Study of Thermal Conductivity of Soils for Varying Density & Water Content Profiles

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Abstract. In Analytical *Theory of Heat*, 1822 Joseph Fourier stated, “The problem of terrestrial temperatures presents one of the most beautiful applications of the theory of heat.” The experimental schedule is planned so as to study a wide variety of artificially mixed soil using naturally available single component soils i.e. sand, silt and single mineral clay (kaolinite) to remove heterogeneity due to variation of various minerals in naturally occurring soils for the thermal conductivity as measured in laboratory set-up, on the basis of physical properties of the soil. The objectives of this investigation of the thermal conductivity of soils are to employ the thermal probe method to obtain reliable thermal conductivity data for different local natural soils. For evaluating the radial flow of the heat, the soil is compacted in porcelain pipes. It has thermocouple controlled vertical heater rod placed at the center as source and 20 thermocouples placed radially in four directions perpendicular in plan for temperature profile readings. The second setup fabricated in house was aimed at studying the flow of thermal energy in longitudinal direction as well as with depth for which a rectangular steel tank was fabricated. The heat source was placed at one end of the tank whereas the thermocouples were placed all along the length and a second row placed at different depths along the length. The influence of soil properties such as water content, dry density and porosity on thermal conductivity is also observed.

Keywords: thermal conductivity, thermocouple, kaolinite.

1 Introduction

In 1822 Joseph Fourier stated that the theory of heat will always attract the attention of mathematicians, by the rigorous exactness of its elements and the analytical difficulties peculiar to it, and above all by the extent and usefulness of its applications; for all its consequences concern at the same time general physics, the operations of the arts, domestic uses and civil economy. The migration of heat in porous media has attracted attention of the research fraternity, since almost a century. Studies conducted in the past reveal that heat migration in a medium primarily depends on its thermal resistivity (defined as the ability of the material to resist heat flow in it), its specific heat (defined as the ability of the material to store heat) and thermal diffusivity (which combines the transmission and storage properties of the material and is an indicative of the rate of change of temperature within the material).Soil thermal properties are of great importance in many engineering projects and other situations where heat transfer takes place in the soil. For example, they are of great importance in the design of roads, airfields, pipelines or buildings in cold regions as well as underground power cables, hot water pipes or cold gas pipelines in unfrozen ground. They are also important in such fields as agriculture, meteorology and geology. Furthermore, soil-water interaction and soil microstructure are important to the renewed focus on the fundamentals of soil behavior.

1.1 Literature Review

Folaranmi et al (2009) studied the effect of additives namely ashes and sawdust on the thermal conductivity of clay collected from a deposit with no moisture content. For average clay, the thermal conductivity is 0.25 W/m K for no moisture, about 1.0 W/m K for 10% clay moisture (% by volume), 1.25 W/m K at 14%, 1.67 W/m K at 30% and about 2.0 W/m K at 50 %. Tien et al(2005) , Chu et al(2005), Chuang et al(2005), studied that in the Thermal-Hydraulic-Mechanical environment, the thermal conductivity varies due to the change in clay density, the water content, and the volumetric fraction of sand or crushed granite. The result of thermal conductivity of pure bentonite with different dry density and different water content showed that the thermal conductivity rises while water content increases. Abu-Hamdeh et al (2000), and Reeder et al (2000) carried out laboratory experiments using the single probe method to determine thermal conductivity. The soils used were classified as sand, sandy loam, loam, and clay loam along with two salts NaCl and $CaCl_2$. Thermal conductivity ranged from 0.58 to 1.94 for sand, from 0.19 to 1.12 for sandy loam, from 0.29 to 0.76 for loam, and from 0.36 0.69 W/m K for clay loam at densities from 1.23 to 1.59 g cm^{-3} and water contents from 1.4 to 21.2%. Nusier et al(2003), Abu-Hamdeh et al (2003) found out thermal conductivity of two soils, investigated through laboratory studies. The soils used were classified as sand and loam. Thermal conductivity measured using single probe method ranged from 0.95 to 2.11 for sand and from 0.49 to 0.76 W/m K for loam. Thermal conductivity measured using dual probe method ranged from 0.98 to 2.17 for sand and from 0.51 to 0.78 W/m K for loam. Shah et al(1993), Shroff et al(1993) and Naik et al (1993) studied the physical, engineering and electrical properties of different soils are discussed in this paper. A series of experimental for determination of resistivity, dielectric constants and unconfined compressive strength of different types of soils (CH, CL, CI and ML) at various densities and moisture content were performed in the laboratory. From the analysis of experimental results, it is observed that the resistivity value decreases with increases of dry density and moisture content. Resistivity value decreases with increases of unconfined compressive strength.

2 Material

The present study was carried out on artificially prepared/ mixed soil using naturally available single component soils i.e. sand, silt and single mineral clay to remove heterogeneity due to variation of various minerals in naturally occurring soils. Sand used for the study was collected from Bhadarpur, Gujarat and washed to free it from any silt and clay content. This was then dried and used for the study further. Silt, component for the study was collected from the college campus and sieved to pass through 75micron sieve and all organic matter removed. The soil was then put into suspension form to remove the clay content. The single mineral clay, kaolinite was procured from the commercial market and used directly for the study. The various mix proportions studied are tabulated below in Table-1.

Table 1. Mix Proportions

Mix	Sand	Silt	Clay
1	60%	20%	20%
2	50%	20%	30%
3	40%	20%	40%

Basic physical and engineering properties for each of the mix were determined as per India Standard specifications. The properties found are: specific gravity, grain size distribution, liquid and plastic limit, maximum dry density (*MDD*) and optimum moisture content *(OMC)*, shear strength parameters at 95% *MDD* on the wet side of *OMC* as tabulated in Table-2.

Table 2. Properties of soil

Mix		1	2	3
MDD (g/cc)		1.96	1.88	1.8
OMC (%)		9.4	12.4	15.8
Specific Gravity, G_s		2.51	2.68	2.54
Liquid limit, *L.L.* (%)		27.46	36.3	42.58
Plastic limit, *P.L.* (%)		15.22	20.28	20.83
Plasticity Index, *PI* (%)		12.24	16.02	21.75
Grain Size	% Gravel	0.27	0.5	0.73
	% Sand	60	49.2	40
	% Silt & Clay	39.73	49.5	59.27
IS Soil Classification		CL	CI	CI
Cohesion, C (g/cm^2)		0.1	0.13	0.15
Angle of internal friction		22	20	24

2.1 Thermocouple

Laboratory measurements typically employ a 150 mm long, 10 mm diameter stainless steel thermal heater and a 5 mm diameter, 160 mm long stainless steel thermocouple, which are both electrically isolated from the stainless steel (Shown in Figure 1 and

Figure 2). Stainless steel thermal heater and steel thermocouple is combined to form a new modified thermocouple controlled heater rod as shown in Figure 3. This new thermocouple is prepared so that maximum surface area is obtained.

2.2 Thermal Conductivity Measured Radially

The soil is compacted in porcelain pipes having an internal diameter of 20.32 cm (8 inch) with a height of 30 cm, with the soil being filled up to a height of 25 cm only. It is covered with acrylic sheet from bottom. It has thermocouple controlled vertical heater rod placed at the center as source and 20 thermocouples placed radially in four directions perpendicular in plan for temperature profile readings as shown in Figure 4. The sample is placed in a porcelain pipe container and compacted at density 95% OMC on the wet side. The heat is supplied to the thermocouple till its temperature reaches 70°C and left for 5 mins. Then the temperature distribution is noted from the 20 thermocouples for an hour.

Fig. 1. Heater

Fig. 2. Thermocouple

Fig. 3. Modified thermocouple controlled heater rod

Fig. 4. Experimental setup

2.3 Thermal Conductivity Measured Longitudinally

The soil sample is filled in a rectangular stainless steel tank having length 76.2 cm, height 30.48 cm and width 17.78 cm. This tank is kept in another tank as shown in Figure 5. Sawdust was spread at the bottom of the steel tank and all sides are covered with cerra-wool for thermal insulation. The soil is compacted with the fabricated hammer till density 95% of OMC on the wet side is achieved required depth (25 cm) is obtained. The heat source was placed at one end of the tank whereas 15 thermocouples were placed all along the length and a second row of 5 thermocouples placed at different depths along the length as shown in Figure 6. The heat is applied till the temperature of the thermocouple reaches 70°C and left for 5 mins.

Fig. 5. Steel tank is kept within this tank for insulation

Fig. 6. Experimental setup

3 Results

3.1 Radial Experiment

MIX-1

The graphs plotted below shows the temperature variation with respect to time. The minimum temperature reached is 21.61°C at 0 seconds and the maximum temperature obtained is 74.24°C at 480 seconds.

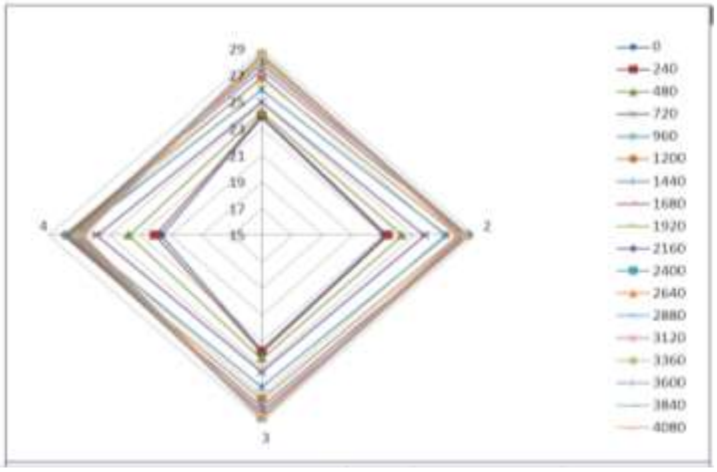

Fig. 7. Temperature v/s Time (Mix 1)

MIX-2

The graphs plotted below shows the temperature variation with respect to time. The minimum temperature reached is 21.98°C at 0 seconds and the maximum temperature obtained is 81.25°C at 480 seconds.

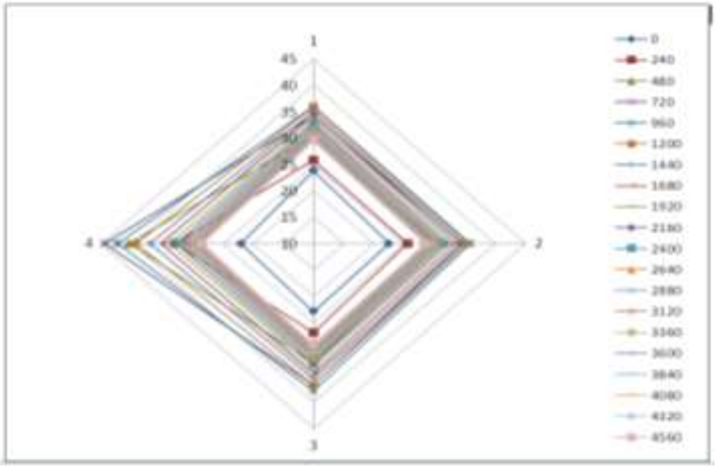

Fig. 8. Temperature v/s Time (Mix 2)

MIX-3

The graphs plotted below shows the temperature variation with respect to time. The minimum temperature reached is 23.2°C at 0 seconds and the maximum temperature obtained is 45.73°C at 1200 seconds

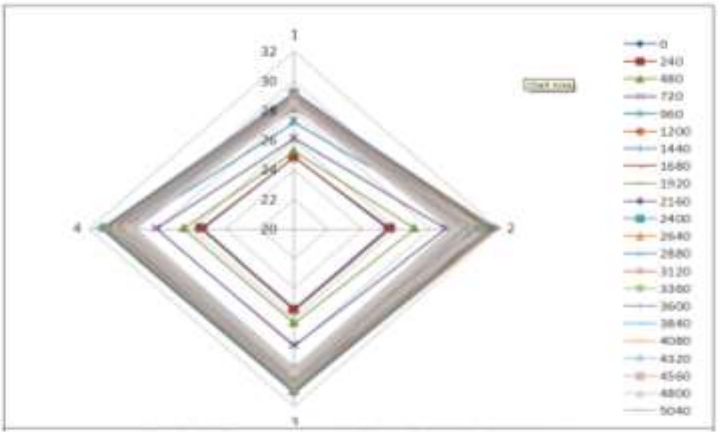

Fig. 9. Temperature v/s Time (Mix 3)

The coloring lines in the above graphs indicate the temperature variations from the 20 thermocouples placed radially in four directions perpendicular in plan (figure 4) with respect to time. From the above graph it is observed that temperature distribution is almost same in all the directions. When the sand content increases, the thermal conductivity of such soil shall increase with increase in moisture content. The reason for this is that as air is replaced by water (which has thermal conductivity 22 times higher than air) the thermal conductivity of the soil increases as a whole. This same reason is responsible for soils with higher clay content showing higher conductivity with no apparent decrease in the value with time since the clay mineral can hold onto water better as compared to sand which in case the water content increase more than its holding capacity shall readily drain off the water. The results of thermal conductivity of radial arrangement was calculated using Johanson's model(1975) , as shown in Table-3.

$$\rho_w = 1 \quad q = 0.4 \quad \lambda_0 = 2 \quad \lambda_w = 0.59 \quad \lambda_q = 7.7 \quad \lambda_s = 3.43 \tag{1}$$

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \qquad \lambda_{sat} = \lambda_s^{1-n} \times \lambda_w^n \qquad \lambda_s = \lambda_q^q \times \lambda_0^{1-q} \tag{2}$$

$$n = \frac{1-\rho_d}{G\rho_w} \qquad \lambda_{dry} = \frac{(0.135\rho_b + 64.7)}{(2700 - 0.947\rho_b)} \tag{3}$$

Table 3. Radial method calculation

Mix		1	2	3
ρ_d	g/cc	1.86	1.78	1.71
G		2.51	2.51	2.68
n		0.258	0.332	0.327
w	%	13.6	12.2	15.59
e		0.348	0.498	0.485
S_r	%	98.14	65.7	81.59
Soil	Kg	14.73	13.6	13.53
Water	Ml	2	1.66	2.11
Volume	cu.m	0.0079	0.0076	0.0079
ρ_b	kg/cu.m	2115.02	2007.37	1976.87
λ_{dry}	W/mK	0.5	0.42	0.4
λsat	W/mK	2.18	1.92	1.93
Ke	W/mK	0.00458	0.00367	0.00494
λ	W/mK	0.51	0.426	0.408

Where, ρ_d= dry density of soil, G= specific gravity, w= water content, e= void ratio, K_e = Kersten number, λ_{dry} and λ_{sat} = thermal conductivity of dry and saturated soils ($Wm^{-1}K^{-1}$) respectively, Sr= normalized soil water content (Sr = θ/θ_s), where θs is the saturated water content, λ_w= thermal conductivity of water($Wm^{-1}K^{-1}$), n= soil porosity, λ_s= effective thermal conductivity of soil solids($Wm^{-1}K^{-1}$), *q*= quartz content of the total solids content , λ_q= thermal conductivities of quartz ($Wm^{-1}K^{-1}$), λ_o= thermal conductivities of other minerals($Wm^{-1}K^{-1}$), ρ_b = the bulk density of soil (kg m^{-3}), λ= thermal conductivity of soil from radial test($Wm^{-1}K^{-1}$)

3.2 Longitudinal Experiment

The temperature variation with respect to time is then noted for an hour along the length and depth.

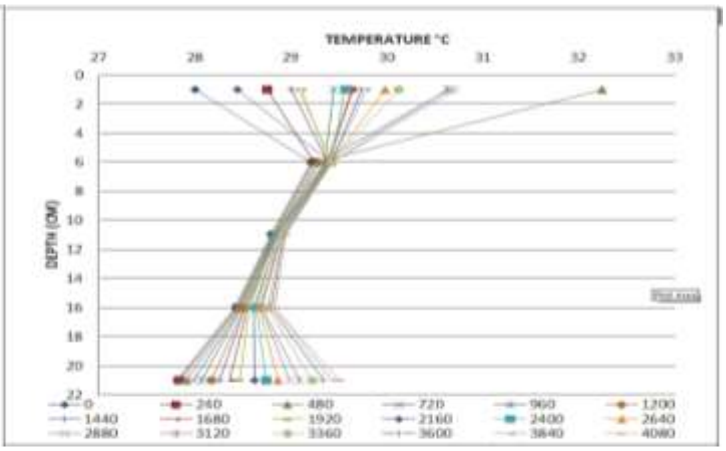

Fig. 10. Temperature v/s Depth (Mix 1)

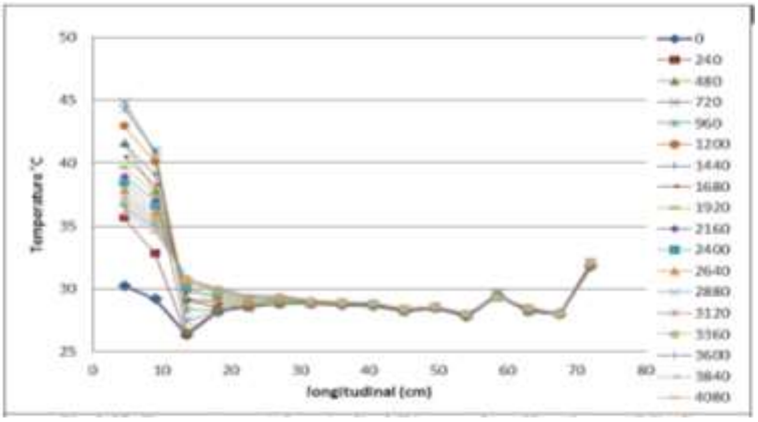

Fig.11 Temperature v/s Longitudinal Distance from Heat Source (Mix 1)

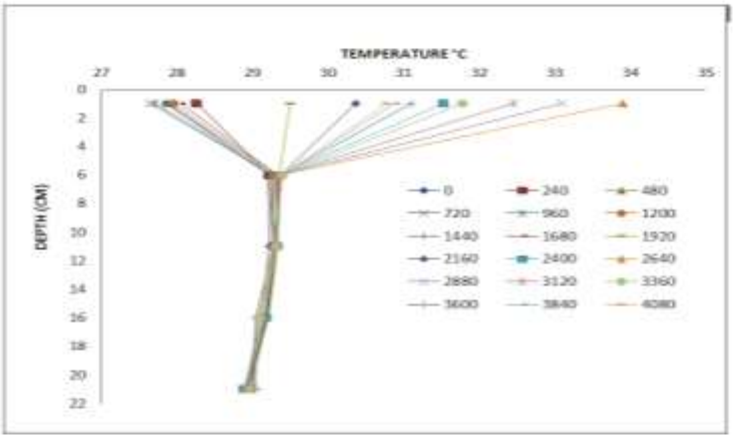

Fig. 12. Temperature v/s Depth (Mix 2)

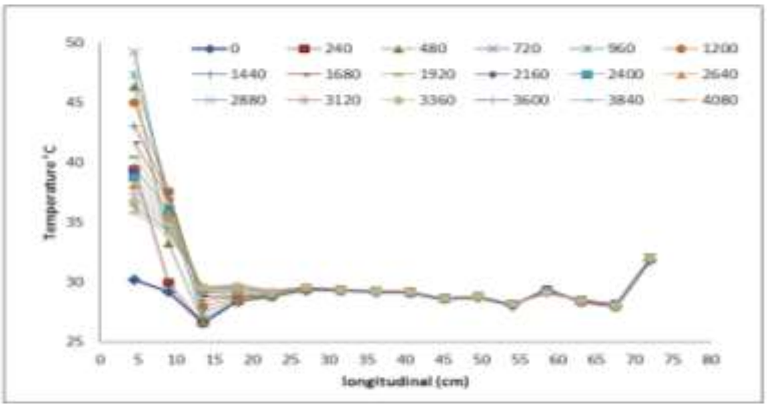

Fig. 13. Temperature v/s Longitudinal Distance from Heat Source (Mix 2)

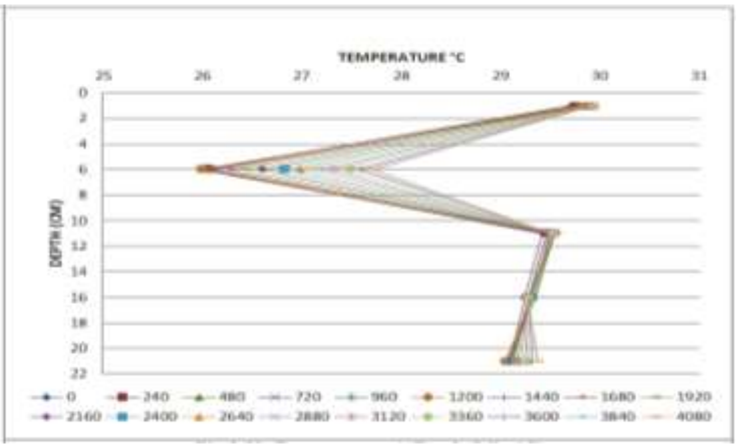

Fig. 14. Temperature v/s Depth (Mix 3)

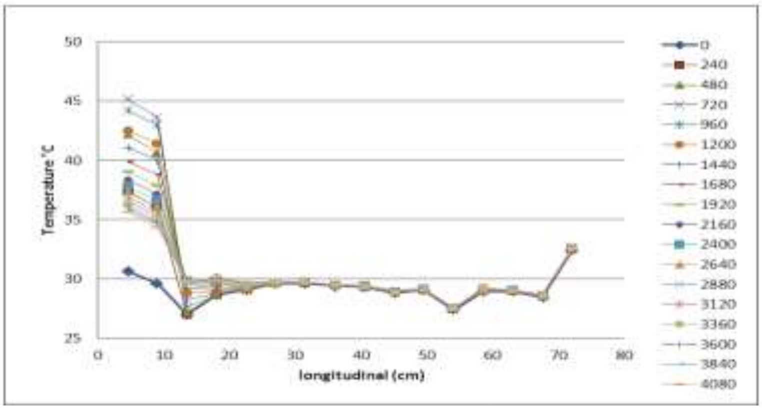

Fig.15 Temperature v/s Longitudinal Distance from Heat Source (Mix 3)

The variation of the temperature with the increase in the longitudinal distance is plotted. It is observed that at the distance near to the heat source, temperature is more. As the distance increases from the heat source, temperature decreases. Hence the soil temperature is almost equal to the room temperature as distance increases from the source. Since the present setup could not be used to estimate the change in moisture content with respect to the applied thermal flux, neither could the soil water flux measurements be made. The temperature variation almost remains constant at greater depth. The results of thermal conductivity of longitudinal arrangement was then calculated using Johanson's model (1975), as shown in Table-4

Table 4. Longitudinal method cal culation

Mix		1	2	3
ρ_d	g/cc	1.86	1.78	1.71
G		2.51	2.68	2.54
λ_0	W/mK	13.6	12.2	15.57
w	%	35	51	49
e		0.26	0.34	0.33
S_r	%	98.17	64.32	80.29
Soil	kg	60.49	58	56
Water	kg	7.38	9.03	9.79
ρ_b	kg/cu.m	2003.93	1979.19	1942.66
λ_{dry}	W/mK	0.42	0.4	0.38
λsat	W/mK	2.18	1.9	1.93
Ke	W/mK	0.00458	0.00367	0.00494
λ	W/mK	0.42	0.4	0.38

Where, ρ_d= dry density of soil, G= specific gravity, w= water content, e= void ratio, K_e = Kersten number, λ_{dry} and λ_{sat} = thermal conductivity of dry and saturated soils ($Wm^{-1}K^{-1}$) respectively, Sr= normalized soil water content ($Sr = \theta/\theta_s$), where θs is the saturated water content, λ_w= thermal conductivity of water($Wm^{-1}K^{-1}$), n= soil porosity, λ_s= effective thermal conductivity of soil solids($Wm^{-1}K^{-1}$), *q*= quartz content of the total solids content , λ_q= thermal conductivities of quartz ($Wm^{-1}K^{-1}$), λ_o= thermal conductivities of other minerals($Wm^{-1}K^{-1}$), ρ_b = the bulk density of soil (kg m^{-3}), λ= thermal conductivity of soil from longitudinal test($Wm^{-1}K^{-1}$)

$$\rho_w = 1 \quad q = 2 \quad n = 0.4 \quad \lambda_w = 0.59 \quad \lambda_q = 7.7 \quad \lambda_s = 3.43 \tag{4}$$

$$Volume = 0.03387 cu.m \tag{5}$$

$$\lambda = (\lambda_{sat} - \lambda_{dry})K_e + \lambda_{dry} \qquad \lambda_{sat} = \lambda_s^{1-n} \times \lambda_w^n \qquad \lambda_s = \lambda_q^q \times \lambda_0^{1-q} \tag{6}$$

$$n = \frac{1-\rho_d}{G\rho_w} \qquad \lambda_{dry} = \frac{(0.135\rho_b + 64.7)}{(2700 - 0.947\rho_b)} \tag{7}$$

3.3 Effect of soil properties on thermal conductivity

The influence of soil properties such as saturation, water content, density, porosity and void ratio on thermal conductivity is plotted for radial and longitudinal experiments.

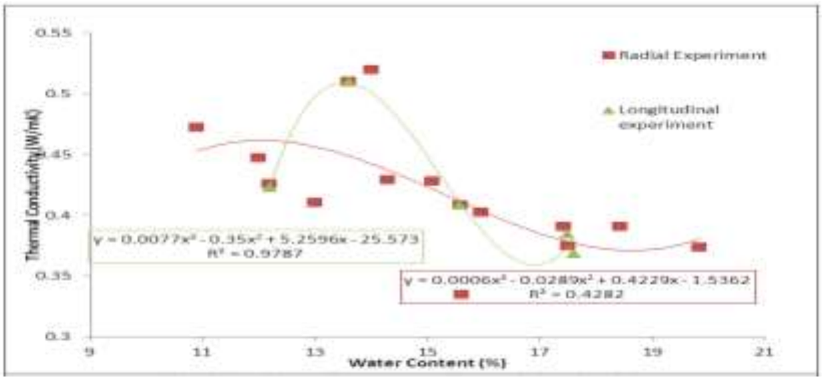

Fig. 16. Water Content v/s Thermal Conductivity

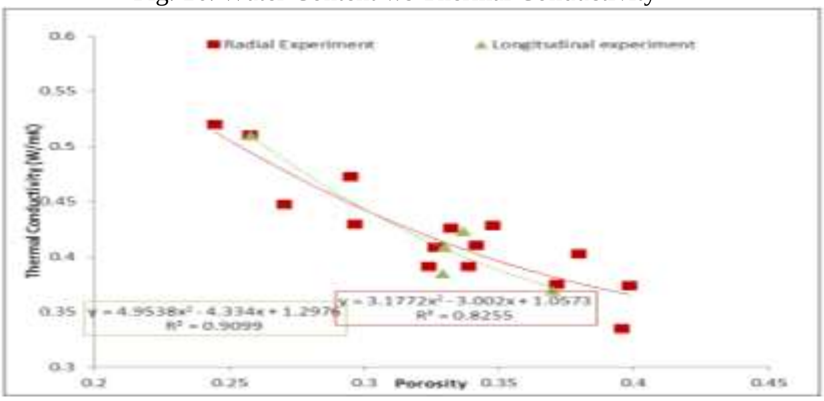

Fig. 17. Porosity v/s Thermal Conductivity

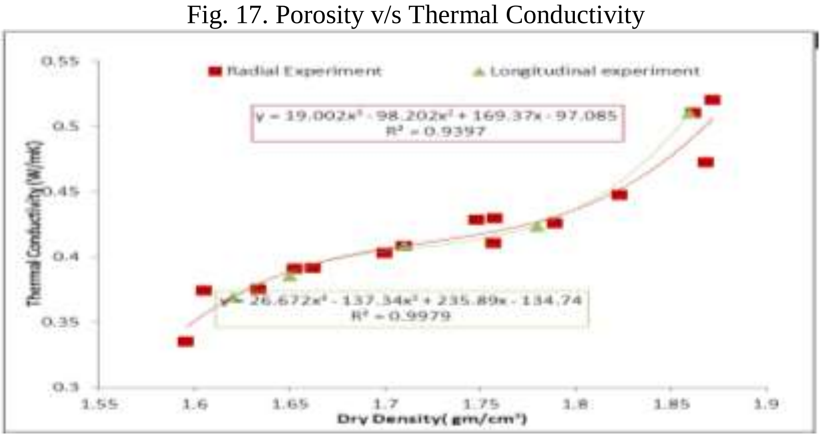

Fig. 18. Dry Density v/s Thermal Conductivity

4 Conclusion

The plot for thermal conductivity with respect to water content concludes that the plot has three stages with respect to moisture content. The first stage can be stage from the point of zero moisture to the point when the moisture content is just below the critical moisture content, the second stage from this critical stage to the point when the thermal conductivity shows no change in the value with increase in the moisture content and thereafter the third stage which has the thermal conductivity approximately constant with increase in moisture content. During the stage two which is principally the stage under study for the present work a continuous water layer is provided and all the soil grains are coupled with water. It can be noted that as the percentage of fines in the soil is increase the critical moisture content shall also increase in the case. This can be attributed to increase in the total particle surface area as the amount of fines increase require more water to form a film around each of the particles. Same is the case with the radial experiments; the water starts to move towards the outer edge of the soil with increase in temperature as well as there is evaporation of the water from the surface which has not been taken into considerations. This in turn leads to cooling of the soil due to formation of vapor, since water is now free to move in both its liquid and vapor phase. The plot of dry density shows that as the density increases the thermal conductivity increases since increasing the density increase the number of particles per unit volume thereby increasing the point contact and decreasing the air volume resulting in better heat transfer. The trend followed in plot of porosity with thermal conductivity is a peculiar in nature and does not fall into any category for curve fitting as visible from the R2 values of the plot.

5 References

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