THERMAL DIFFUSIVITY, THERMAL EFFUSIVITY AND SPECIFIC HEAT OF SOILS IN OLORUNSOGO POWERPLANT, SOUTHWESTERN NIGERIA

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ABSTRACT

The determination of soil thermal properties, such as thermal resistivity, thermal conductivity, thermal diffusivity, thermal effusivity and specific heat, is of great importance for various civil and electrical engineering projects where heat transfer takes place through the soil mass. Some of these projects include design and laying of high-voltage buried power cables, oil and gas pipe lines, nuclear waste disposal facilities. Many workers have focussed their attention on determining only the thermal resistivity of materials for making recommendations when executing various engineering projects. However, it is important to evaluate thermal diffusivity, thermal effusivity and specific heat, not thermal resistivity alone when dealing with protecting any buried pipe from freezing. This research work therefore intends to determine these properties in soils of Olorunsogo Gas Turbine Power Station (335 MW Phase 1) which is located in Ogun State, Southwestern Nigeria.

Ten pits, each of about 1.5 m below the ground surface, were established in and around the power plant in order to measure thermal conductivity, thermal diffusivity and specific heat of soil in-situ. A KD 2 thermal analyzer was used for the in-situ measurement of thermal properties. Samples were also collected from the ten pits for laboratory determination of the physical parameters that influence thermal properties. The samples were subjected to grain size distribution analysis, compaction, specific gravity, porosity and permeability tests, and moisture content determination. The thermal conductivity, density and specific heat were used to calculate the thermal effusivity of the soil

The results show that thermal diffusivity, thermal effusivity and specific heat range from 0.346 – 0.752 mm^2/s, 1.38 – 4.01 $Jm^{-2}K^{-1}S^{-1/2}$ and 1.152 – 3.361 mJ/m^3K respectively. Also, the physical parameters such as moisture content, porosity, degree of saturation, dry density and permeability vary from 13.00 – 16.20 %, 39.74 – 45.64 %, 40.72 – 63.52 %, 1725.05 – 1930.00 Kg/m^3 and 0.0144 – 0.0316 cm/s respectively. The temperature ranges from 28.92 – 35.39 ^oC with an average of 32.11 ^oC in the study area.

It was found that the thermal properties of soils in the area are good enough for proper laying of cables or pipelines. Also the variation of thermal properties with physical parameters match with the results reported in literatures except for the variation of porosity with specific heat. Therefore, for safe and proper execution of various civil and electrical engineering projects, determination of thermal properties of soils is quite essential.

Keywords: *Thermal diffusivity, thermal effusivity, specific heat, physical parameters, Civil and electrical projects, Olorunsogo, Gas Turbine, Southwestern Nigeria.*

Abbreviations

w - Moisture content
ρ_d- dry density
S- degree of Saturation
MW – Mega Watts
G_s – Specific Gravity
e - Void ratio
TP – Test Point
R – Coefficient of correlation
SD – Standard Deviation
N – Number of samples
XRD – X-Ray Diffractometer

1. INTRODUCTION

For safe and proper execution of various civil and electrical engineering projects, determination of thermal properties of soils such as thermal resistivity [1], thermal diffusivity [2]; [3] and specific heat [4] is quite essential. However, thermal properties of rocks would play an important role for extremely environmental sensitive projects such as disposal of high-level radioactive waste in deep underground disposal sites or repositories ([5]; [6]), various engineering projects such as design and laying of high voltage buried power cables, oil and gas pipe lines, ground modification techniques employing heating and freezing.

Many workers have focussed their attention in determining only the thermal resistivity for making recommendations when executing various engineering projects. However, it is important to evaluate thermal diffusivity and specific heat, not thermal resistivity alone when dealing with protecting any buried pipe from freezing [7].

Several researchers ([8]; [9]; [10]; [11]; [12]; [13]; [14]; [15]; [16]) have shown that the thermal properties of soil depends on numerous parameters such as mineralogical composition, grain size of soil and physical properties like moisture content (w, %), porosity, dry density (ρ_d, g/cm^3) and saturation (S, %). Therefore, these factors have to be taken into account when performing measurements at laboratory and field scale.

1.1 SITE DESCRIPTION

The study area is a 335 MW phase I, Olorunsogo Gas Turbine Power Station in Ogun state, Southwestern Nigeria. It is located within longitudes 03^o 18' 45" to 03^o 19$^'$ 50" and latitudes 06^o 52$^'$ 45$^"$ to 06^0 53$^'$ 00$^"$. The major road in the area runs from Papalanto in the Western part of the area to Ikereku in the eastern part. Another major road runs from Wasimi in the Northwestern part of the area to Isoku in the central North. There are so many minor paths in the area (Figure 1).

1.2 GEOLOGY OF THE STUDY AREA

The study area fall within the alluvium, littoral and lagoonal deposits (Fig. 2)

1.2.1 Lithoral and Lagoonal Deposits

The sediments here consist of unconsolidated sands, clays and muds with a varying proportion of vegetal matter. Occasional beds of sandstone with ferruginous cement were encountered during the drilling of test wells by Mobil Exploration Nigeria Incorporated. Correlation between one borehole and the next was usually very poor, the sediments were clearly deposited under littoral and lagoonal conditions and reflect continuously shifting lagoon and sea beach patterns and the varying sedimentation conditions within the lagoons.

1.2.2 Alluvial Deposit

Alluvium is typically made up of a variety of materials, including fine particles of silt and clay and larger particles of gravel and sand. When this loose material is deposited or cemented into a lithological unit or lithified, it is referred to as alluvial deposits (Geology Dictionary, 2012)The alluvial plain of the Ogun is 14 miles wide at one point and smaller areas of alluvium follow the lower courses of the other major rivers. The borehole drilled penetrated clays and shales overlying alternating limestones and shales of the Ewekoro Formation.

2. MATERIALS AND METHODS

The thermal diffusivity and specific heat of soils around Olorunsogo Power Plant were determined using KD2 Pro. The KD2 Pro (Plate 1) is a fully portable field and laboratory thermal properties analyzer. It uses the transient line heat source method to measure the thermal diffusivity, specific heat (heat capacity), thermal conductivity and thermal resistivity. Sophisticated data analysis is based on over thirty years of research experience on heat and mass transfer in soils and other porous materials.

To determine the thermal diffusivity and specific heat, a small dual-needle sensor (SH-1) [Plate 2] was employed (Decagon Devices Inc.). This kind of sensor use the heat pulse methodology and yield reliable soil thermal diffusivity (α) and volumetric specific heat capacity (C) estimations by a non-linear least squares procedure during both processes. However, thermal admittance/effusivity was calculated as the square root of the product of thermal conductivity (λ) and heat capacity (ρC) i.e. effusivity = $\sqrt{\lambda\rho C}$.

2.1 SH-1 30 mm Dual Sensor

The SH-1 is the only sensor that measures thermal diffusivity and specific heat. It is 30 mm long, 1.28 mm in diameter and 6 mm spacing between the two needles (Plate 2). It also measures thermal resistivity and thermal conductivity.

Range: 0.02 to 2.00 W/mK (thermal conductivity)
50 to 5000 ^{o}C-cm/W (thermal resistivity)
0.1 to 1 mm^2/s (diffusivity)

0.5 to 4 mJ/m^{3}K (volumetric specific heat)
Accuracy: (Conductivity): ± 10 % from 0.2 – 2 W/mK
± 0.01 W/mK from 0.02 – 0.2 W/mK
(Diffusivity): ± 10 % at conductivities above 0.1 W/mK
(Volumetric Specific Heat): ± 10 % at conductivities above 0.1 W/mK
Cable Length: 0.8 m.

2.2 Field Procedure

The first step to develop a protocol to measure the thermal properties begins with the field sampling design.

2.1.1 In-situ Measurements

The measurement include establishments of ten pits of about 1.5 m below the ground and verification and preparation of the thermal sensor (calibration) using standard glycerol in order to check whether it was functioning properly ([1], [17], [18]). The thermal sensor to be used was then selected (SH-1 was used). The ground was then scooped to allow firm positioning of the thermal sensor with the ground. The needle was positioned with respect to the pit established. Thermal diffusivity and volumetric specific heat were then measured by using the thermal sensor SH-1.

To take measurements with the KD2 Pro; appropriate sensor was attached and the KD2 Pro was turned on; sensor was properly inserted into the material to be measured (for the dual needle sensor, the needles must remain parallel to each other during insertion); when the KD2 Pro turns on, one should be in the Main Menu, press enter to begin the measurement. The instrument was allowed to rest for about ten minutes before taking the next reading.

2.1.2 Collection of Samples

Ten samples were collected at the established pits for laboratory analyses (Fig. 3). The samples were kept in polythene bags and stored in a cool dry place before the necessary tests were carried out on them.

2.2 Analytical Laboratory Procedures

To characterize the soil of Olorunsogo Power Plant, the physical variables, particle size distribution, bulk density, dry density, specific gravity, degree of saturation, porosity, permeability, moisture content and mineralogical composition were determined in the laboratory.

Due to the various fractions present in the soil, two stages are involved in the grain size distribution determination, as follows:
(a)Mechanical or sieve analysis
(b)Hydrometer analysis
Mechanical or sieve analysis was used for the coarse grained fraction (particle size >0.063µm in diameter) while hydrometer analysis was used for the fine grained fraction (Particle size <0.063µm in diameter).

Compaction tests were also carried out on the samples to determine the bulk density, Optimum moisture content and maximum dry density. Specific gravity, porosity and permeability tests were carried out on the samples to determine specific gravity, porosity and permeability respectively. The degree of saturation was calculated from the formular: $Se = wG_s$ where S = degree of saturation, e = void ratio, w = moisture content and G_s = specific gravity.

3. RESULTS AND DISCUSSION

3.1 Thermal Properties

3.1.1 Thermal Diffusivity

The thermal diffusivity in the study area ranges from 0.346 to 0.752 mm^2/s (3.46 x 10^{-7} to 7.52 x 10^{-7}m^2/s) with an average of 0.622 mm^2/s (6.22 x 10^{-7} m^2/s) (Table 1). It can be observed that the thermal diffusivity values in the study area are moderate to high since r*ange of measurement of SH-1 for thermal diffusivity is 0.1 to 1 mm^2/s.* Figure 4 shows that there is no much variation in the thermal diffusivity of soil in the area with an exception at TP 5 with relatively low thermal diffusivity (0.346 mm^2/s). This may be as a result of high coefficient of permeability which could make less heat to be dispersed at that point compared to other points. Substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings because they conduct heat quickly in comparison to their volumetric heat capacity or 'thermal bulk' and they generally do not require much energy from their surroundings to reach thermal equilibrium [19]. Therefore, it could be said that the soils in the study area will rapidly adjust to any change in temperature.

3.1.2 Specific Heat

The specific heat in the study area ranges from 1.152 to 3.361 mJ/m^3K with a mean of 2.601 mJ/m^3K (Table 1). These values are considerable moderate *since range of measurement of SH-1 for volumetric specific heat is 0.5 – 4* mJ/m^3K. Figure 5 shows there is no much variation in the specific heat of the soil in the study area except at TP 6 that is considerably lower. This may be as a result of high density at that point. Substances with a high specific heat capacity absorb more energy before they change in temperature than substances with low specific heat capacity [20].

3.1.3 Thermal Effusivity (Thermal Admittance)

Thermal admittance in the study area ranges from 1.38 to 4.01 $Jm^{-2}K^{-1}S^{-1/2}$ with a mean of 2.841 $Jm^{-2}K^{-1}S^{-1/2}$. The thermal admittance of soils in the study area is given in Table 2. The thermal effusivities for common materials is also given in Table 3. Figure 6 shows the variation of Thermal effusivities in the study area. The effusivity of materials varies due to their differing ability to transfer heat. This is due to differences in heat transfer through and between particles, and is therefore a function of particle size (Table 5 and Figure 7), particle shape, density, morphology, crystallinity and moisture content.

[21] opined that materials with high thermal effusivity cannot hold heat long enough because heats will quickly dissipitate from its surface as soon as surrounding temperature drops. On the other hand, materials with low thermal effusivity will hold heat much longer. Therefore it could be said that soil in the study area with low thermal effusivity will hold heat much longer following the conclusion of [21].

3.2 Variation of Thermal Properties with Physical Properties of Soil

The summary of the results of physical properties determined in the laboratory are presented in Table 4.

3.2.1 Moisture Content

The moisture contents of soil in the study area range from 13.0 to 16.2% with an average of 14.2 %. In Figure 8a, a positive correlation exists between thermal diffusivity and moisture content. This is in line with [22]; [23]; [24] and [25]. Also in Figure 8b, there is a positive correlation between specific heat and moisture content as reported in literatures [23]. This may be attributed to the fact that soil grains are better conductors of heat than water, the biggest gains in heat conduction will then come from adding enough water to provide an efficient transmission path from one soil grain to another through a separating layer of water.

3.2.2 Dry Density

The dry density in the study area ranges from 1725.05 to 1930.00 Kg/m^3 with a mean of 1855.61 Kg/m^3 (Table 4). A weak positive correlation exists between dry density and thermal diffusivity and specific heat. (Figures 9a & 9b). This may be due to the improved contact between the soil grains that leads to better conduction of heat.

3.2.3 Degree of Saturation

The degree of saturation varies from 40.72 % to 63.52 % with an average of 51.11 % (Table 2). This means that soils in the study area is partially saturated [26]. A soil's thermal property is significantly influenced by its saturation [27].

The thermal diffusivity and specific heat correlate negatively with the degree of Saturation (R = -0.4 and -0.7 respectively). (Figures 10a and 10b).

3.2.4 Porosity

The data presented in Table 4 have been used to establish the influence of porosity of the soil on its thermal properties as depicted in Figures 11a and 11b. Porosity of soil samples varies from 39.74 % to 45.64 % with an average of 42.40 %. It can be noted that with increase in porosity thermal diffusivity and specific heat decreases (R=-0.4 and -0.8 respectively). Also the relationship between porosity and thermal diffusivity agrees with [28]. However the relationship between porosity and Specific heat did not agree with literature as literature reported that increase in specific heat will lead to increase in porosity. But as observed in Figure 10b, increase in porosity resulted in a decrease in specific heat with R = -0.8.

3.3.5 Permeability

Permeability in the study area ranges from 1.44×10^{-2} to 3.16×10^{-2} cm/s with an average of 2.31×10^{-2} cm/s. [29] classified soils into different degree of permeability as shown in Table 5. From Table 5, the degree of permeability in the study area can be classified as medium

Also the plots of thermal properties against permeability are shown in Figures 12a and b.

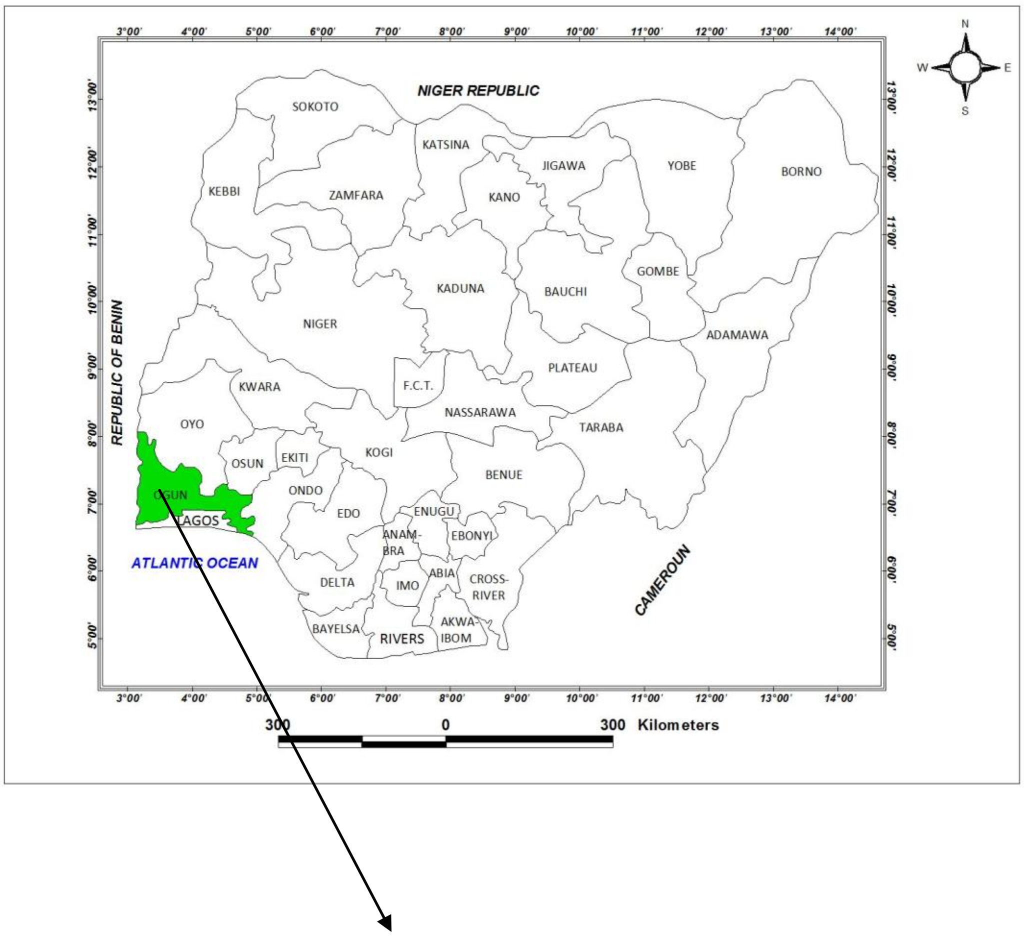
Thermal diffusivity has a negative correlation (r = -0.2) with the coefficient of permeability (Fig. 12a). Specific heat on the other hand has a positive correlation (r = 0.2) with the degree of permeability (Fig. 12b). As the soil becomes more permeable, the heat has less rate of dispersion.

3.3.6 Temperature

The temperature of soils in the study area ranges from 28.72 to 35.0 8 ^{o}C with a mean of 32.11 ^{o}C. There is little variation in temperature of soil in the area as shown in Figure 13.

The relationship between thermal diffusivity and temperature is shown in Figure 14a. There is a weak positive correlation between them (R = 0.1). Substances with high thermal diffusivity rapidly adjust their temperature to that of their surroundings because they conduct heat quickly.

In Figure 14b, the relationship between Specific heat and temperature is almost zero (R= 0.03) i.e. as temperature increases, the specific heat also increases. This is in agreement with [30] who stated that specific heat increases with temperature. However, [31] stated that for a soil in place, the temperature typically varies over a small enough range to have only a small effect on thermal properties (unless the soil freezes).



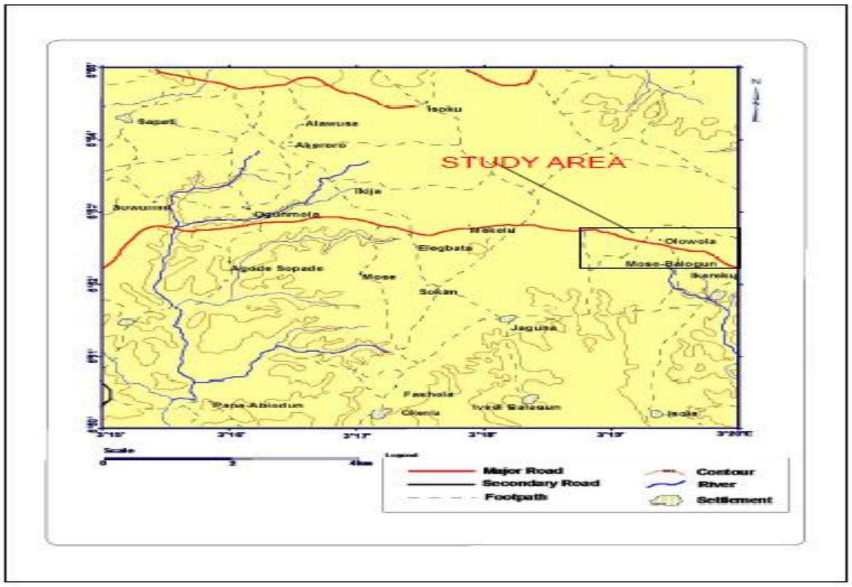


Figure 1: Map of Nigeria showing location of the study area [32]

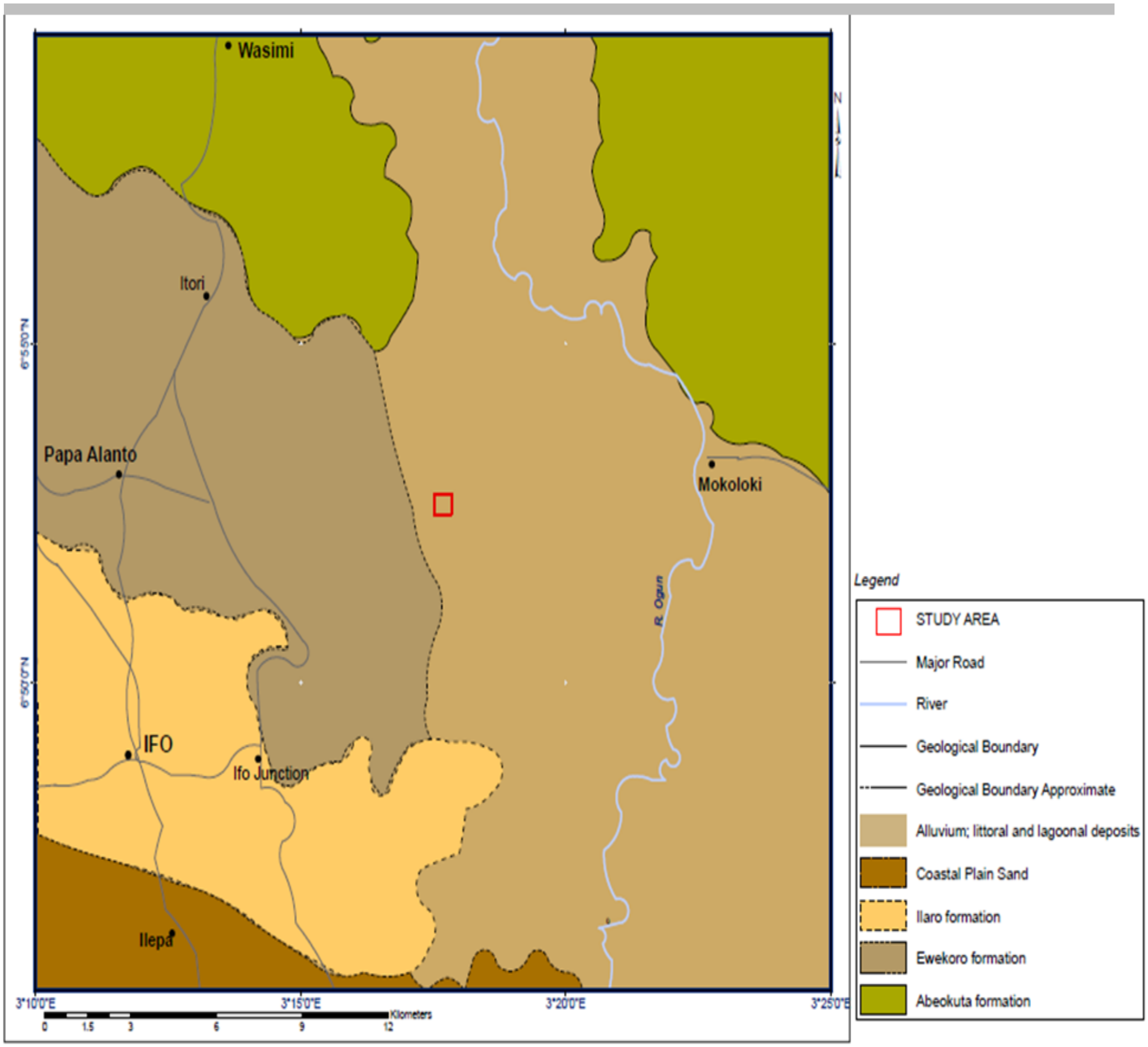


Figure 2: Geological Map of Ifo showing location of Olorunsogo Power Plant

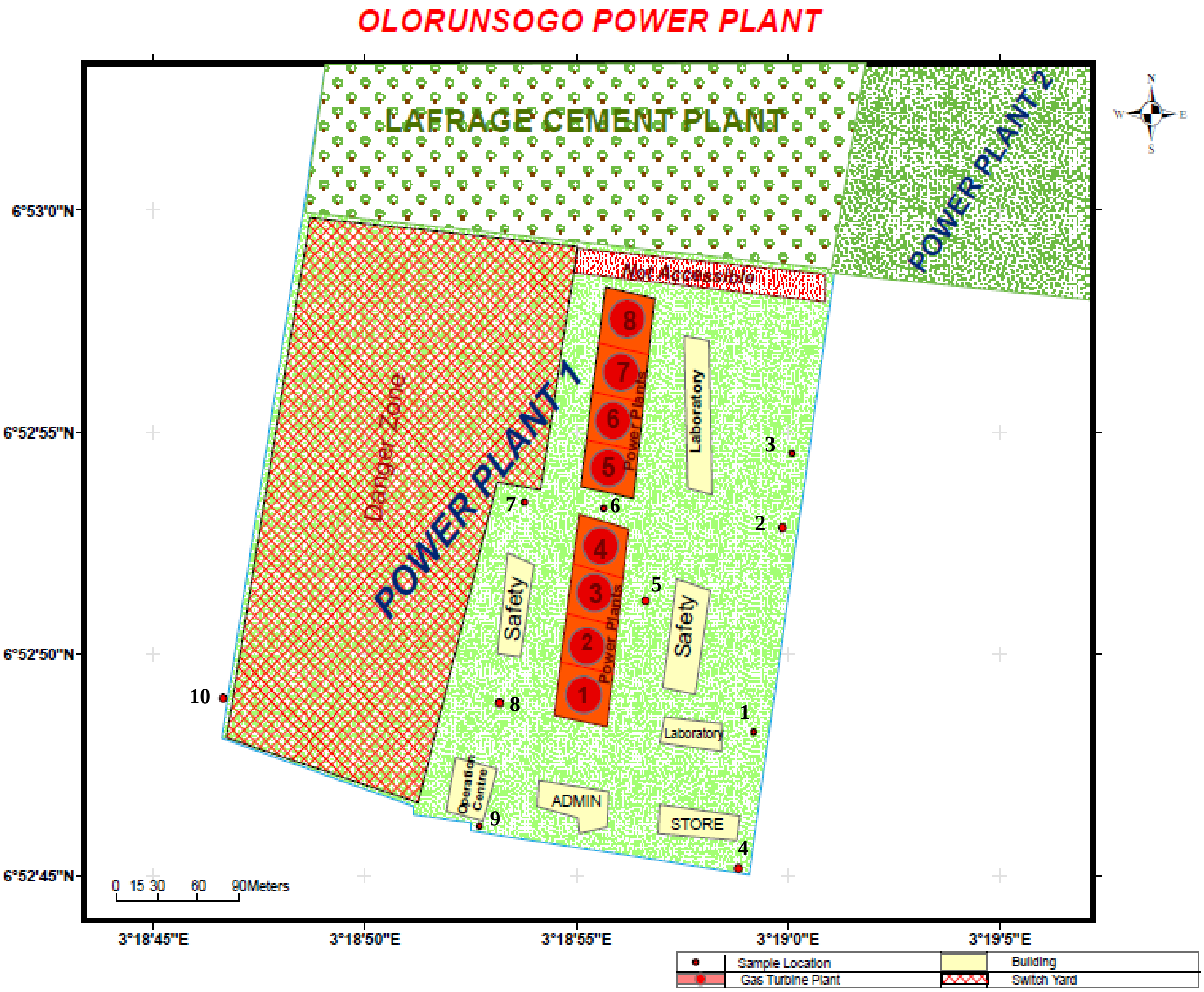


Figure 3: Map of the study area showing the test points

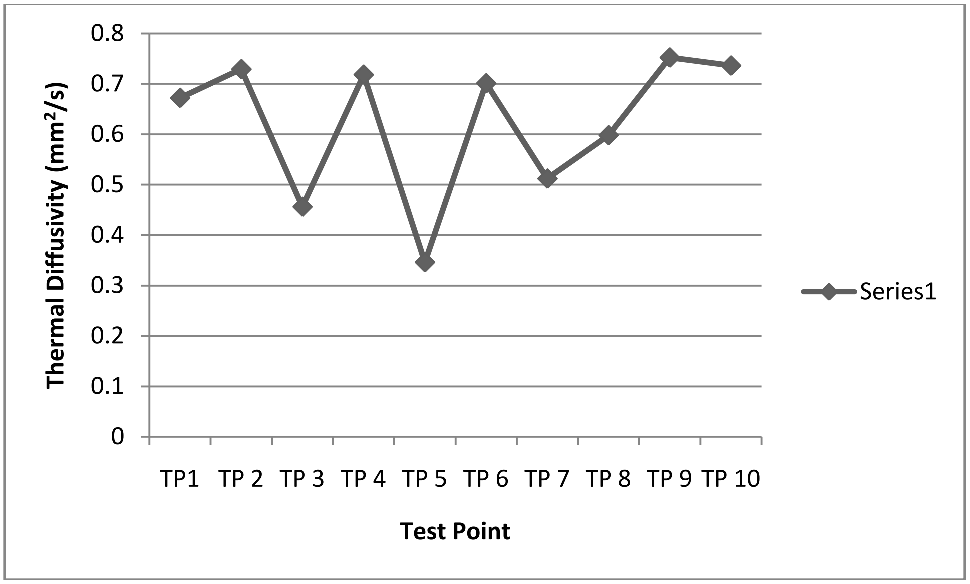


Figure 4: Variation of Thermal Diffusivity within the study area.

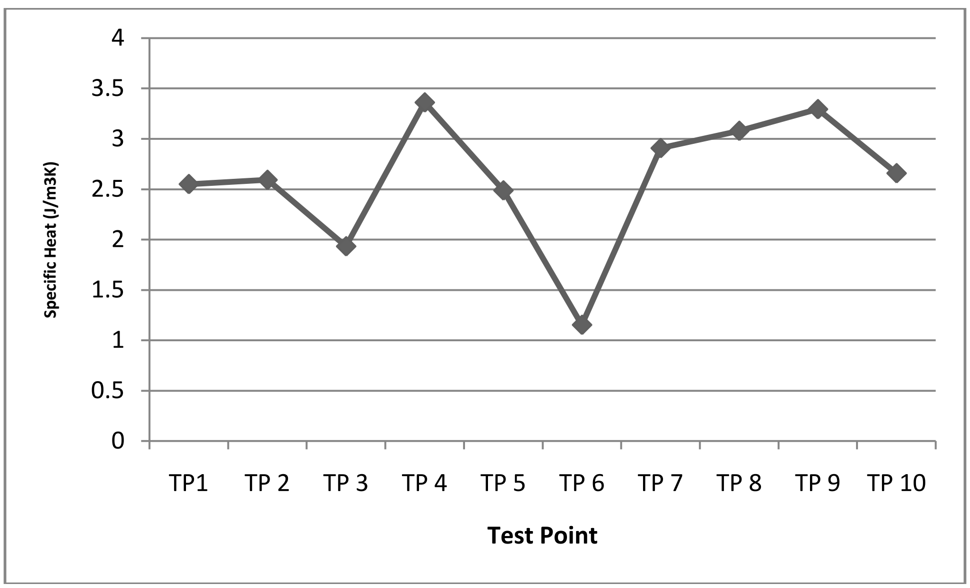


Figure 5: Variation of Specific Heat in the study area

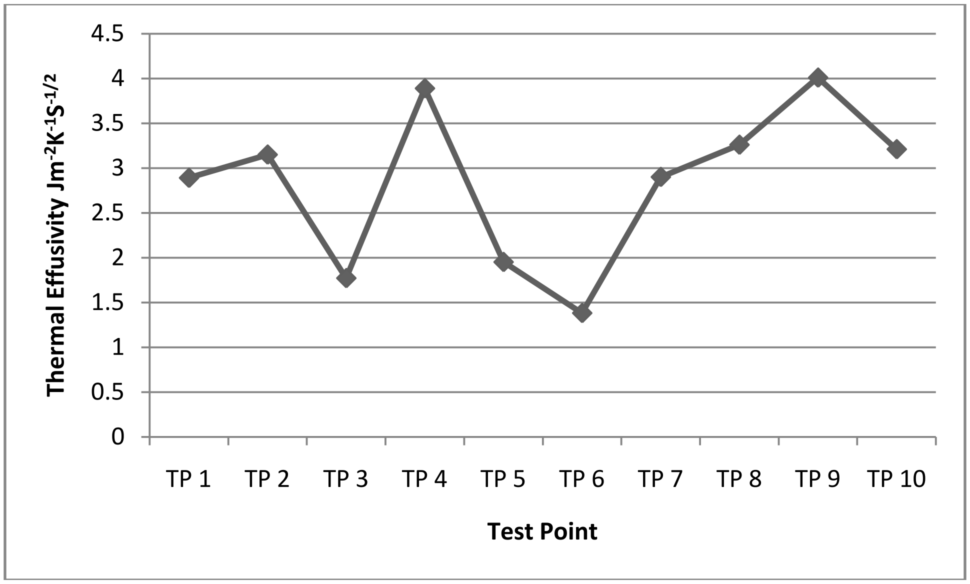


Figure 6: Variation of Thermal Effusivity in the study area

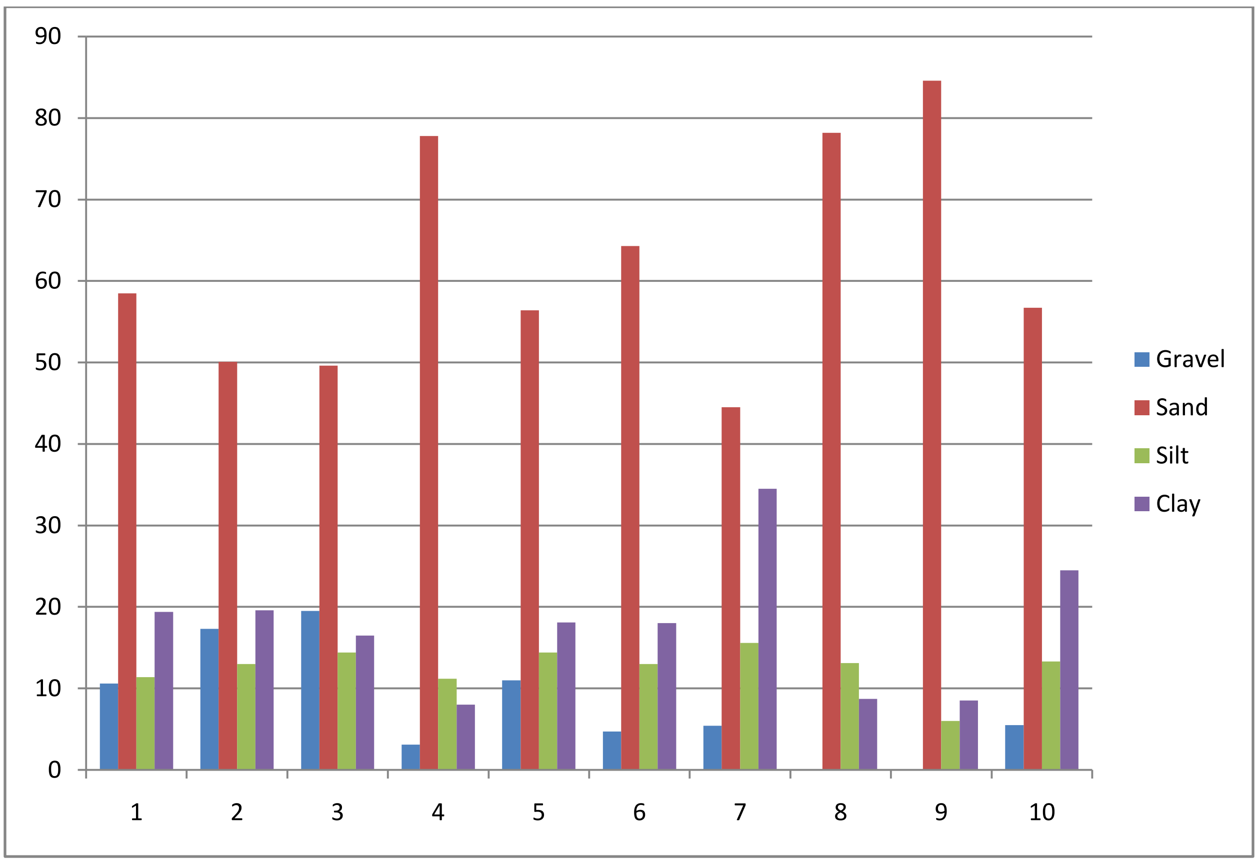


Figure 7: Bar graph showing grain size distribution of soils in Olorunsogo Power Plant

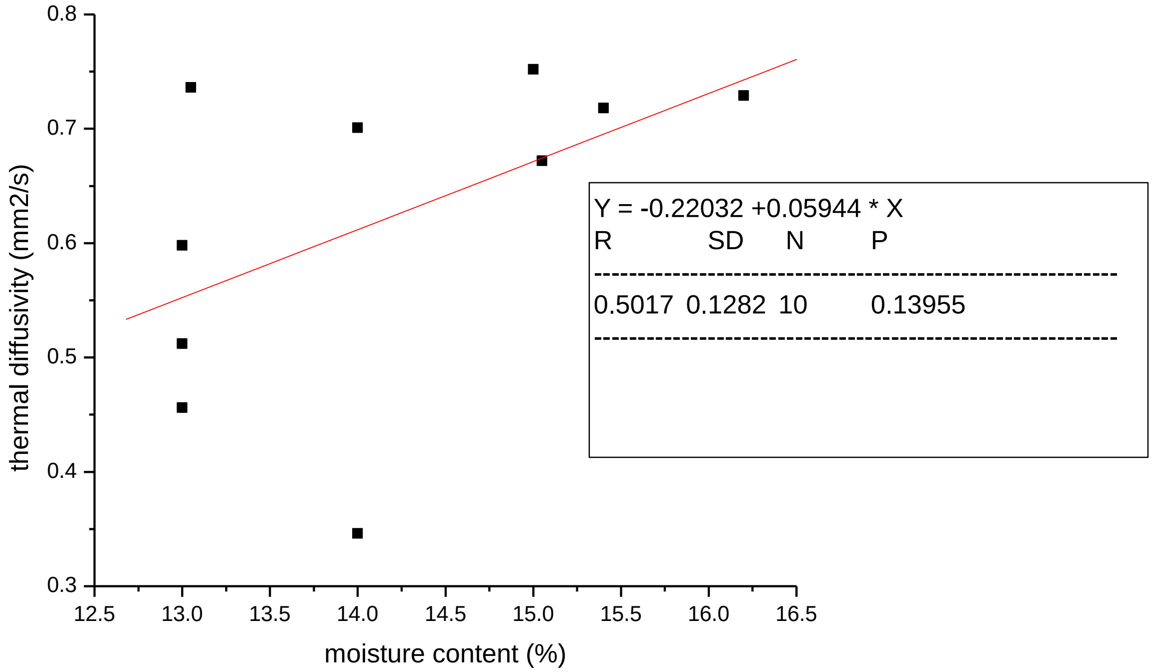


Figure 8a: Variation of Thermal Diffusivity with moisture content

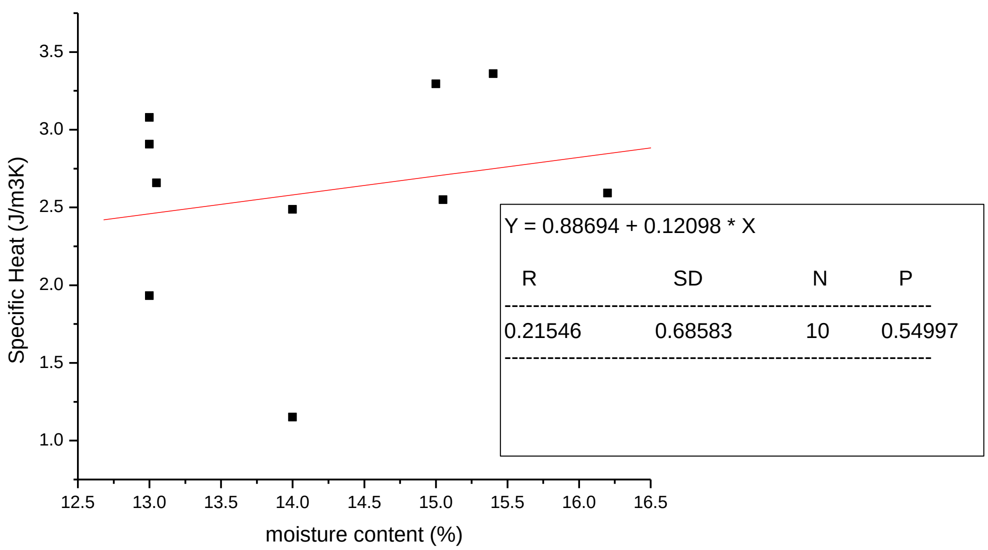


Figure 8b: Variation of specific heat with moisture content

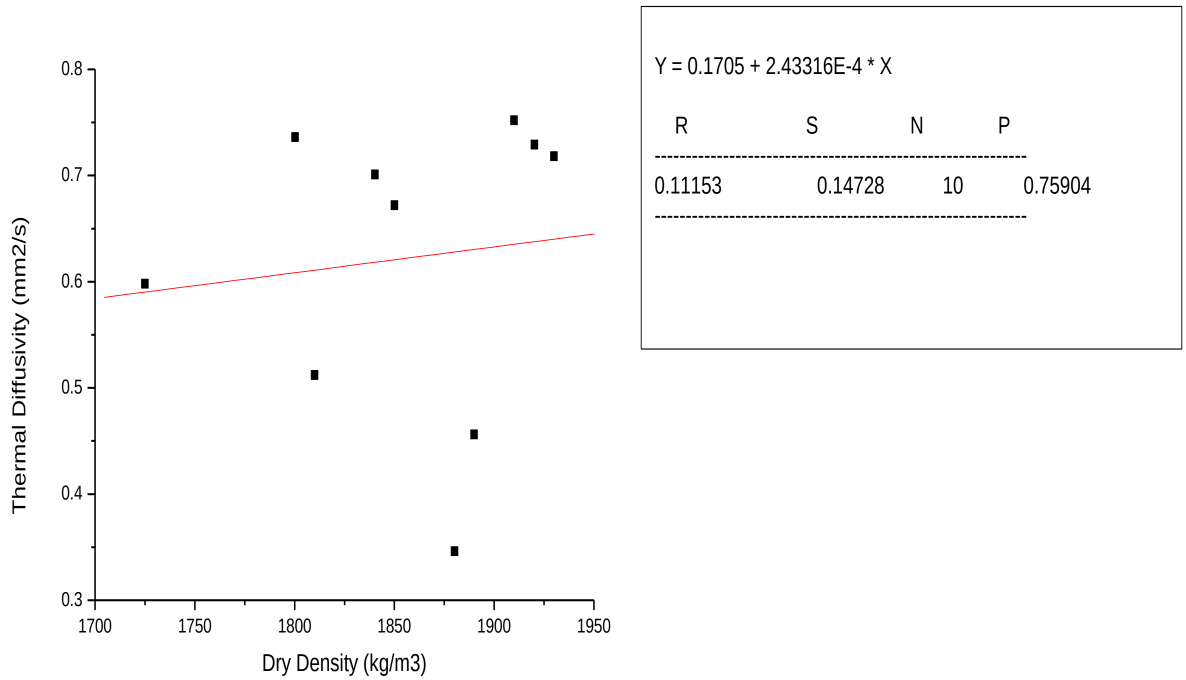


Figure 9a: Variation of Thermal Diffusivity and Dry Density

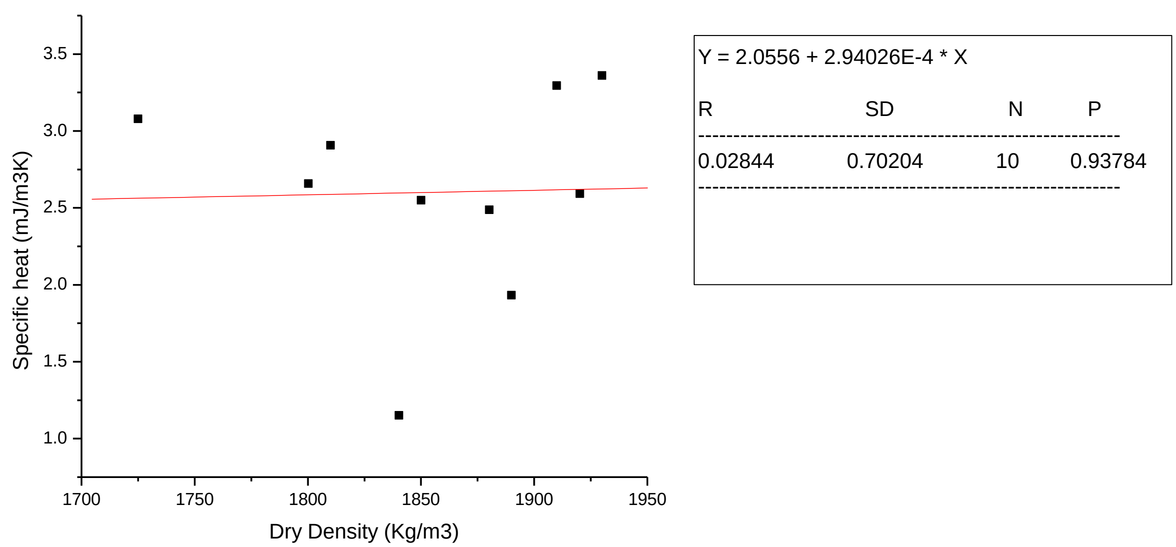


Figure 9b: Variation of specific heat with dry density

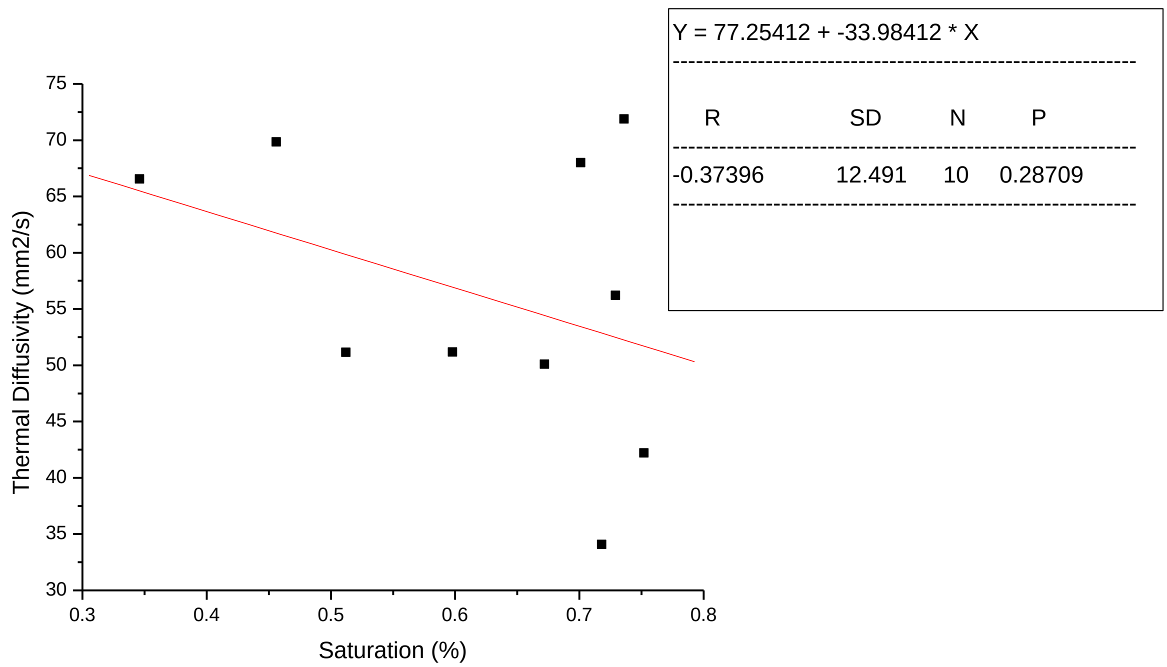


Figure 10a: Variation of thermal diffusivity with degree of saturation

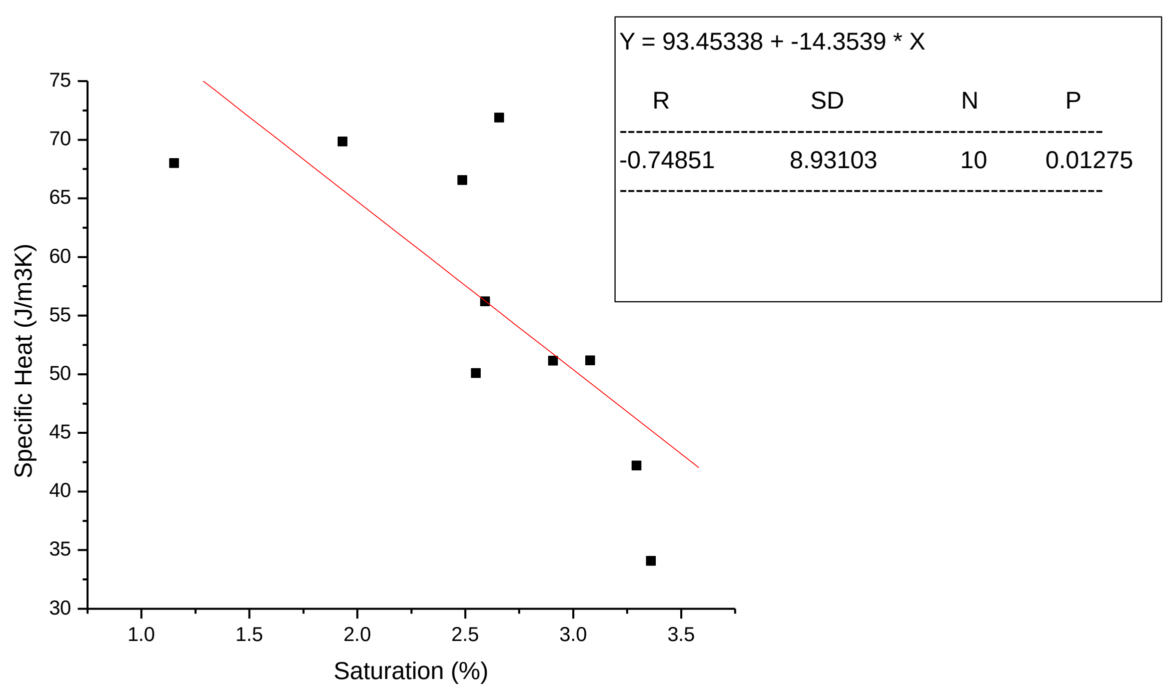


Figure 10b: Variation of specific heat with degree of saturation

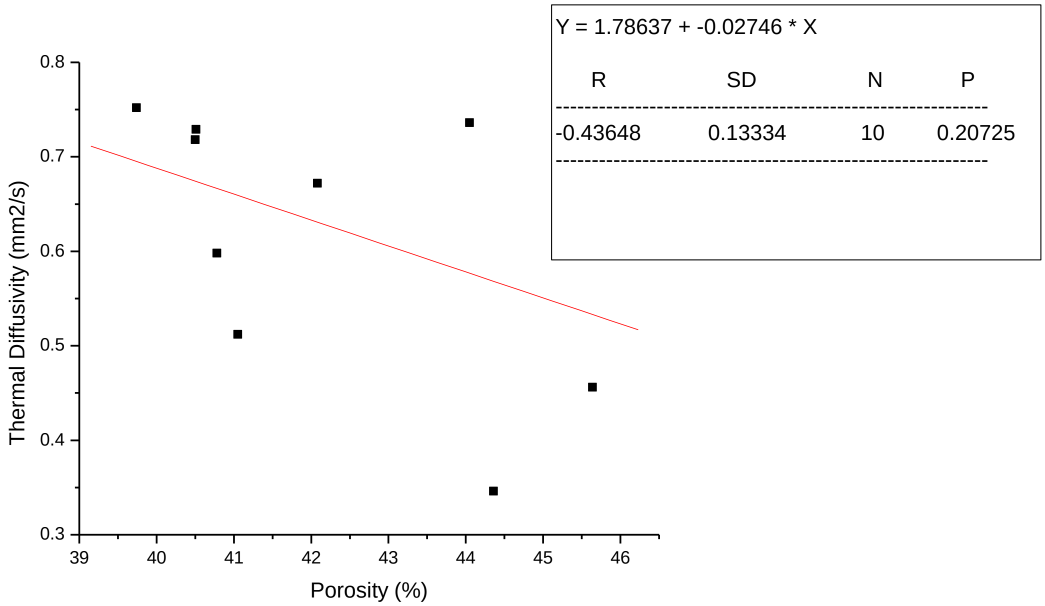


Figure 11a: Variation of thermal diffusivity with porosity

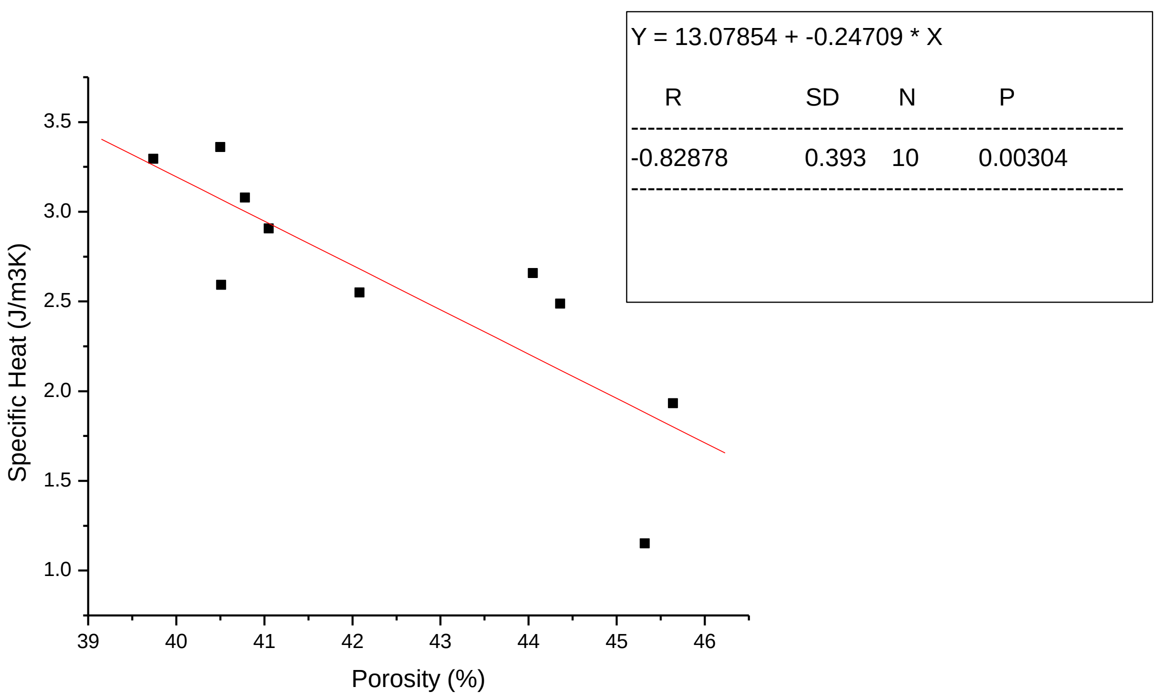


Figure 11b: Variation of specific heat with Porosity

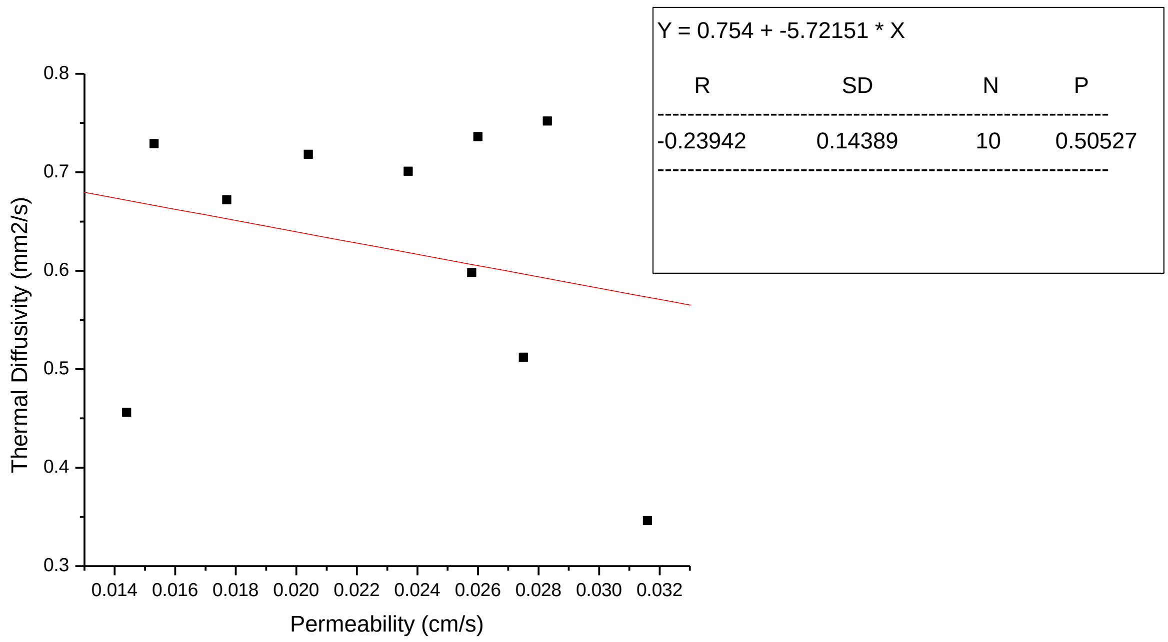


Figure 12a: Variation of thermal diffusivity with coefficient of permeability

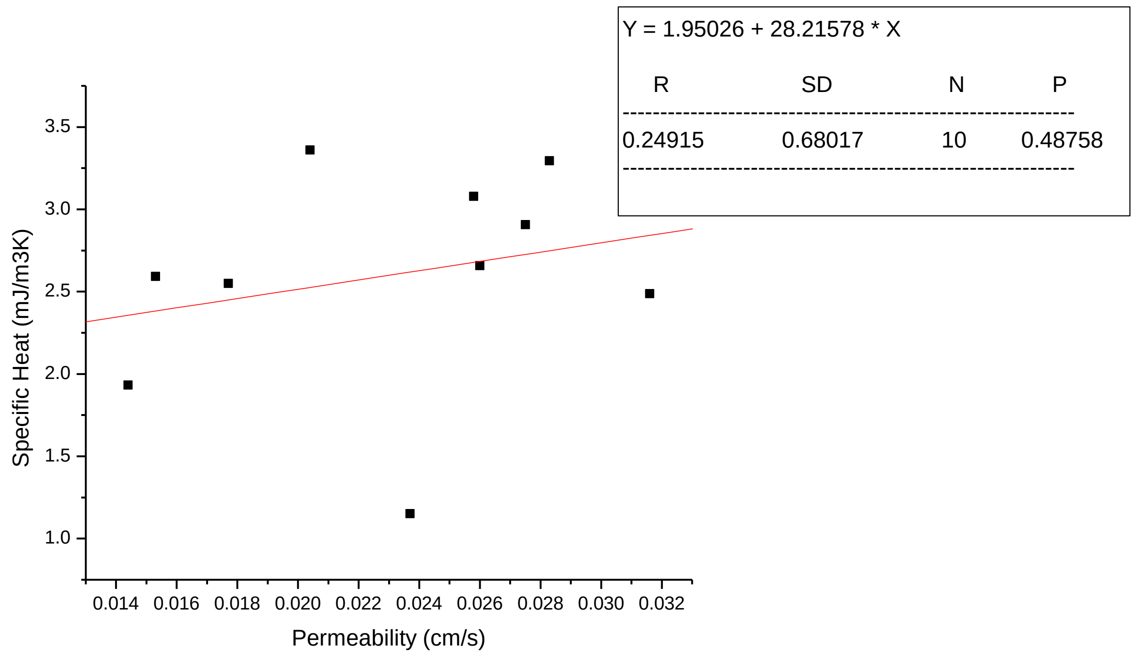


Figure 12b: Correlation of specific heat with coefficient of permeability

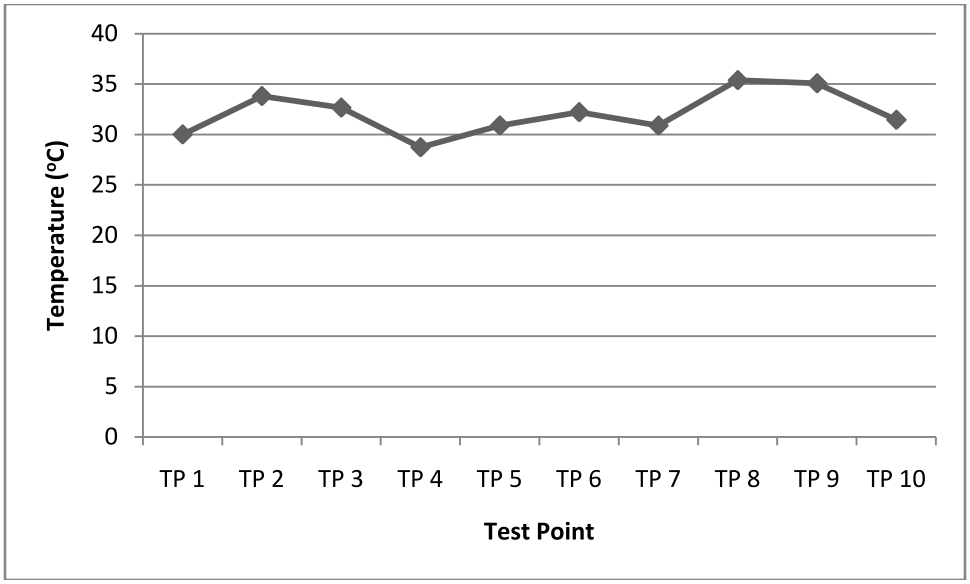


Figure 13: Variation of Temperature of soil in Olorunsogo Power Plant

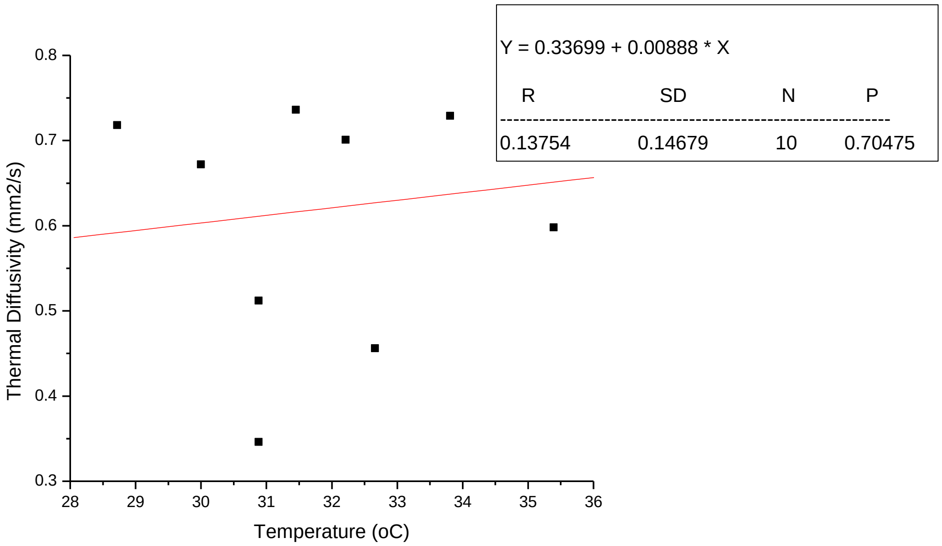


Figure 14a: Variation of thermal diffusivity with temperature

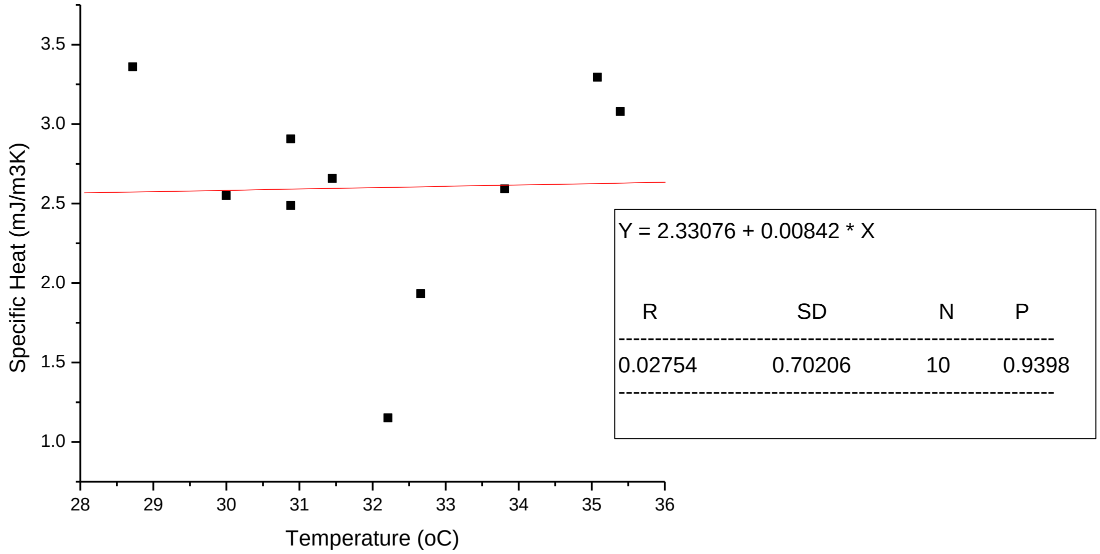


Figure 14b: Correlation of Specific heat with Temperature

Plate1: Photograph showing KD 2 Pro Meter

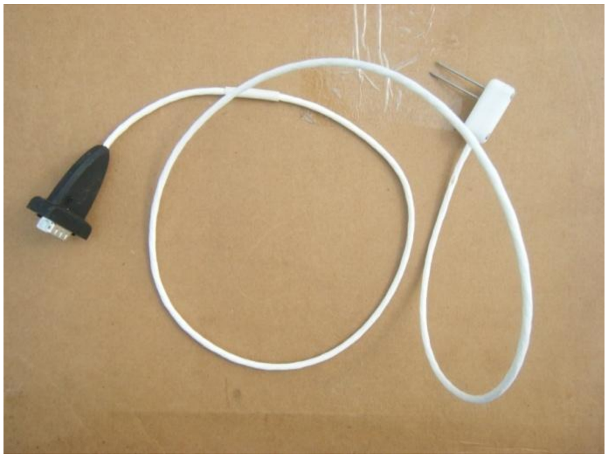


Plate 2: SH-1 Needle

Table 1: Thermal Properties of soils in Olorunsogo power plant

Test Point	Thermal Conductivity (W/mK)	Thermal Diffusivity (mm^2/s)	Specific Heat (mJ/m^3K)	Temperature (^oC)
1	1.714	0.672	2.550	31.13
2	1.890	0.729	2.592	32.21
3	0.881	0.456	1.932	35.39
4	2.414	0.718	3.361	28.72
5	0.861	0.346	2.487	33.04
6	0.807	0.701	1.152	33.81
7	1.490	0.512	2.907	32.66
8	1.843	0.598	3.079	32.41
9	2.476	0.752	3.294	31.98
10	1.955	0.736	2.658	34.20
Mean	1.633	0.622	2.601	32.11

Table 2: The thermal admittance of soils in the study area

S/N	Thermal Conductivity (W/Mk)	Density, ρ (Kg/m^3)	Specific Heat, C (mJ/m^3K)	Thermal Effusivity, β ($Jm^{-2}K^{-1}S^{-1/2}$)
1	1.714	1949.79	2.550	2.89
2	1.890	2024.78	2.592	3.15
3	0.881	1845.71	1.932	1.77
4	2.414	1864.85	3.361	3.89
5	0.861	1766.95	2.487	1.95
6	0.807	2058.16	1.152	1.38
7	1.490	1947.07	2.907	2.90
8	1.843	1875.26	3.079	3.26
9	2.476	1971.76	3.294	4.01
10	1.955	1980.75	2.658	3.21
Mean	1.633	1855.61	2.601	2.841

Table 3: Thermal Effusivities for common materials

Material	Thermal Effusivity ($Jm^{-2}K^{-1}S^{-1/2}$)
Static air	5
Standard pharmaceutical solids	150-800
Water	1600
Advanced composite materials	Several thousands

Source: [33]

Table 4: Physical Properties of soil samples in the study area

Sample Points	Optimum Moisture Content (%)	Porosity (%)	Degree of Saturation (%)	Maximum Dry Density (Kg/m^3)	Permeability (cm/s)	Specific Gravity
1	15.05	42.08	54.69	1850.10	0.0177	2.64
2	16.20	40.51	63.52	1920.25	0.0153	2.67
3	13.00	45.64	40.72	1800.25	0.0144	2.65
4	15.40	40.50	53.47	1840.25	0.0204	2.60
5	14.00	44.36	50.22	1725.05	0.0316	2.68
6	14.00	45.32	41.57	1930.00	0.0237	2.60
7	13.00	41.05	49.47	1880.20	0.0275	2.65
8	13.00	40.78	54.49	1810.00	0.0258	2.65
9	15.00	39.74	52.24	1890.02	0.0283	2.66
10	13.05	44.05	50.68	1910.02	0.0260	2.62

Table 5: Grain size distribution of soils in Olorunsogo Power Plant

Sample Point	Gravel (%)	Coarse Sand (%)	Medium sand (%)	Fine sand (%)	Silt (%)	Clay (%)
1	10.6	9.2	31.4	17.9	11.4	19.4
2	17.3	9.2	23.8	17.1	13.0	19.6
3	19.5	10.1	20.9	18.6	14.4	16.5
4	3.1	9.5	53.6	14.7	11.2	8.0
5	11.0	6.6	28.3	21.5	14.4	18.1
6	4.7	5.4	35.9	23.0	13.0	18.0
7	5.4	6.6	22.0	15.9	15.6	34.5
8	0	5.2	44.4	28.6	13.1	8.7
9	0	6.3	57.6	20.7	6.0	8.5
10	5.5	5.8	24.3	26.6	13.3	24.5

4. SUMMARY AND CONCLUSION

4.1 Summary

The thermal properties of soil such as thermal effusivity, thermal diffusivity and volumetric specific heat have been determined at Olorunsogo Power Plant. The thermal diffusivity as well as the specific heat increases with increasing moisture content. On the other hand, the thermal diffusivity and specific heat decreases with increasing dry density. The degree of saturation was also found to influence the thermal properties of soil. Thermal diffusivity and specific heat were found to increase with decreasing degree of saturation. It was found that both thermal diffusivity and specific heat decreases with increasing porosity. Specific heat was found to increase with increasing permeability while the thermal diffusivity was found to decrease with increasing permeability. Thermal diffusivity and specific heat were found to increase with increasing temperature. Soil in the study area with low thermal effusivity will hold heat much longer.

4.2 Conclusion

For safe and proper execution of various civil and electrical engineering projects, determination of thermal properties of soils such as thermal resistivity, thermal diffusivity, thermal effusivity and specific heat is quite essential. However, thermal properties of rocks would play an important role in various engineering projects such as design and laying of high voltage buried power cables, oil and gas pipe lines, ground modification techniques employing heating and freezing.

It has however been shown by various researchers that the thermal properties of soil depend on numerous parameters such as mineralogical composition, grain size of soil and physical properties like moisture content (w, %), dry density (ρ_d, g/cm^3) and saturation (S, %).

It has been observed that the thermal properties of soil in the study area and their variation with moisture content, dry density, degree of saturation, porosity, permeability, temperature, grain size and mineralogical composition agrees with the results reported in the literature except for the variation between porosity and specific heat.

From the thermal properties determined and the physical properties, it can be concluded that the soils in Olorunsogo Power Plant are good enough for laying of gas pipeline or buried cable.

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