Determination of Effective Thermal Conductivity for Tripoli Sand as Influenced by Changing Water Content and Density

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Abstract:

The thermal properties of soils are of great importance in many thermo-active ground structures such as energy piles, borehole heat exchangers and underground power cables. The steady state apparatus used in the determination of the thermal properties of soils, were designed to provide high performance in controlling all boundary conditions. In this study thermal cell apparatus was chosen due to its simplicity and because it is inexpensive and does not require a large *quantity of sample. This study was conducted to determine the effect of moisture content and density of the soil on the effective thermal conductivity of Tripoli sand, through a series of laboratory experiments, at different porosity and saturation values. For specimens with low moisture contents, the results showed a nonlinear increase in the effective thermal conductivity, while for soils with high moisture contents, the thermal conductivity was observed to have linearly increased. The maximum value for the effective thermal conductivity was obtained at the maximum dry density at the saturation state. In contrast, the minimum value was at the minimum dry density at the dry state.*

Keywords: *Tripoli sand; Thermal conductivity; Steady state apparatus; Borehole heat exchangers; Energy piles; Temperature measurement.*

1.Introduction.

Ground source heat pump (GSHP) systems provide a viable alternative to conventional heating and cooling systems in framework of developing sustainable buildings solutions, this is a technology that tap into the thermal energy present in the ground then utilize it for heating or cooling buildings, it is an effective method in terms of quality and cost [3]. The ground provides a reliable heat store due to its high heat capacity and fairly low thermal conductivity, with ground temperatures below a few meters depth staying relatively constant throughout the year, this means that the ground iswarmer than the air during winter, and cooler than the air during summer. The required heat is transferred between the ground and the building by means of a fluid pumped through a series of pipes buried in the ground, to minimize initial construction costs the pipes can be placed inside the building foundations before casting it, eliminating the need for further excavations, these are known as energy piles Figure 1, [3]. In the winter when indoor temperatures are cold, heat extracted from the ground is pumped to heat the building through the central heating system. In the summer, the fluid takes the excess heat from the building through the central heating system, and exchange the heat with the soil.

Figure 1: Heat transfer pipes in energy piles [2].

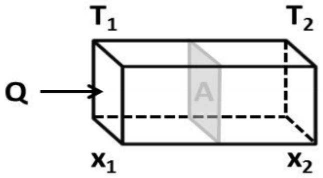
The rate of heat transfer of a single energy pile depends primarily on the temperature of the fluid carrying heat and the thermal conductivity of the soil surrounding the pile, so it is important in respect of designing such a system, to model and analyze accurately the heat transfer process between the foundations and the soil, where it is from the important parameters for such analysis is the effective thermal conductivity of soil [1].

The main objectives of this study are to find effective thermal conductivity coefficient of soil, study effect of porosity and particle arrangement (density) and the water content on the thermal conductivity of Tripoli sand using one dimensional conduction test (steady state method).

Background:

Soil thermal conductivity depends on many factors, which may be primarily classified into three groups: the nature of soils, including the texture, mineral composition, shape and size of soil particles; the structural condition, including porosity and particle arrangement; and the physical condition, including water content, temperature, and pressure, all these influences make the evaluation of thermal conductivity of soil a complex process. There are several laboratory methods of measuring thermal conductivity of soils. They fall into two categories: steady state or transient state. Steady state methods are more time consuming as they involve applying a constant heat flux to the sample and waiting until a constant temperature distribution through the sample is reached. The steady state methods such as the guarded hot plate and the thermal cell are simple and need relatively longer time to reach the steady state condition. With transient methods, thermal properties are determined by heating or cooling the sample for a set period of time and monitoring the subsequent temperature variations. The transient methods are the needle probe, dual-probe heat-pulse and the transient plane source methods [6,8].

For this study thermal cell method was chosen due to the simplicity of the apparatusand because it is inexpensive and does not require a large amount of sample. Generally, the thermal conductivity of a cylinder of soil is measured by generating one-directional heat flow along the axis of the specimen. The heat is generated by a cartridge heater embedded in the aluminum platen. Provided the specimen is well insulated so that radial heat losses can be neglected, the heat flow through the specimen during steady state is governed by Fourier’s Law of heat conduction [3] :



$$k_t = \frac{Q/A}{\Delta T/\Delta L} \tag{1}$$

Figure 2: Heat Transfer

Where: Q is the power input, A is the cross-sectional area, ΔT is the temperature difference across the length of the specimen, and L is the length of the specimen.

Literature Review

Several soil thermal conductivity prediction methods exist in the literature. These methods vary in applicability, complexity and may be limited to only certain soil types under specific condition. A brief survey of some of selected prediction methods is given below.

To quantify the thermal properties of soil, numerous influential variables were identified including; mineralogy, density and moisture content, Kersten [8,9] proposed an empirical relation between the logarithm of the thermal conductivity and the dry density at constant water content, and can be expressed as a linear relationship, as that the slope of the linear relation is also approximately the same at different water contents.

In 1975, Johansen considered the relation between the effective thermal conductivity and the water content as being a linear relationship. Johansen further developed a method for predicting thermal conductivity of soils by combining the conductivity at the two moisture extremes (dry and saturated) [10].

Later In 2000, Singh and Devid found that the thermal conductivity at first increases rapidly as the moisture content increases, but beyond a certain moisture content, the rate of increase becomes much less.[11] Singh and Devid proposed several empirical equations for the estimation of thermal resistivity of soils at dry and moist conditions, where they observed that the absolute difference between the thermal conductivity values obtained from the proposed equations and the experimental results (using the transient needle method) was less than 15 to 20%. They also noticed that the predicted and experimental results were very close when the test is conducted on dry soils.

The thermal conductivity of soil has been found to be a function of several parameters such as: dry density, water content, mineralogy, temperature, particle size, particle shape and volumetric proportions of the soil constituents [12]. They investigated the thermal conductivity of two soil samples as a function of the bulk density using transient methods. The soil samples chosen were sand and silt. They conclude that the thermal conductivity increased with increasing bulk density for the two samples, and they found that sandy soils had higher thermal conductivity values than silty soil at all bulk densities.

In 2008, based on a laboratory investigation of sandy soil, Chen proposed an empirical equation of thermal conductivity expressed as a function of porosity and degree of saturation. The equation is based on 80 needle-probe experimental test on four types of sandy soil with different degrees of saturation at different porosities [13].

The work presented in [5], showed that the thermal conductivity of soil increases significantly below a certain level of saturation and started to decelerate above this level. The validation of some selected prediction models against the experimental results revealed that none of these models can be used to predict the thermal conductivity of the tested soil at all conditions, where some can provide good agreement at dry or nearly dry condition, while others perform well at high saturation degrees, and an empirical model based on the experimental results has been obtained to obtain effective thermal conductivity in terms of water content and porosity. The behaviour of energy stalls in Malaysia, for soil with low to medium moisture content is studied in [7], these soils exhibited a linear increase in the thermal conductivity as the moisture content gradually increased, for soils with high moisture content, an opposite trend was observed, in which the thermal conductivity decreased, as the moisture content increased from 22 to 32 %.

Experimental Setup and Procedure

In order to achieve the objectives of this investigation, several tools, and laboratory instruments were used during this study; Figure 3 shows the complete set-up of the apparatus as listed below.

1. Personal computer (PC).
2. Thermal cell to place the soil samples for testing.
3. Thermal interface unit board.
4. Board of temperature control and transducers.
5. Digital Voltmeter and Ammeter.
6. Temperature sensor.
7. Temperature sensor
8. Temperature sensor.
9. Heating Element.
10. DC Power supply resource.
11. Wire fastener.
12. Sensitive balance.
13. Electric Oven.
14. Set of standard sieves.
15. Water vial and mixing tray.

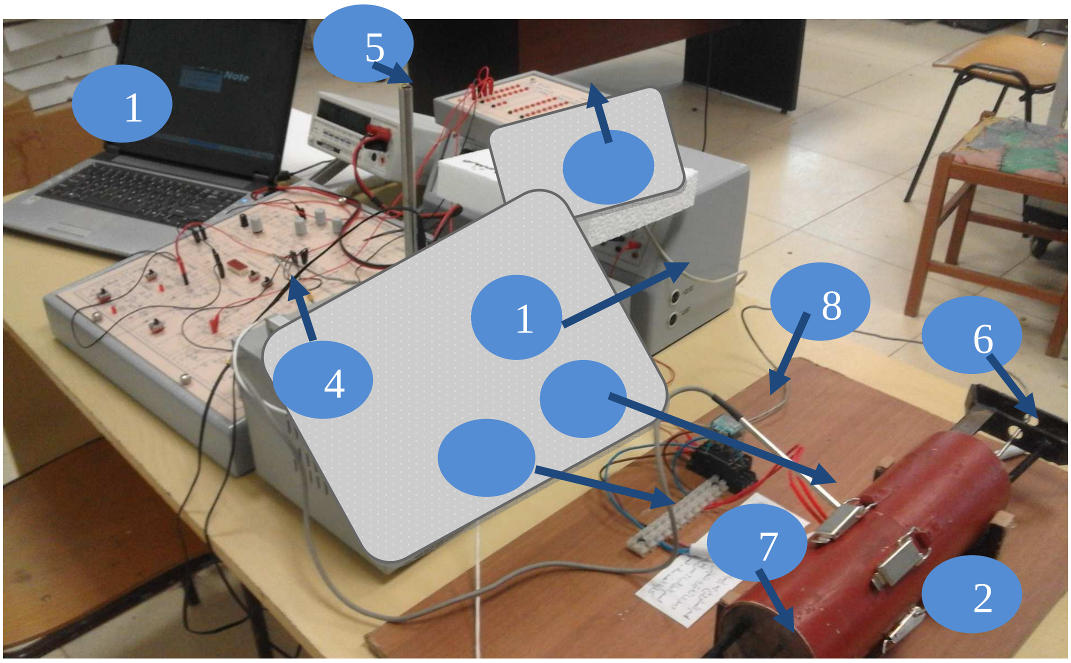


Figure 3: Complete set-up of the apparatus

The cell body consists of three main parts: two insulating cylinders made from PVC tube, heater disc and two aluminium sink discs. Figure (4) shows a thermal cell apparatus in which a heater disc is placed between the two specimens and a thermal gradient parallel to the axis of the specimen is generated by a cartridge rod heater that can be easily inserted into the heater disc through a drilled hole in the aluminium disc. Two aluminium sink discs, at the unheated ends of the specimen, were used to dissipate the heat from the outer ends of the specimens. The heater disc, sink discs and specimens have the same diameter (84 mm).

Figure 4: The Thermal Cell

Soil Samples (Tripoli sand)

Tripoli sand is widely available and typical of most Tripoli area. It was obtained from one location in order to eliminate variations in its engineering properties. The samples tested were extracted from a depth of one meter from Tripoli University. Sieve analysis following BS 1377, indicates that this soil can be classified as a fine sand with coefficients of uniformity and curvature of 1.52 and 0.893, respectively , This sandy soil is classified as (SP) according to the unified classification system , and average specific gravity is equal to (2.658). Figure 5 displays the wet sieve analysis results.

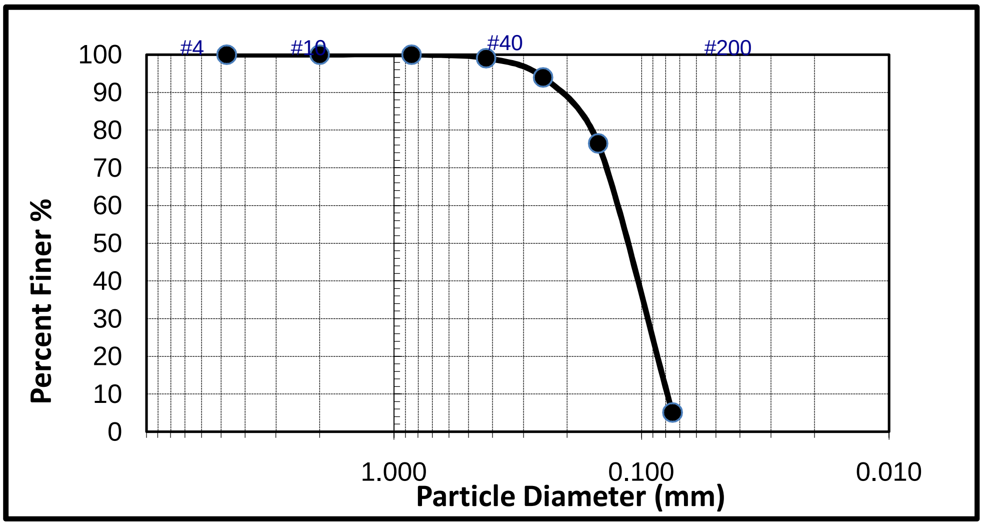


Figure 5 : Grain Size Distribution of Tripoli Sand Sample

Sample preparation:

The study focused on the effects of degree of saturation and porosity on the thermal conductivity of Tripoli sand. For the interpretation of the test data, both porosity and degree of saturation were controlled. To study the effect of changing density, six different dry densities were selected. Furthermore, ten values of water contents were used to study the effect of changing water content. It should be noted that it was difficult to prepare samples with higher degree of saturations, especially at low soil densities, as disaggregation occurs due to the elimination of the friction force between sand grains caused by the high water contents.

The soil was first oven dried for 24 hrs and allowed to cool in a dry place before being used. For each particular condition, the water content, dry density, and bulk density were calculated using mass-volume relations. According to the desired moisture content, a dry soil mass was mixed with the appropriate amount of water. By knowing the volume of the specimen the required wet mass to obtain the predefined dry density can be calculated. The positions of the sink discs in the two specimen cylinders were adjusted to maintain the desired volume.

Steady state thermal conductivity measurement

The thermal conductivity of the soil was measured at different degrees of saturation using a thermal cell that utilises the steady-state method. The design of the apparatus is based on the application of Fourier’s law, where a one-directional uniform heat flux is generated through two identical specimens. The main body of the cell is made of PVC, whose low thermal conductivity helps in minimising the radial heat loss and whose stiffness allows specimens to be compacted during preparation if required. In steady state conditions, the temperature of at least three points for each specimen can be plotted versus time.

Test procedure:

After preparation of the specimens was completed, the two cylinders containing the soil samples were then inserted into the insulating cylinder. The length of the specimen cylinders is designed to ensure complete contact between the heater disc and the two specimens when they reach their final position inside the insulating cylinder.

To monitor the temperature gradient along each specimen length, temperature sensor was pushed longitudinally through the holes in the centre of the specimens in the two cell cylinders to reach depths of 0, 35, 65, and 100 mm from the heater. Another temperature sensor was used to control and monitor the temperature of the heater disc.

Once thermal equilibrium was achieved, the DC power supply was switched on and the test run until steady state condition was achieved. The power selection depends on the required temperature gradient. For unsaturated conditions, the temperature gradient was kept as low as possible near the room temperature to avoid moisture migration. The power ($Q = V * I$) supplied to the heater is controlled by changing the voltage V and current I supplied by the DC power supply. Using Equation 1, the effective thermal conductivity k_e can be determined. Three thermal conductivity values were calculated using different specimen lengths. The thermal conductivity results were then plotted against the corresponding specimen lengths. The radial heat losses along the specimen length can be identified by the slope of the line connecting these thermal conductivity values. If the line is not horizontal, radial heat losses took place during the test period. A correction step can be applied by extrapolating the thermal conductivities to a specimen length of zero [4].

Results and Discussion:

In this experiment, the focus was on the influence of changing water content and sand density on the thermal conductivity of Tripoli soil. The effect of each of these factors is studied separately and the results are discussed below.

The influence of Changing Water Content :

From the experimental results of specimens having different water contents, the relations between the physical properties of Tripoli sand and thermal conductivity can be assessed. Figure (6) shows a typical temperature versus time curve.The steady state can be clearly recognized after 4 hours from the start of the experiment.

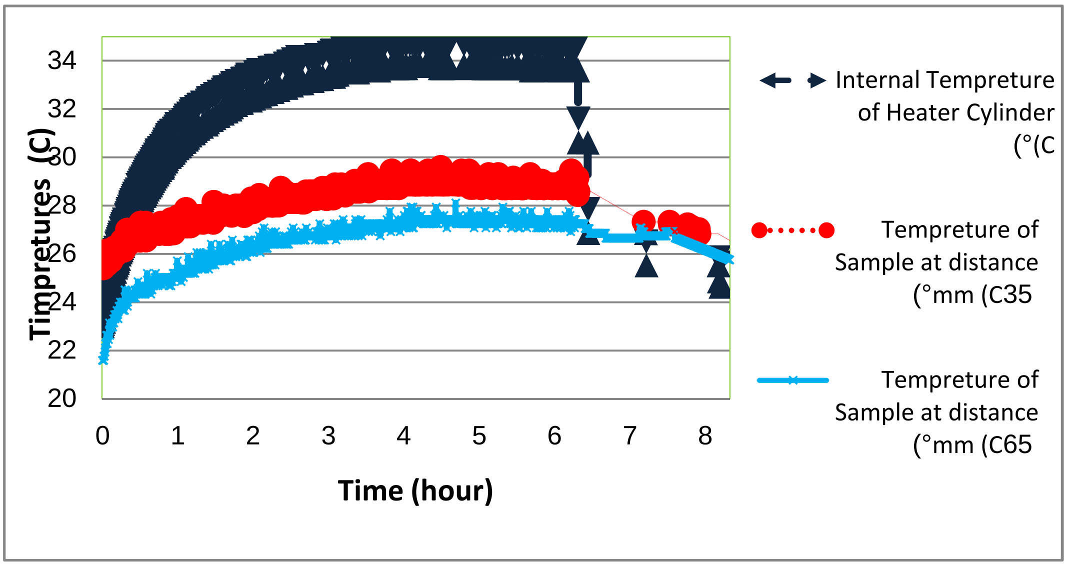


Figure (6): Temperature of the heat cylinder and soil sample

Figure (7) shows relationship between T and L, Figure (8), shows example of the thermal conductivity correction method.

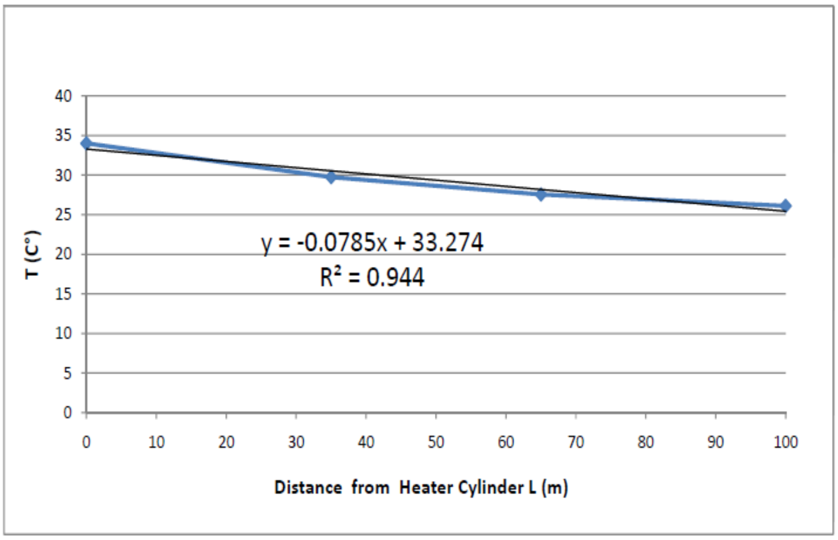


Figure (7) : Temperature gradient (Relationship between T and L) of soil sample

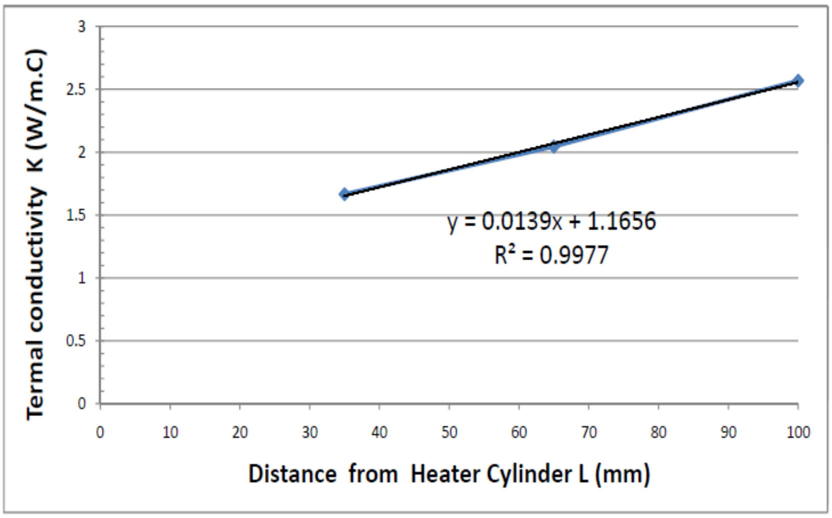


Figure (8): Relationship between k_e and L of a soil sample

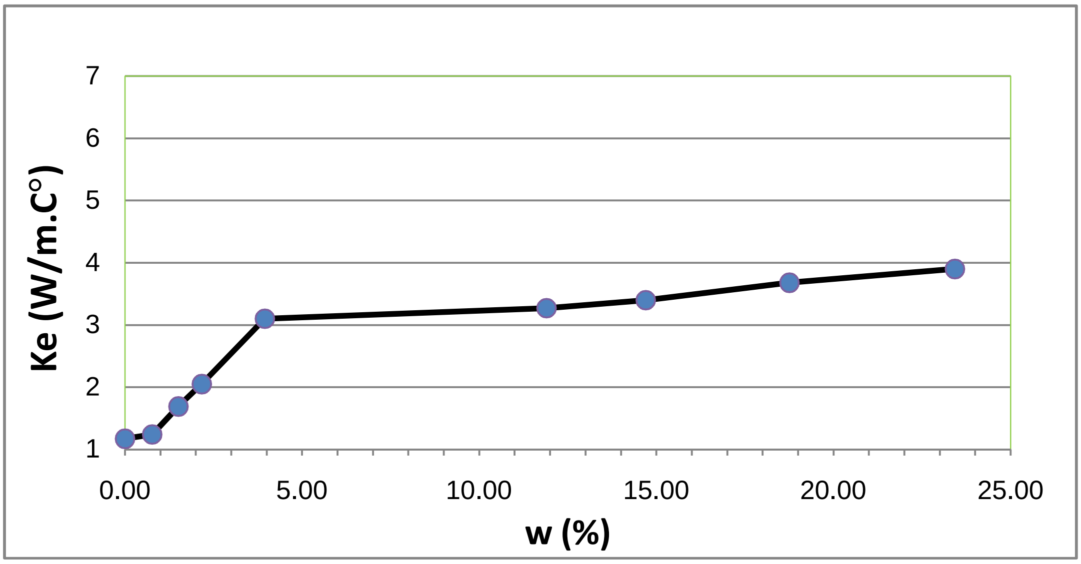


Figure (9) : Effective thermal conductivity (k_e) Versus moisture content (w %)

The evaluation of the experimental results obtained from the tests shows that in figure (9) for specimens with low moisture content (<5%), a nonlinear increase in the effective thermal conductivity, while for soils with high moisture content, the thermal conductivity was observed to have linearly increased , this is due to the disruption of the thermal flow continuity in the soil matrix which effected by the migration of moisture in the porous. The values of the effective thermal conductivity obtained in this study are in the normal range for soils between 0.15 to 4.0 W/m°C.

Effect of Changing Density:

From Figure (10), the thermal conductivity increased nonlinearly with increasing the density, this can be explained by the replacement of the air voids in the dry state or the water in the saturation state by the soil grains which has high thermal conductivity compared to the air or water.

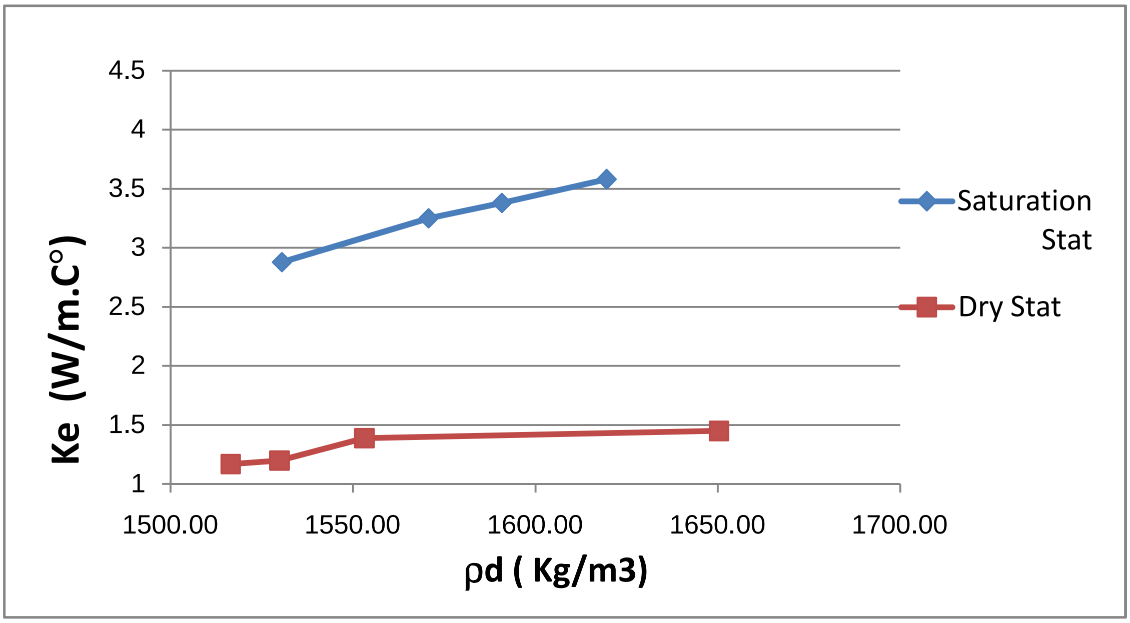


Figure (10) : Relationship between (k_e) Versus (ρ_d) for dry and saturated states

For unsaturated conditions, the temperature gradient was kept as low as possible near the room temperature to avoid moisture migration. The effect of other properties such as mineralogical composition and grain size cannot be evaluated as they were identical in all tests.

Conclusions:

Based on the experimental work conducted in this investigation and the analysis of results, the following conclusions could be drawn: Thermal cell method is one of the best practical methods for determining the effective thermal conductivity of soils because of the simplicity of the apparatus, inexpensive and does not require a large amount of sample and can be accommodated with soil samples retrieved from routine soil investigations. The radial heat losses along the specimen length can be identified by the slope of the line connecting the thermal conductivity values. If the line is not horizontal, radial heat losses took place during the test period. The results have shown that for soils with low to medium moisture content, a nonlinear increase in the thermal conductivity, while for soils with high moisture content, the thermal conductivity was observed to have gradually linearly increased. The thermal conductivity is increased nonlinearly with increasing the density since, the void air between particles of soil is decreased which has low thermal conductivity compared to the soil grains. This means increasing the solid material per unit volume increases the effective thermal conductivity. The results obtained in this research lie well within the normal range of soils (0.15 to 4.0 W/m^{o}c)

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