}\frac{-1}{(d\Theta/dx)_{\text{end}}} \quad (7)$$

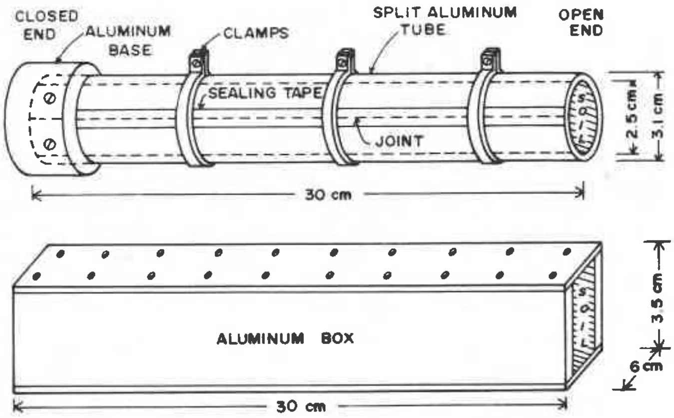

FIG. 2—*Split tube and aluminum box used for isothermal evaporation tests.*

where E is the evaporation rate, A is the cross-sectional area of the soil sample, and $(d\Theta/dx)_{\text{end}}$ is the volumetric moisture content gradient in the soil at the open end of the split tube or aluminum box. This test was conducted in a moisture and temperature regulated room because the rate of drying is controlled by both the boundary conditions and physical characteristics of soil. $D_{\Theta v}$ and $D_{\Theta l}$, which are two components of D_Θ, were determined using the procedure described by Philip and de Vries. When the experimental results representing the D_Θ versus Θ relation are plotted, the curve exhibits a distinct local minimum value for D_Θ at $\Theta = \Theta_{crit}$ as shown in Fig. 3. Above the critical value of volumetric water content, the contribution of vapor diffusivity is assumed negligible. For moisture less than Θ_{crit}, the contribution of liquid flow is considered negligible.

Evaluation of D_T

The second set of experiments was designed to evaluate D_T from the steady state profile of moisture content in a confined soil specimen under a temperature gradient. Figure 4 shows the test setup

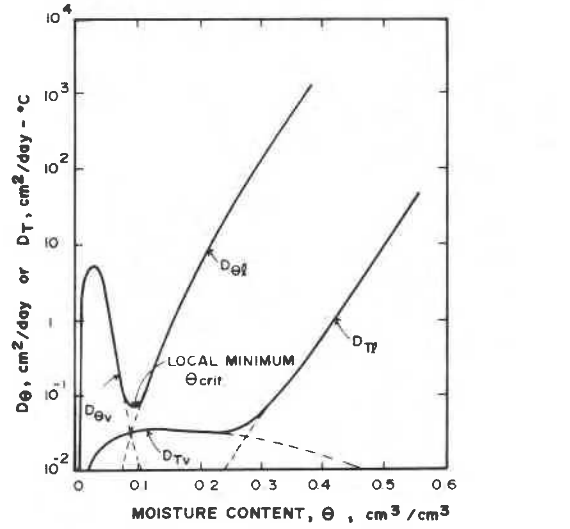

FIG. 3—*Transport coefficients as a function of moisture content* [7].

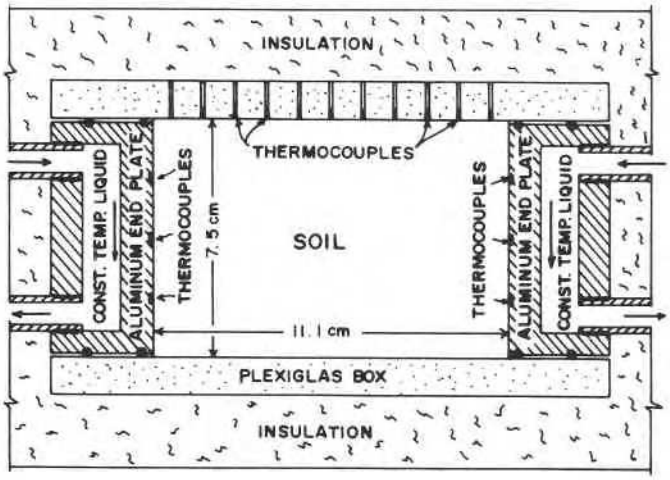

FIG. 4—*Variable temperature test apparatus with rectangular cross section.*

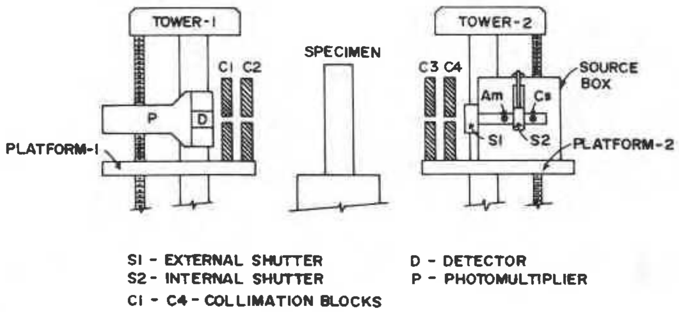

FIG. 5—*Schematic diagram of gamma-ray scanner.*

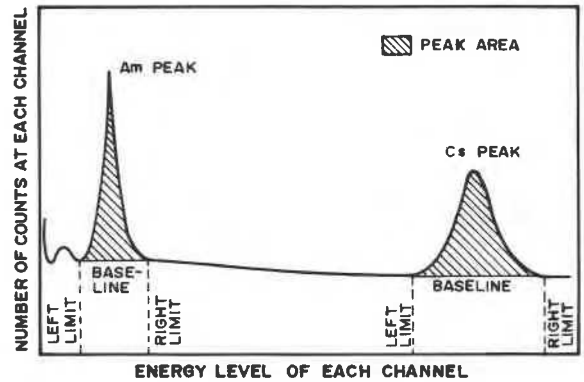

FIG. 6—*Determination of the area under a peak in TPA method.*

for this type of experiment. When the temperature and moisture content distributions reach a steady-state, the following equation can be written

$$D_T \frac{dT}{dx} + D_\Theta \frac{d\Theta}{dx} = 0 \qquad (8)$$

The determination of D_T requires, therefore, the results of both types of tests. Once the results for the D_Θ versus Θ relation and $d\Theta/dx$ are obtained from the isothermal evaporation test, they are substituted in Eq 8 along with the results of the temperature gradient tests. The D_T values evaluated at different locations along the specimen can be plotted against Θ to establish the functional relation between D_T and Θ. The division of D_T into its components, D_{Tv} and D_{Tl}, is based on the assumption that the curve representing the D_T versus Θ relation has a considerable change in its slope at some moisture content value below which the moisture flow caused by temperature gradient takes place in vapor phase and above that value of moisture content the liquid flow is the main component of the moisture flow.

Dual Gamma-ray Scanner

The gamma-ray scanner used in this study is shown schematically in Fig. 5. Cesium-137 (Cs) and Americium-241 (Am) isotopes are used in this equipment as in most dual gamma-ray scanners. When these radioactive sources are used simultaneously, the strong source, Cs, affects the count rates of the weaker source, Am. The analysis of experimental data requires the removal of the Cs effects from the Am reading.

Several methods have been described in the literature for the analysis of complex gamma spectra; they are summarized in Ref *12.* A direct method which is called the "Total Peak Area" (TPA) has been employed in the present work.

Figure 6 shows, in general, a complex gamma spectrum for the Am and Cs isotopes, in which the number of counts recorded by the detector is plotted against the energy level of each channel in the recorder. According to the TPA method, a "baseline" is drawn, as indicated in the figure, to divide the area under a peak into two sections. It is assumed that the counts above the baseline are due to the isotope associated with the energy level of the peak and that the area below the baseline corresponds to the background radiation plus the scatter from the other isotope. For each peak, the counts from all the channels between the left and right limits of the area are added first. The number of counts corresponding to the area under the baseline is then subtracted from the total. Equation 9 is used to calculate the area above a linear baseline

$$\text{AREA} = \sum_{i=L}^{R} a_i - \frac{(a_L - a_R)}{2}(R - L + 1) \qquad (9)$$

where

a_i = number of counts in channel i,
L = channel number at left limit of peak, and
R = channel number at right limit of peak.

In the present study, the accumulated information during the use of TPA method has resulted in the development of a calibration curve shown in Fig. 7. The Cs influence on the Am count rates was not random, but it was correlated to the cesium counts through a well defined relationship.

In order to find the count rates, I_{Am} and I_{Cs}, the number of counts obtained from Eq 9 was divided by the length of time the shutter was open. I_{Am} and I_{Cs} were used in Eqs 10 and 11 to calculate the moisture content and density of soil

$$I_{Am} = I^{\circ}_{Am}\, e^{-\mu'_{Am}\rho' x' \, - \, \mu''_{Am}\rho'' x''} \qquad (10)$$

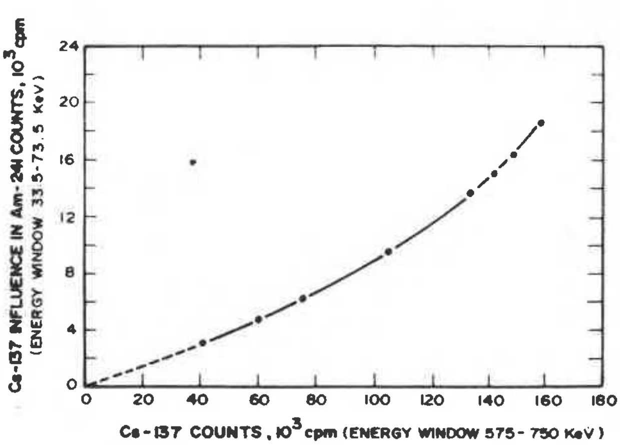

FIG. 7—*Cs-137 influence on Am-241 readings in present study.*

$$I_{Cs} = I^{o}_{Cs}\, e^{-\mu'_{Cs}\rho' x' - \mu''_{Cs}\rho'' x''} \tag{11}$$

where

I^{o}_{Am}, I^{o}_{Cs} = intensities of gamma-rays through air,
μ'_{Am}, μ''_{Am} = mass attenuation coefficients of water and silt for Am source,
μ'_{Cs}, μ''_{Cs} = mass attenuation coefficients of water and silt for Cs source,
ρ', ρ'' = densities of water and soil solids, and
x', x'' = thickness of water and soil solids.

In these two equations, x' and x'' are the unknowns. Once x' and x'' are determined, they are used to find the density and moisture changes in the soil.

Measurement of Coefficient of Thermal Conductivity

The thermal conductivity of the soil has been determined by using a standard conductivity probe, which had high precision thermistors with accuracy $\pm 0.005°C$. The details of this test can be found, for example, in Ref *13*.

Experimental Results

The transport coefficients measured in the present experimental study on the Mackenzie silt are presented in the following.

Transport Coefficient D_Θ

The silty soil with a uniform initial moisture content was compacted, approximately in 1-cm layers, into one of the molds shown in Fig. 2. In the cylindrical mold, each layer received 5 blows from a 676-g tamping rod dropped from 7-cm height. A different tamping rod was used for the compaction of soil into the rectangular mold. The compaction energy used per unit mass of soil, however, was kept constant for soils in both types of molds. All specimens, were kept closed for about 24 h to reduce any moisture content variation caused by the compaction. Subsequently, evaporation from one end was allowed for about 6 h in most cases. The evaporation time was around 24 h for the remaining samples. Variations in both the initial moisture content and the total evaporation time were needed to obtain D_Θ for a large range of moisture content. The amount of moisture loss from the open end during the evaporation is shown in Figs. 8 and 9 as a function of time. At the end of the evaporation period, the moisture content distribution along the soil sample was determined. Figure 10 shows the measured values of the volumetric moisture content.

The experimental values of the isothermal soil-water diffusivity D_Θ are plotted in Fig. 11 as a function of volumetric moisture content. Within the range of moisture content used in these experiments, the diffusivity D_Θ reached a local minimum around $\Theta_{crit} = 7\ cm^3/cm^3$. Dry densities of the soil specimens at the beginning of the isothermal evaporation tests are given in Table 1. In addition to the initial differences among the specimens, the dry density ρ_{dry} along each soil sample changed further during drying as a function of changes in volumetric moisture content. Therefore, the ρ_{dry} at the data points shown in Fig. 11 are not exactly the same; their values are given in Table 1.

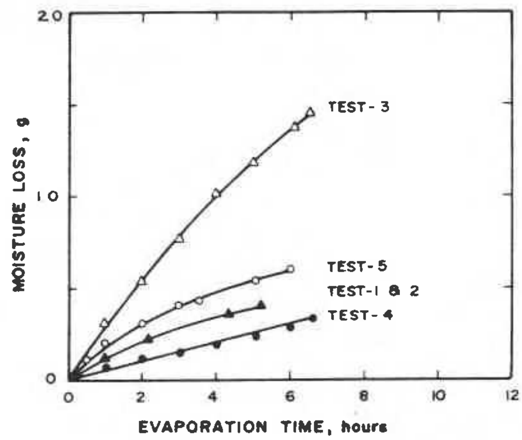

FIG. 8—*Isothermal evaporation curves.*

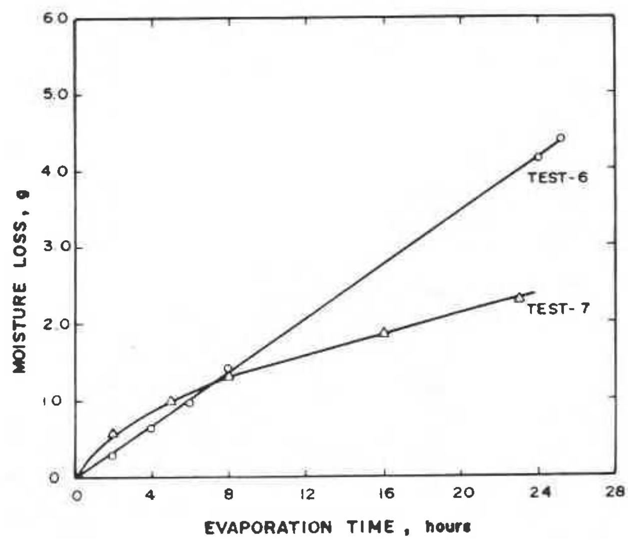

FIG. 9—*Isothermal evaporation curves.*

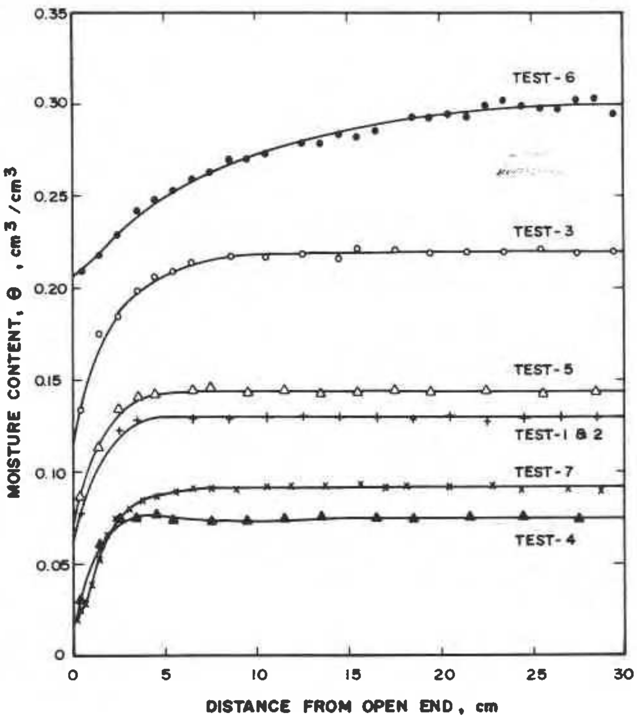

FIG. 10—*Moisture content distribution along soil specimens.*

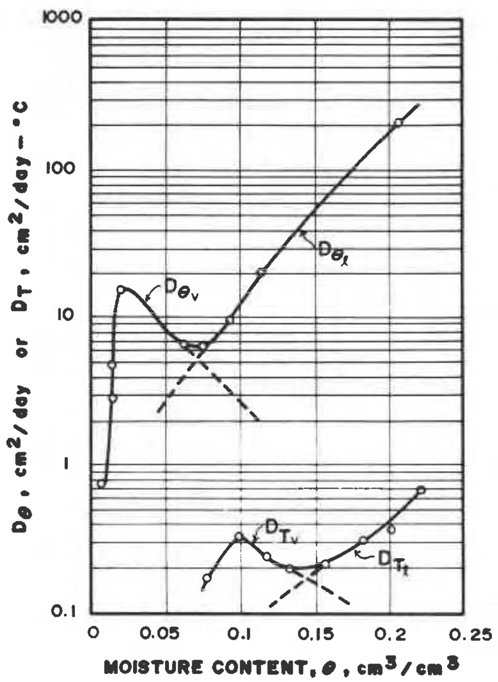

FIG. 11—*Transport coefficients as a function of volumetric moisture content.*

Transport Coefficient D_T

To obtain the coefficient D_T, the soil specimen with a uniform moisture content was compacted in a specially designed plexiglas cell shown in Fig. 4. Liquid cooled/heated heat exchangers were placed at both ends of the cell to impose a thermal gradient on the soil specimen. In order to reduce any moisture content variation that might be caused by the compaction, the sample was kept at room temperature overnight. The next day, the test started with the application of a temperature gradient. The heat flux at both ends of the specimen was measured by the heat flow metres. Some of the details of the heat flow meter are given in Ref *14*. The temperature distribution in the soil specimen was measured by a set of thermocouples located at the interface of the cell wall and the soil. Two tests were carried out with different temperatures applied at the ends of the soil specimen. For both tests, the initial temperature of the soil was 23°C, and the initial volumetric moisture content was 0.172 cm³/cm³. The dry density was 1629 kg/m³ for both specimens. The tests were initiated by circulating a liquid through

TABLE 1—*Dry densities of soil specimens.*

Parameters	Specimen Number 1	2	3	4	5	6	7
Initial ρ_{dry}, kg/m³	1446	1440	1570	1458	1507	1690	1581
Final ρ_{dry}, kg/m³	1630	1629	1735	1555	1655	1702	1550

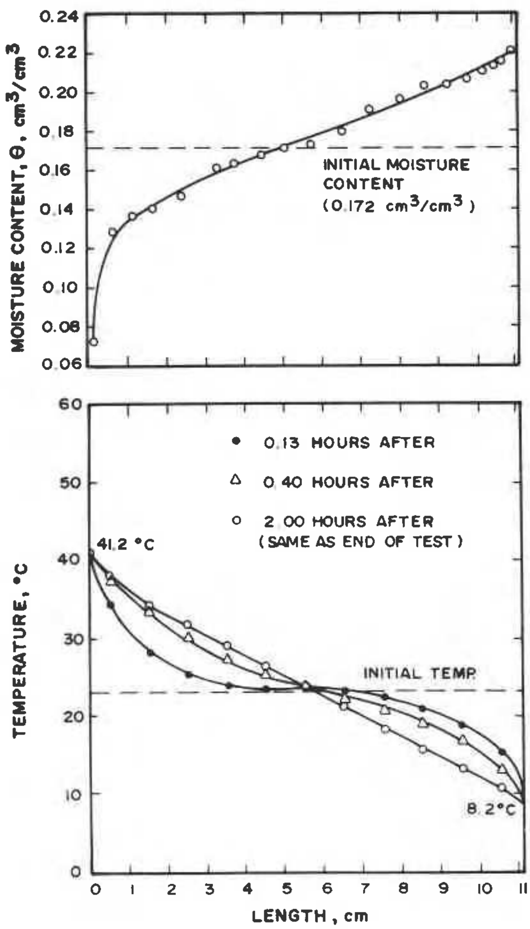

FIG. 12—*Temperature and moisture content distribution along the specimen.*

each end plate. Two temperature baths were used to keep the temperatures of the end plates at the specified values. The change in temperature of the end plates from the initial room temperature to the specified values took only a few seconds. During the tests, the temperatures at the surface of the ends of the soil specimen were kept constant with a variation less than 0.1°C. The temperature and moisture content along the specimen between the two ends, however, changed with time until a steady state was reached. In the first test, the temperatures at each end of the specimen were 8.2 and 41.2°C. In the second test, the temperatures were 26.5 and 43.0°C.

The measured steady state profiles of temperature and volumetric moisture content are shown in Figs. 12 and 13. The temperature distribution along the specimen was linear except at the ends. The steady state moisture content was reached in about two weeks. However, the temperature profile was almost at its steady state level about 1 or 2 h after the beginning of the test. This is demonstrated in Fig. 14, where the measured heat flux at the ends of the soil specimen is shown as a function of time. The temperature profile in the experiment where the temperature boundary conditions were 8.2 and 41.2°C reached the steady state in approximately 1 h, but the heat flux at the warm end was still decreasing for a number of days. This process coincided with a slow moisture transfer and further drying of a thin layer of soil next to the warm plate.

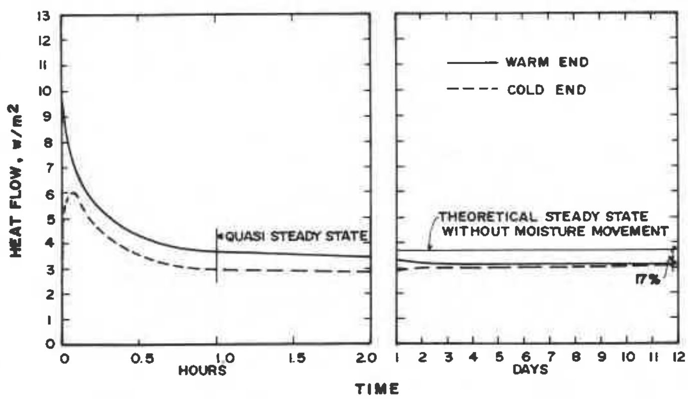

FIG. 14—*Heat flux as a function of time.*

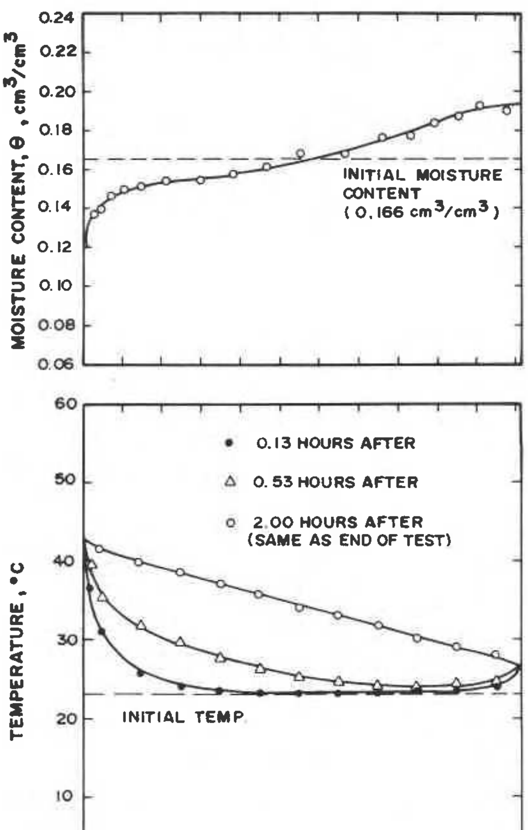

FIG. 13—*Temperature and moisture content distribution along the specimen.*

The diffusivity coefficient D_T was determined from Eq 8. Table 2 shows the values of D_T. These results are also plotted in Fig. 11 for the test with the end temperatures 8.2 and 41.2°C. The curve representing the D_T versus Θ relation showed a significant change in slope around Θ = 0.15 cm³/cm³. It can be assumed that for Θ less than 0.15 cm³/cm³, the moisture flow is mainly in vapor form. To the right of the local minimum the liquid flow is the main component of the moisture flow under the temperature gradient. The data provided in Table 2 show that the D_T values obtained from tests with two different temperature ranges differ significantly. This suggests that the transport coefficient D_T is also a function of the temperature gradient across the soil specimen. Additional tests, however, would be necessary to confirm this possibility.

Coefficient of Thermal Conductivity

The thermal conductivity measurements for the silty soil are given in Table 3. In general, the coefficient K is a function of the soil type, mineral composition, dry density, temperature range, and most importantly the moisture content. Table 3 shows, to

TABLE 2—*Coefficient of soil-water diffusivity under temperature gradients.*

θ, cm³/cm³	D_T, cm²/day · °C
TEMPERATURE DIFFERENCE, 8.2 TO 41.2°C	
0.08	0.18
0.10	0.32
0.12	0.23
0.14	0.20
0.16	0.21
0.18	0.32
0.20	0.38
0.22	0.68
TEMPERATURE DIFFERENCE, 26.5 TO 43.0°C	
0.12	0.42
0.14	0.33
0.15	0.38
0.16	0.20
0.17	0.36
0.18	0.79
0.19	0.81

TABLE 3—*Thermal conductivity of Mackenzie silt using various compositions.*

Parameters	Sample Unit			
	1	2	3	4
w,[a]%	6.0	9.7	15.4	19.9
ρ_{dry}, kg/m^3	1456	1466	1670	1674
ρ_{wet}, kg/m^3	1544	1713	1927	2005
K, W/m°K	0.72 ± 0.28%	1.20 ± 0.33%	1.58 ± 0.49%	1.60 ± 0.58%

[a]w = water content by weight.

some extent, the influence of moisture content on K. Additional experiments would be necessary if the influence of each variable on the coefficient of conductivity is required.

Discussion

The measurement of the transport coefficients presented here required a considerable time because of the difficulties encountered in the calibration of the dual gamma-ray scanner. Different methods used previously [*15*] in the geotechnical field to calibrate a dual gamma-ray scanner were not applicable in this case for the reasons explained in Ref *16*. The calibration curve shown in Fig. 7 is unique for a given scanner with a constant collimation size and a fixed distance between the source and the detector. The determination of a calibration curve takes only a few hours once the method is established.

The transport coefficients obtained at very low moisture content values may not be very accurate because of possible errors involved in the measurement of the gradient of moisture content in a narrow, very dry zone. This problem exists both in isothermal tests and thermal gradient tests. More reliable measurements of $d\Theta/dx$ can be obtained by using a narrower collimation. In the present study the collimation height was 2 mm. In all the tests, it was assumed that the moisture flow was one dimensional. During the evaporation period in an isothermal test, the soil shrinks continuously. In the present investigation, it was assumed that the soil did not shrink sufficiently to reduce its cross section and result in a gap between the soil and the container. This would invalidate the assumption of one-dimensional moisture flow. Experiments with initially saturated silts and clays would require a different test arrangement because the shrinkage would be excessive, and the soil would separate from the rigid container. A flexible membrane with negligible permeability would be more suitable, if it could follow the shrinkage of soil, to justify the assumption of one-dimensional moisture flow.

Conclusions

The main conclusions of the experimental work may be summarized as follows:

1. The relation between the transport coefficients and volumetric moisture content of a compacted Mackenzie Valley silt was similar to that of other soils tested by Refs *4,7,8,* and *11*.
2. The measurement of the transport coefficient D_T requires considerable time, about 2 to 3 weeks, because the steady state of moisture content must be attained for a given temperature gradient.
3. The use of a calibration curve accelerates the analysis of the results of a dual gamma-ray scanner, and it yields satisfactory results for the measurement of density and volumetric moisture content.
4. Future research is needed to accurately measure the volumetric moisture content gradient in soils at very low moisture content. This will in turn be used to calculate more reliable transport coefficients.

Acknowledgment

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