An Apparatus For Determination of Thermal Conductivity of Soils

by

P.L. Juneja*
S.K. Gulhati**
Alam Singh***
G. Venkatappa Rao****

Introduction

Thermal conductivity of soils is an important factor in problems relating to heat flow through soils. It has relevance in the design of submarine pipe lines, of furnaces etc. It is rarely possible to measure this property *in situ*, thus its determination either analytically or experimentally in the laboratory becomes imperative.

Heat transfer is well understood in a homogeneous single phase medium. In a heterogeneous medium like soil, however a number of heat transfer mechanisms combine in different ways and to varying degrees, thus making it complicated. Natural soils have solid, liquid and gas as their constituents. Thus in an unsaturated soil sample three heat transfer mechanisms *i.e.* conduction, convection and radiation all, will operate. In saturated soils radiation would be absent. If a liquid is heated from the top, only conduction will take place, there will be no convection. Hence a saturated soil sample when heated from the top will have only conduction, whereas if heated from bottom, it will usually have both conduction and convection. Thus, apparent conductivity of soil samples will reflect the effect of conduction and convection when heated from any direction other than the top.

Many apparatus have been designed and used to measure the thermal conductivity of soils (Penner *et. al.*, 1975, Mitchell and Kao, 1978 and Rawat *et. al*, 1982). However no single apparatus enables one to study all the factors affecting thermal conductivity *i.e.* soil type, physical state, temperature range and direction of heat flow. A new apparatus has been designed, which is versatile enough to enable one to investigate all the factors mentioned above.

This paper presents the features of this new apparatus and also presents results of tests conducted on water and soils to demonstrate the validity of measurements made, using this apparatus.

---

* Senior Scientific Officer
** Professor
**** Principal Scientific Officer,
} Civil Engineering Department, Indian Institute of Technology, Delhi New Delhi, 110016, India.

*** Professor and Head of Civil Engineering Department, M.B.M. Engineering College, Jodhpur, India.

(*This paper was received in 1984 and is open for discussion till the end of July 1985*)

The New Apparatus

Principle of the Apparatus

The apparatus designed is based on Lee's (Rajam, 1962) disc method for poor conductors. One-dimensional steady state heat flow is established in this apparatus and thermal conductivity (K) is determined from the equation,

$$\frac{dQ}{dt} = -KA\frac{d\phi}{dz} \qquad ...(1)$$

or

$$MS\frac{d\phi}{dt} = -K\frac{\pi D^2}{4}\frac{\phi_1-\phi_2}{Z} \qquad ...(2)$$

where,

M = mass of thin copper disc shown in Figure 1 (= 38.10 g),

S = specific heat of copper = 0.089 cal/g/°C,

D = diameter of specimen = 50 mm,

Z = thickness of specimen = 25 mm,

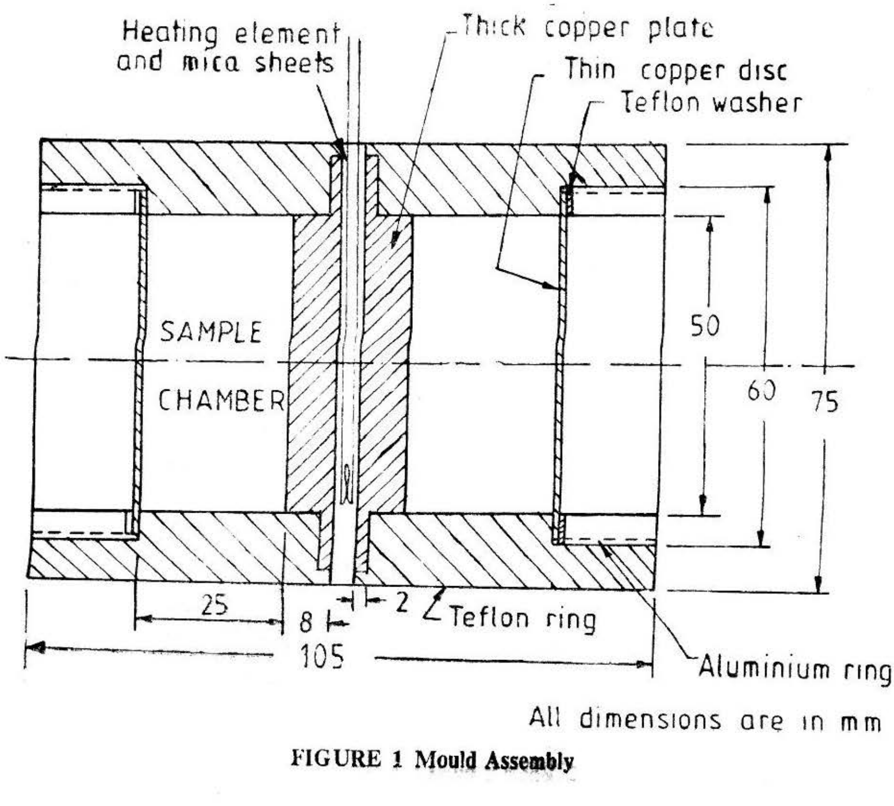

FIGURE 1 Mould Assembly

ϕ_1 = steady state temperature of thick copper plate,

ϕ_2 = steady state temperature of thin copper disc, and

$\frac{d\phi}{dt}$ = rate of cooling of thin copper disc.

Description of the Apparatus

As shown in Figure 2 the apparatus consists of four basic components:

(*i*) A mould assembly which houses two soil samples, one heating element and four thermocouples.

(*ii*) A stand to hold the mould assembly and control its orientation.

(*iii*) A stabilized voltage input and measuring unit to activate the heating element.

(*iv*) A read—out system connected to four thermocouples. Each is described below:

Mould Assembly

The assembly is symmetrical about the heating element as shown in Figure 1. Only one half of it is thus described.

Next to the heating element is placed a mica sheet to protect the element. A thick copper plate abuts the mica sheet and serves the purpose of providing a uniform heat source to the soil which is placed in the sample chamber. On the other end of the soil sample is a thin copper disc from which heat is lost to the atmosphere.

To hold the disc in place, an aluminium ring is screwed into the walls of the teflon ring. The aluminium ring is thermally insulated from the copper disc by a teflon washer. A teflon ring serves as the sample chamber

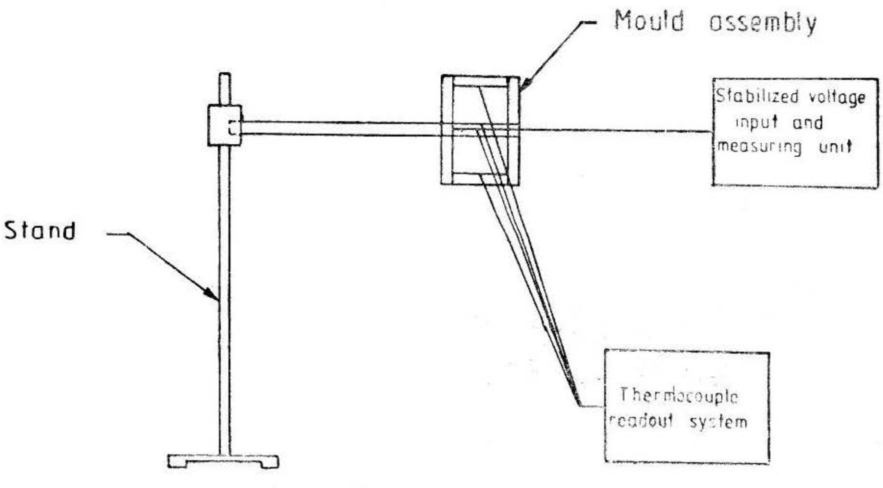

FIGURE 2 Basic Components of the Apparatus

and as seating for the thin copper disc and the aluminium ring. Thermocouples are attached to the thick copper plate and thin copper disc. Figure 3 is a photograph of the components of the mould assembly. Also shown are two cylindrical units used for sample preparation.

Mould Holding Device

The mould assembly is held in a perspex ring which in turn is attached to an ordinary laboratory stand of cast iron through a rod (See Figure 4 when the assembly is in horizontal position). The direction of heat flow can be changed by rotating this rod and thereby giving the soil sample any desired orientation. In the vertical orientation, sample in the upper chamber is heated from bottom and in the lower chamber is heated from top. Figure 5 shows the assembly in vertical orientation along with other instruments.

Stabilized Voltage Input and Measuring System

This part of the equipment comprises of, (*i*) a voltage stabilizer, (*ii*) a voltage regulator, (*iii*) a voltmeter and (*iv*) an ammeter. All these are shown in the left part of Figure 6.

Read-out Unit

Read-out unit consists of a millivoltmeter, which is connected to four copper-constanton thermocouples through a four-way switch. The voltages developed at these four thermocouples due to temperature changes are read on this meter. Using thermocouple calibration, these readings are converted to temperatures existing at the thick copper plates and at the thin copper discs. This unit is shown on the right hand side of Figure 3 which depicts the general arrangement of the instruments and working block diagram.

Operation of the Apparatus

Soil samples of any type and state are placed in the two teflon moulds.

FIGURE 3 Components of Mould Assembly

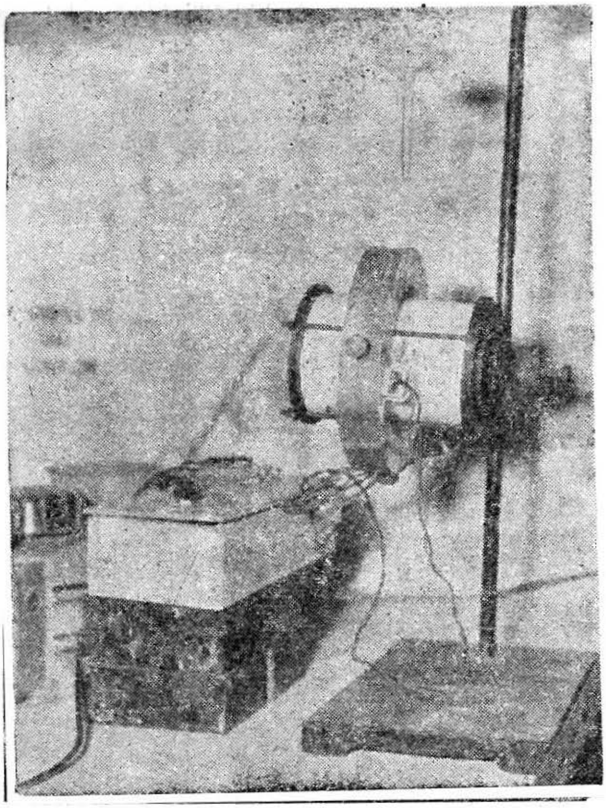

FIGURE 4 Mould Assembly in Horizontal Position

The mould is assembled and positioned in the desired orientation. The temperature of the heating element is adjusted to the required level by adjusting the voltage being supplied to the element. This can be achieved by prior calibration.

The readings at all the four thermocouples are noted in turn until steady state is attained. Usually the time required to reach steady state for temperature range of 70-80°C is about three hours.

After steady state is achieved the experiment can be terminated and the sample is used for final moisture content determination. A typical calculation of thermal conductivity is given below. The data is for the chamber filled just with water.

Steady state temperature, $\phi_1 = 71.68°C$

Steady state temperature, $\phi_2 = 47.78°C$

$$\phi_1 - \phi_2 = 23.90°C$$

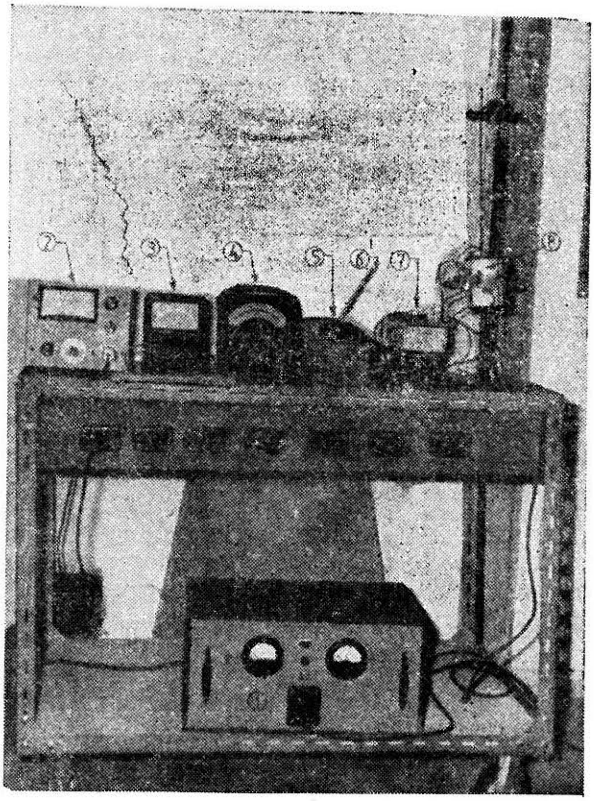

FIGURE 5 Mould Assembly in Vertical Orientation, with Other Instruments
1. Voltage Stabilizer, 2. Millivoltmeter,
3,4. Multimeters, 5. Voltage Regulator,
6. Thermometer, 7. Four-way Switch,
8. Mould Assembly.

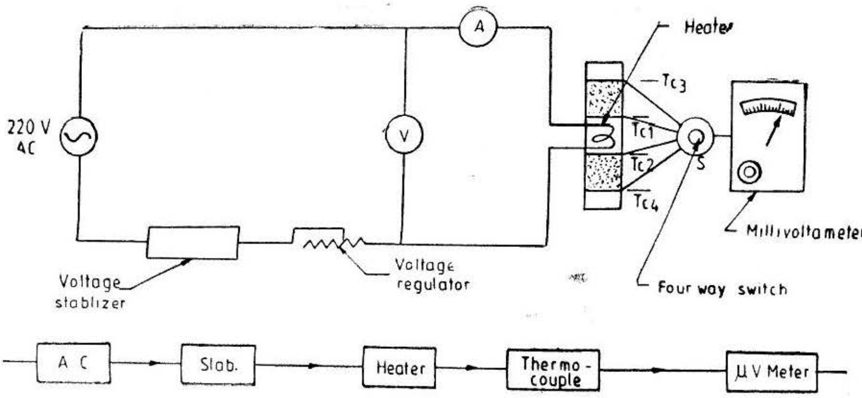

FIGURE 6 General Arrangement of Instruments

$$\left(\frac{d\phi}{dt}\right) 47.78 = 8.00 \times 10^{-2}\ ^{\circ}\mathrm{C/sec}$$

(To be read off from a calibration curve between $\frac{d\phi}{dt}$ and Temperature, in°C. The method of obtaining this calibration curve is described in the Appendix).

$$K = \frac{4\ MSZ}{\pi D^2 (\phi_1 - \phi_2)} \quad \frac{d\phi}{dt}$$

$$= \frac{4 \times 38.10 \times 0.089 \times 2.5}{\pi \times 5^2 \times 23.91} \times 8.00 \times 10^{-2}$$

$$= 1.44 \times 10^{-3}\ \mathrm{Cal/cm^2\text{-}sec\ ^{\circ}C/cm}.$$

Validation of New Apparatus

That this new apparatus gives correct and valid results, can be established by comparing the thermal conductivity values determined experimentally with those available in literature.

The validity of the results obtained for water using the new apparatus is established by looking at Table-1. From this table it is clear that the experimental value is in close agreement with values quoted in literature.

TABLE 1

Thermal Conductivity of Water, Heated from Top

Sl. No.	Source	Temperature °C	Thermal conductivity of water, cal/cm²—sec °C/cm
1.	Mitchell and Kao (1978)	—	1.41×10^{-3}
2. (*i*)		0	1.32×10^{-3}
(*ii*)	Ingersoll et. al. (1969)	80	1.64×10^{-3}
(*iii*)		average	1.43×10^{-3}
3.	IIT Delhi (1979)	average	1.43×10^{-3}
4.	From experiments conducted with new apparatus.	70	1.44×10^{-3}

Some Results Obtained For Soils Using The New Apparatus

The apparatus designed has been used to determine thermal conductivity of six soils: four sands and two clays. See Tables 2 and 3. The experiments have been conducted with heating element heated to 70°C by positioning the assembly in two orientations horizontal and vertical. The latter orientation provides results for soil which is heated from bottom as well as for soil which is heated from top. Each soil was tested at more than one initial moisture content. The complete experimental programme is given in Table 4.

TABLE 2

Classification Properties of Sands

Sl. No.	Soil	Sand %	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	G_s	Coefficient of curvature $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$	Coefficient of uniformity $C_u = D_{60}/D_{10}$	Remarks
1.	Badarpur Sand	100	0.31	0.45	0.62	2.65	1.05	2.00	Angular, oxidized quartzite quarried sand.
2.	Jamuna Sand	100	0.13	0.18	0.22	2.65	1.13	1.69	Micaceous river sand.
3.	Dune Sand	100	0.11	0.14	0.17	2.66	1.06	1.55	Wind blown deposit.
4.	Lakshdweep Sand	100	0.18	0.21	0.21	2.65	1.14	1.39	Consisting of corraline debris with intraparticle voids. Chemically 100% $CaCo_3$.

TABLE 3

Physical Properties of Clays

Soil	Sand %	Silt %	Clay %	LL	PL	PI
Bentonite	0	0	100	410	60	350
Kaolinite	0	0	100	41	26	15

TABLE 4

Experimental Programme

Soil / Moisture Content & orientation	Four Sands	Two Clays
Moisture Content	2	4
Two Orientations leading to three heating positions	3	3
Total experiments	24	24
Grand Total	48	

Thermal conductivity values for samples being heated from top have been designated as K_T and values for samples being heated from bottom as K_B. K_H represents the thermal conductivity of samples heated horizontally. The results of tests on sands are tabulated in Table 5 and those of clay are presented in Table 6.

That the values obtained from the new apparatus are reproducible is established by the fact that K_H values are the same for the two samples in the two different chambers of the mould on either side of the heating element (See Tables 5 and 6).

That the results obtained for soils are also valid is demonstrated in Figure 7 by comparing them to the values estimated using Kersten's (1969) empirical relations. Experimental values by and large fall within $\pm$ 25% which is the accuracy of Kersten's relationship.

Confining oneself to K_T values one can make the following observations :

(*i*) The thermal conductivity of sands with high quartz content is high

TABLE 5

Thermal Conductivity Values for Coarse Grained Soils

SOIL TYPE	Dry density γ_d, (g/cm^3)	Moisture content, *w* %	Thermal Conductivity '*K*' in c.g.s. units cal/cm^2—sec °c/cm				K_B/K_T	K_H/K_T
			K_B	K_T	K_H			
					L.H.S. Mould	R.H.S. Mould		
Badarpur Sand	1.44	0	7.92×10^{-4}	4.86×10^{-4}	6.55×10^{-4}	6.55×10^{-4}	1.63	1.34
	1.44	31.0	4.13×10^{-3}	2.81×10^{-3}	3.29×10^{-3}	3.29×10^{-3}	1.47	1.17
Jamuna Sand	1.44	0	7.19×10^{-4}	4.90×10^{-4}	4.24×10^{-4}	4.24×10^{-4}	1.46	0.87
	1.44	29.0	2.98×10^{-4}	1.78×10^{-3}	4.11×10^{-3}	4.11×10^{-3}	1.67	2.30
Dune Sand	1.61	0	7.82×10^{-4}	6.43×10^{-4}	4.58×10^{-3}	4.58×10^{-4}	1.22	0.71
	1.61	23.0	3.44×10^{-3}	3.22×10^{-3}	3.22×10^{-3}	3.22×10^{-3}	1.06	1.00
Lakshdweep Sand	1.49	0	5.92×10^{-4}	2.92×10^{-4}	3.66×10^{-4}	3.66×10^{-4}	2.02	1.25
	1.49	31.0	2.08×10^{-3}	1.31×10^{-3}	2.35×10^{-3}	2.35×10^{-3}	1.58	1.79

TABLE 6

Thermal Conductivity Values for Fine Grained Soils

Soil Type	Dry density γ_d, (g/cm³)	Moisture content, *w* %	Thermal Conductivity '*K*' in c.g.s. units cal/cm²–sec °c/cm				K_B/K_T	K_H/K_T
			K_B	K_T	K_H			
					L.H.S. Mould	R.H.S. Mould		
Bentonite	1.36	0	9.05×10^{-3}	4.13×10^{-4}	5.87×10^{-4}	5.87×10^{-4}	2.19	1.42
	1.05	31.5	2.97×10^{-3}	1.97×10^{-3}	2.79×10^{-3}	2.79×10^{-3}	1.51	1.42
	0.78	91.6	2.30×10^{-3}	1.39×10^{-3}	1.90×10^{-3}	1.90×10^{-3}	1.65	1.37
	0.115	319.5	1.72×10^{-3}	0.82×10^{-3}	1.40×10^{-3}	1.40×10^{-3}	2.09	1.71
Kaolinite	0.93	0	6.13×10^{-4}	3.13×10^{-4}	8.39×10^{-4}	8.39×10^{-4}	1.95	2.85
	1.36	19.2	4.24×10^{-3}	3.23×10^{-3}	5.24×10^{-3}	5.24×10^{-3}	1.31	1.62
	1.36	34.7	2.65×10^{-3}	4.14×10^{-3}	2.62×10^{-3}	2.62×10^{-3}	0.64	0.63
	0.36	232.0	1.23×10^{-3}	1.67×10^{-3}	3.22×10^{-3}	3.22×10^{-3}	0.74	1.93

as has been noted before by Randkivi and Nguyen (1976). Badarpur sand has the highest quartz content followed by Jamuna sand and Lakshdweep sand has no quartz content. Dune sand is not considered herein because its density is not comparable with the density of the other three sands (Table 5).

(*ii*) Thermal conductivity is observed to decrease with decreasing size of particles. Badarpur sand is the coarsest and Lakshdweep the finest. This observation is consistent with the work reported by Polton* (1909) as quoted by Rooyan and Winterkorn (1957) and Hamilton and Crosser (1962).

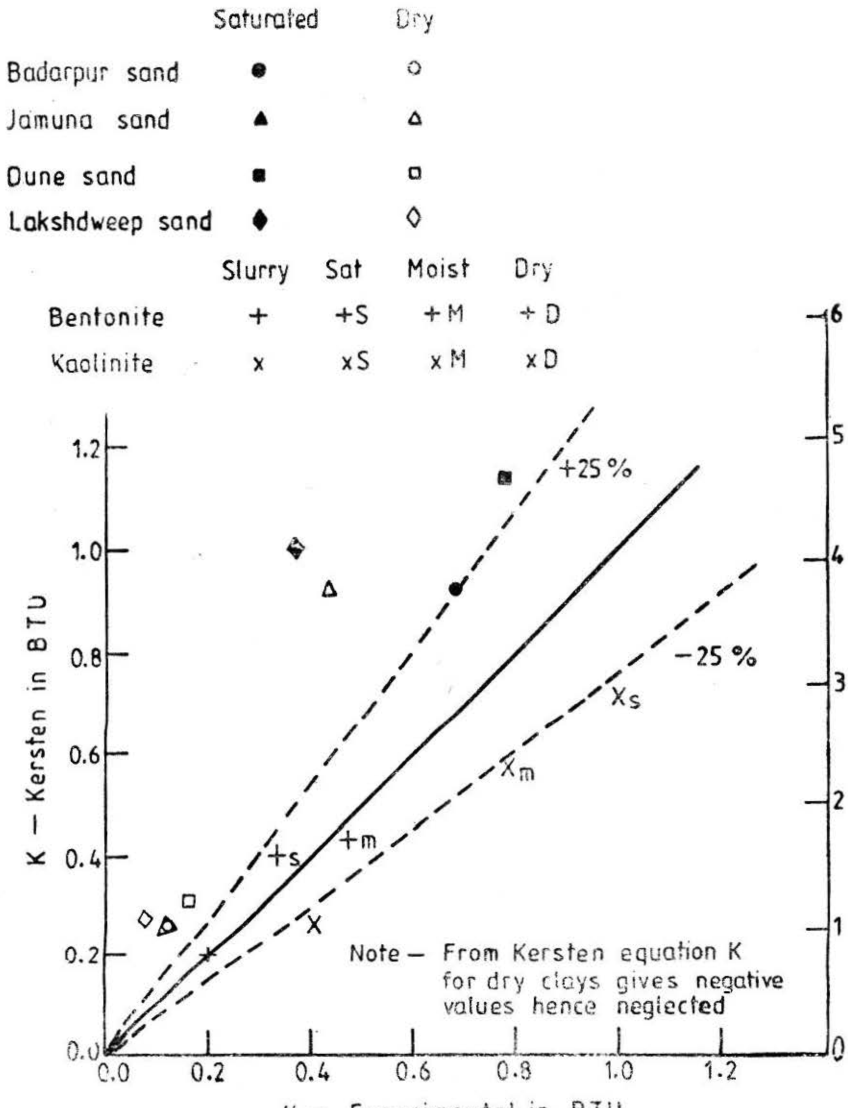

FIGURE 7 Comparison of K-Kersten and K-Experimental

(*iii*) Thermal conductivity is high for moist and saturated samples in comparison to the values for dry samples. This is readily understood when one notes that the thermal conductivity of water is about 20 times than that of air.

(*iv*) In clays, thermal conductivity is observed to increase with moisture content and there-after the thermal conductivity reduces gradually as moisture content increases at 100% saturation to approach the value of thermal conductivity of water (see Figure 8). Similar observations have been made by Kersten (1949), Kalyasev and Gupelo (1958) and by Rawat et. al (1982).

Versatility of New Apparatus

As has been pointed out before, the new apparatus is versatile in that it enables measurement of thermal conductivity of soils in different states at different temperature ranges and in different orientations. Only the latter aspect is discussed below.

In Figure 7 the values of thermal conductivity determined by top heating have already been shown to be consistent with values normally associated with soils. Columns 4 and 5 of Tables 5 and 6 show that the values of thermal conductivity obtained by bottom heating are more than those obtained from top heating. The ratio K_B/K_T is thus always greater than 1.0 with minor exceptions. This is to be anticipated since bottom heating will not only induce conduction but also convection. The ratio K_B/K_T is greater than unity even when soil is dry, when heat movement by convection is not relevant. One can explain this tentative observation only in terms of possible density currents which may by established in dry soils.

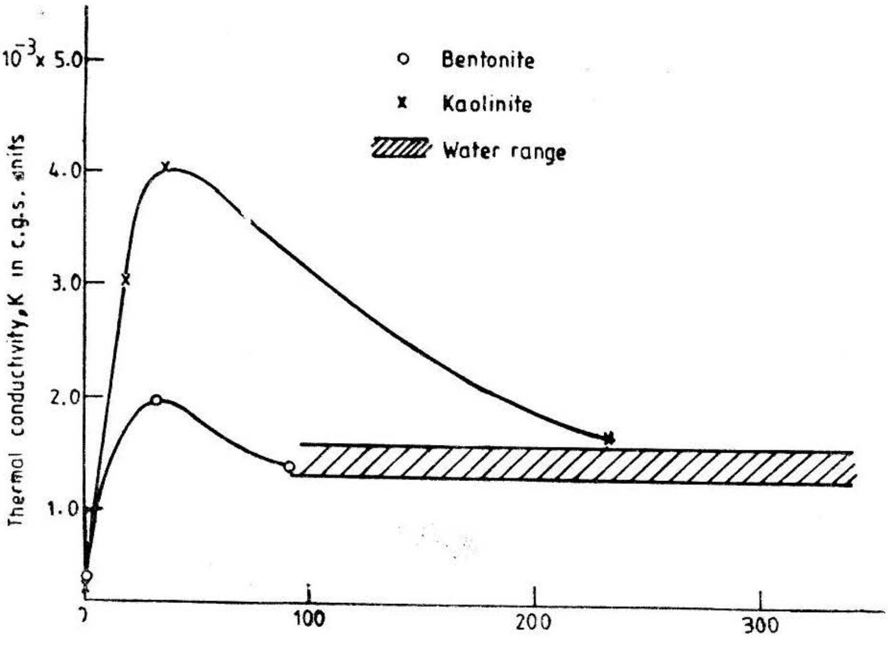

FIGURE 8 Variation of Thermal Conductivity with Varying Moisture Content

K_H/K_T values are also normally more than unity indicating that heat transfer mechanisms other than just conduction are also operative.

One thus observes that the newly designed apparatus described herein provides valid measurements of thermal conductivity. The apparatus gives reproducible results and is versatile enough to enable one to conduct a detailed study of problems affecting heat flow in soils.

Appendix

Calibration Curve Between $\frac{d\phi}{dt}$ and Temperature, ϕ

For the calculation of thermal conductivity by steady state method, one needs the plot of cooling curves i. e. temperature ϕ of the thin copper disc v/s the rate of cooling $\frac{d\phi}{dt}$ of the thin copper disc. Three cooling curves have been drawn for two orientations of the mould assembly,

(*i*) for assembly in horizontal position,

(*ii*) for assembly in vertical position noting the cooling of top thin copper disc, and

(*iii*) for assembly in vertical position noting the cooling of bottom thin copper disc.

The calibration procedure for all the three was identical. It consisted of heating the thin copper disc to a temperature about 20° higher than that required during actual experimentation without placing any sample in the mould and then allowing the assembly to cool and observing the drop in temperature versus time of the thin copper disc. From this data a plot between temperature and time is drawn as shown in Figure 9.

To obtain the relation between $\frac{d\theta}{dt}$ and temperature θ, tangents are drawn at different points on this curve for different values of temperature e.g. at 10°, 20°, 30°, 40°, 50°, 60° and 70° etc. Slope of these tangents is determined and then $(d\theta/dt)$ values are plotted against the temperature (room temperature $\times$ temperature read) corresponding to each tangent. Such a plot for the mould assembly in horizontal position (room temperature 25°C) is presented in Figure 10. Similar plots are obtained for the cooling curve for top and bottom discs in vertical orientatation of the mould,

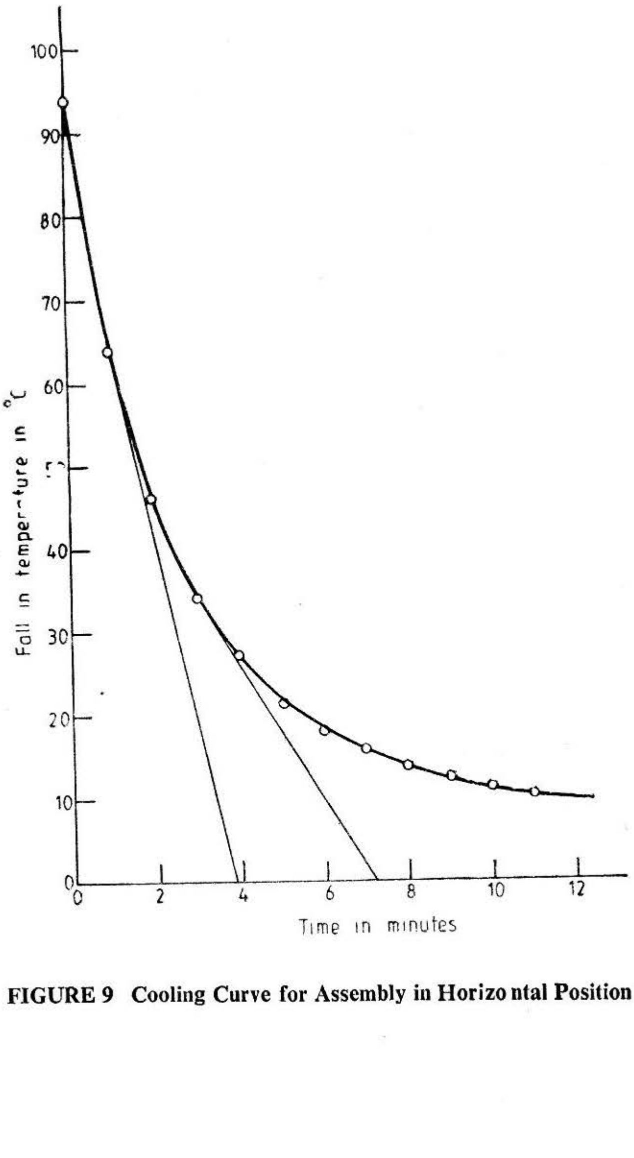

FIGURE 9 Cooling Curve for Assembly in Horizontal Position

References

HAMILTON, R.L. and CROSSER, O.K. (1962), "Thermal Conductivity of Heterogeneous Two Component Systems". *Ind. and Engg. Chem.* I. 3: 187-191.

IIT DELHI REPORT, (1979) : "*Determination of Thermal Conductivity of Soils*", Soil Engg. Div. Civil Engg. Deptt., IIT, New Delhi.

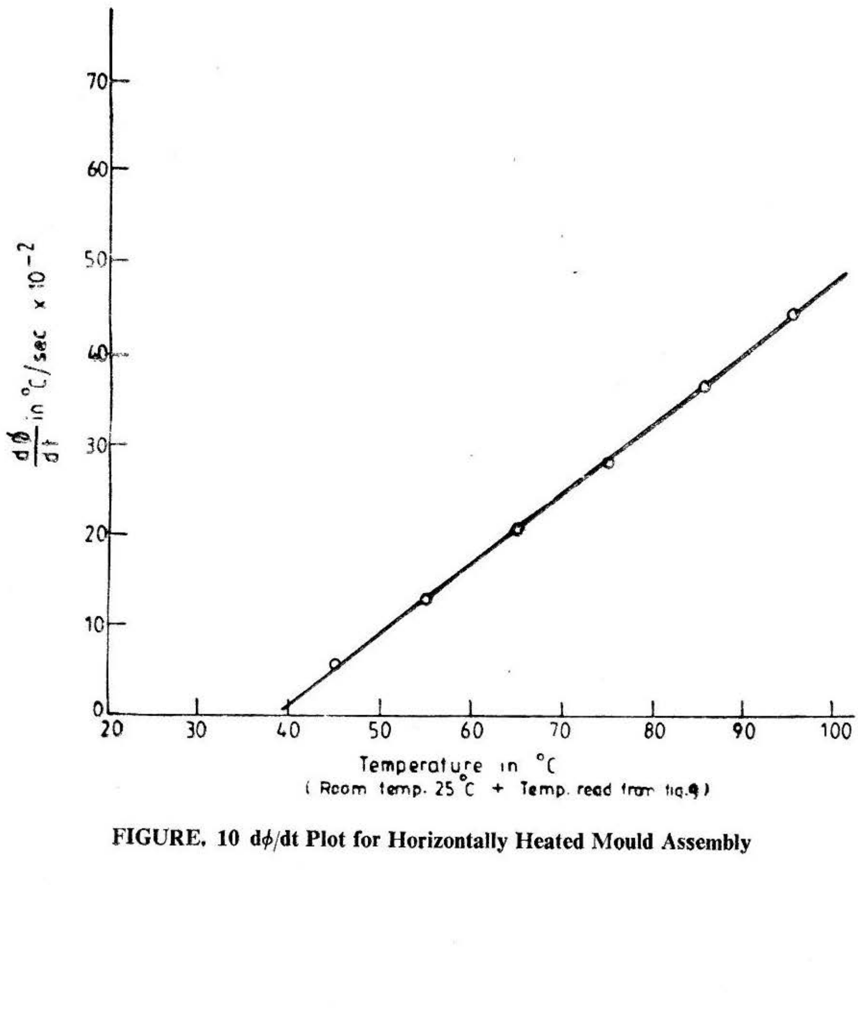

FIGURE. 10 dφ/dt Plot for Horizontally Heated Mould Assembly

INGERSOLL, L.R., ZOBEL, O.J. and INGERSOLL, A.C., (1969) "*Heat Conductivity with Engineering Geology and Other Applications*". Oxford & IBH Publishing Co., New Delhi.

KALYASEV, F.E. and GUPELO, A.I. (1958) : "On the Correlation Between Heat and Moisture Properties of Soils", *Highway Research Board*, Special Report 40. Washington, pp. 106-112.

KERSTEN, M.S. (1969) : "Thermal Properties of Soils", *Bulletin 28, Engg. Exp. Station*, Univ. of Minnesota, U.S.A.

MITCHELL, J.K. and KAO, T.C. (1978). "Measurements of Soil Thermal Resistivity", *J. of Geotech Engg* Div., *Proc ASCE*, 104 : GT 1O : 1237-1320.

PENNER, E., JOHNSTON, G.N. and GOODRICH, L.E. (1975) : "Thermal Conductivity Laboratory Studies of some Mackenzie Highway Soils". *J Canadian Geotech*., 12 : 3 : 271-288.

RAJAM, J.B. (1962) : "*A Text Book of* ***Heat***", S. Chand & Co., New Delhi.

RANDIKIVI, A.J. and NGUYEN, V.U. (1976) : "Soil Moisture Movement", *J. of Geotech. Engg*. Div, Proc ASCE, 102 : GT 12 : 1225-1244.

RAWAT, P.C., AGARWAL, S.L., MALHOTRA, A.K., GULHATI, S.K. and RAO, G.V. (1982) ; "Determination of Thermal Conductivity of Soils—A Need for Computing Heat Loss through Buried Submarine Pipelines". *Society of Petroleum Engineers* J., 22 : 4 : 558-562.

ROOYEN, M.V. and WINTERKORN, H.P. (1957) : "Theoretical and Practical Aspect of Thermal Conductivity of Soils and Similar Granular Systems", *Highway Researeh Board*, Bulletin 168, pp. 143-205.