

Design of a Device for Measuring the Thermal Conductivity of Granular Materials Using the Thermal Probe Method

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Abstract

In West Africa, the behavior of road base layers made of unbound granular materials in the face of temperature remains uncontrollable to date. To better understand this behavior, it is important to design a data acquisition device that allows the calculation of the thermal conductivity of said layers. This device is based on the thermal probe method governed by the ASTM D5334 standard. The device allows the measurement of temperature as a function of time for a minimum duration of 1000 seconds per test. The calibration of the device is done by measuring the respective conductivities of dry swale sand and charcoal powder, two materials whose thermal conductivities are known and documented. The calibration coefficient obtained is identical for the materials and is 0.97, a specific correction factor to be applied to all thermal conductivity values determined by this device.

Keywords

Thermal Probe, Thermal Conductivity, Correction Factor, Base Layers, Unbound Granular Materials

1. Introduction

In tropical countries in general and especially in West Africa, the effects of solar rays constitute one of the factors of degradation of road infrastructure [1]. Similarly, it appears that the temperature on the surface of the road at certain times of the day reaches a peak varying between 63.60°C to 69.30°C, exceeding that taken as a reference in the laboratory which is 60°C. This temperature stored at the level

of the surface layer is transmitted throughout the structure by conduction, weakens the granular base layers and sometimes causes cracks [2].

Therefore, thermal conductivity remains one of the key parameters of heat transfer in materials. It is characterized by its ability to conduct heat under a temperature gradient [3].

Several researchers have established various formulas or methods to evaluate the thermal conductivity of materials. For example, Lord Kelvin [4] [5] developed the thermal probe method in 1882 based on the concept of the infinite linear source. The thermal probe method used to determine thermal conductivity is now one of the essential methods for the thermophysical characterization of materials. It is a fast and practical method for laboratory and in situ measurement of the thermal conductivity of soils. According to De Vries and Peck [6] this method was first suggested by Schleiermacher ([7]) and then by Stalhane and Pyk ([8]). The first applications of this method were carried out by Van Drunen [8] [9] for the measurement of the thermal conductivity of liquids, then by Hooper and Lepper [10] [11] for the measurement of soils. The latter obtained very satisfactory results under unsaturated soils and also showed that there was no significant modification of the water distribution of the sample (subsequently confirmed by De Vries [6]). Since then, several studies have used this method to measure thermal conductivity in soils ([1] [12]-[15]). This method is also the subject of a standard established by ASTM in 2000 ([16]). The principle of this method, therefore, consists of seating linear thermal disturbance in the medium and measuring the temperature variation as a function of time. The test comprises two phases, which are used to determine thermal conductivity. The first is a heating phase, which is followed by a rest phase during which the probe ceases to be excited.

The box method is highlighted for the calculation of the thermal conductivity of materials by Nassima Sotahi ([17]). In 2011, Yves Jeannot [18] implemented the guarded hot plate method to evaluate the thermal conductivity of insulators.

To facilitate the measurement of the thermal conductivity of granular road materials, given the lack of adequate equipment in our laboratories and the very high acquisition cost, it is therefore important to design a reliable, less expensive, and very practical data acquisition device, usable in the laboratory and in situ. For this purpose, the present study is initiated according to the ASTM D5334 version [16].

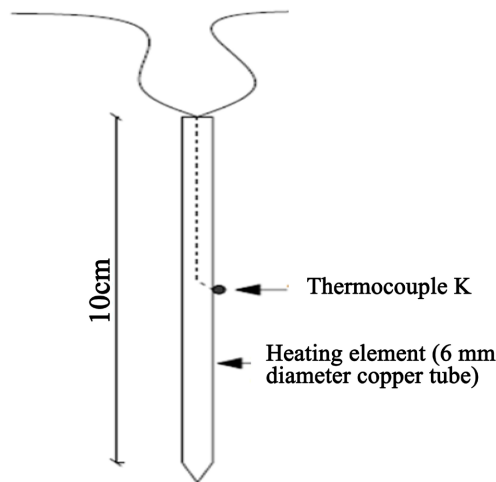
2. Description of the Device

The data acquisition device for determining thermal conductivity is composed of:

- **Thermal needle probe (Figure 1):** This is a device that creates a heat source. This probe incorporates a thermocouple or thermistor, an element that measures the temperature due to the variation of heat at a point along the rod.
- **Heating rod:** This is an aluminum rod with a diameter of 4.9 mm and a length of 10 cm. With a resistance of 52 ohms, it is inserted inside the copper tube and can operate at a temperature between 15°C and 35°C.
- **Constant current source:** This is a direct current with a maximum voltage of

12 V.

- **Power variator (Figure 2):**



It is made up of:

- a copper tube 10 cm long, with an external diameter of 6 mm and a thickness of 0.5 mm,
- a heating wire connected to the current source, and
- a DS18B20 type temperature sensor with very negligible error, accuracy $\pm 0.5^{\circ}\text{C}$ and a measuring range from -55°C to $+125^{\circ}\text{C}$.

Figure 1. Schematic of the thermal probe.



- Brand Eventek KPS305D or equivalent.
- Variable DC power supply (0-30 V; 0-5 A),
- Digital adjustable switching regulated power supply,
- Alligator clips, US power cord with maximum input voltage of 220V against minimum input voltage of 110V.
- Output power: 300 \pm 2 watts.
- Air cooling.

Figure 2. Power variator.

- **Thermal reading unit:** This is a computer designed to read the temperature in degrees Celsius. It is connected to the acquisition box via a USB port.
- **Acquisition box (Figure 3):** this is the central data acquisition engine.



The DataViewPro 2.0 mini system is an advanced temperature acquisition system designed to determine the thermal conductivity of materials. It consists of a physical part for experimental measurements and a software part accessible via the computer to which the system is connected.

Figure 3. Acquisition box.

- **Chronometer** consisted of measuring operating times, in order to allow the calculation of times allocated to range operations;
- **A drill bit:** An instrument capable of drilling a straight vertical hole having a diameter as close as possible to that of the probe and to a depth at least equal to the length of the needle;
- **PVC cylinders** having the characteristics of a Modified Proctor mold;

3. Method for Determining Conductivity

The test for determining thermal conductivity by the quasi-steady-state thermal probe method is defined by ASTM D5334 version [16]. This method allows the determination of the thermal conductivity of soils and soft rocks in the laboratory and *situ*. Thus, the temperature measured during the heating period is the output signal from which the thermal conductivity of the medium is determined under certain assumptions.

The basic assumptions are as follows:

- ✓ H1: Homogeneous, isotropic and infinite material;
- ✓ H2: Uniform and stable material temperature before heating.

3.1. Measurement and Acquisition

3.1.1. Measure

The different key stages of the measurement process with the device can be summarized as follows:

- Put the material into the PVC mold;
- Connect the heating wire of the thermal probe to the constant current source through a power controller;
- Connect the wires from the acquisition system to the computer to be able to read the temperatures;
- Apply a current of constant intensity determined from the characteristics of the heating wire;
- Record temperature readings at 0 s, 5 s, 10 s, 15 s, 30 s, 45 s, and 60 s, then take measurements at 30 s intervals for a minimum of 1000 s;
- Turn off the constant current source once the measurement time has been reached;
- Record temperature readings until the temperature stabilizes;
- Plot the temperature data versus the logarithm of time on a semi-logarithmic graph;
- Select the linear portion of the curve (quasi-stationary phase)
- Draw a straight line passing through the points of the linear portion using the linear regression method, giving a regression coefficient close to 1;
- Read the slope S_h of the regression line;
- Weigh the sample at the end of the test to determine its dry density and take a representative sample of the sample to determine its water content at the end of the test.

3.1.2. Acquisition

The acquisition system connected to the thermal probe is responsible for collecting temperature values over time. It communicates with the thermal probe by means of a control program that contains the test parameters:

- Current intensity supplied by the variator: $I = 0.1 \text{ A}$;
- Probe resistance: $R_{sonde} = 120 \Omega$;
- Probe length: $l = 0.1 \text{ m}$;
- Current voltage $U = 12 \text{ V}$;

This entire system is controlled by a program written in Python. Once the connection between the probe and the acquisition system is established, the control program is sent to the acquisition system, which is responsible for collecting the temperature values every second. As soon as all the necessary measurements are made, they are recorded in an output file, which is used to calculate the thermal conductivity. **Figure 4** below schematically illustrates the method for measuring thermal conductivity.

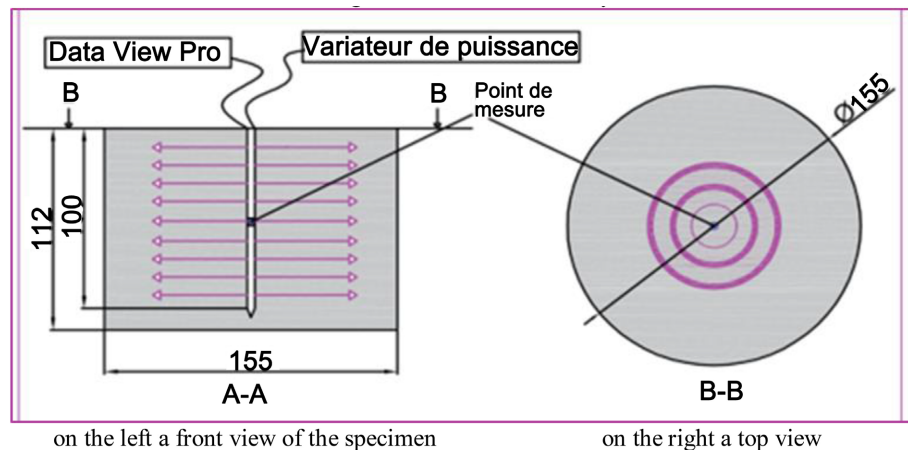


Figure 4. Schematic representation of the thermal conductivity measurement method.

3.2. Calibration

Calibration of the device consists of calibrating the latter to evaluate its efficiency and its precision on the one hand, and to define a correction factor used to correct the measurements on the other hand. The correction factor C_λ is defined by the ASTM D5334 standard [16] as the ratio between the value of the thermal conductivity $\lambda_{matériau}$ of the known material and that measured using the device noted $\lambda_{mesuree}$, such as:

$$C_\lambda = \frac{\lambda_{matériau}}{\lambda_{mesuree}} \quad (1)$$

The calibration material is selected from materials with thermal conductivity in the following range: ($0.2 < \lambda < 5 \text{ W}/(\text{m} \cdot ^\circ\text{C})$). Dry rill sand and charcoal were used in this work. These two materials have well-documented thermal conductivities and are given in **Table 1**.

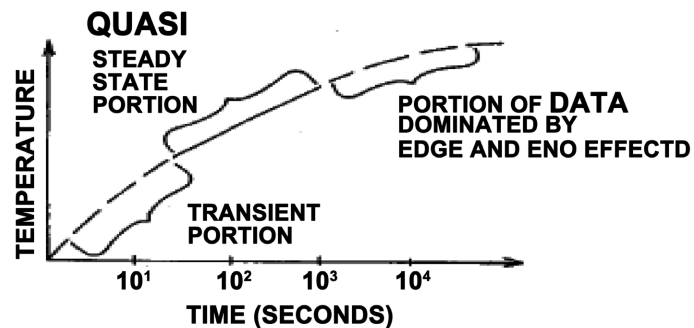
Table 1. Thermal conductivities of the materials used during the calibration phase.

Material	λ (W/(m·°C))	Condition	Reference
Dry rill sand	0.400	$\rho = 1600 \text{ kg/m}^3$	http://fourmailletard.canalblog.com/archives/2008/12/13/12589580.html
Fine coal dust	0.16	$30 \leq T(^{\circ}\text{C}) \leq 150$	http://fourmailletard.canalblog.com/archives/2008/12/13/12589580.html

It is necessary to pay attention to the following points:

- Insert the thermal needle probe into the sample either by pushing the probe into a pre-drilled hole (dense sample) to a depth equal to the probe length or by pushing the probe into the sample (loose sample). Care should be taken to ensure that the thermal probe shaft is fully embedded in the sample and not left partially exposed;
- Dry the calibration material until its mass stabilizes;
- Leave the sample for a while to allow its temperature to stabilize at room temperature.
- ✓ Data analysis

The curve in **Figure 5** corresponds to the ideal result of a thermal conductivity test. The determination of the coefficient λ is done by considering the temperature values of the quasi-steady *state portion*.



A) IDEALIZED CURVE

Figure 5. Ideal curve of temperature as a function of time ([16]).

According to ASTM D5334 ([16]), the transient phase of the test should not be taken into account in the processing of the results. Indeed, when the heat source is generated along the probe, it must pass through the material constituting the probe before reaching the experimental material ([6] [19] [20]). The non-linear part at the beginning, therefore, corresponds to the heating of the probe and must be removed from the analysis.

For the heating phase, a series of points is projected into the plane $(\ln(t), T)$ which made it possible to determine the slope noted S_h of the line obtained by linear interpolation.

The thermal conductivity of the medium is then given by relation 2. To limit errors in the calculation of thermal conductivity, it is necessary to calibrate the

probe ([14] [16] [21]). Thus, the general expression of thermal conductivity which also integrates the correction factor C_λ is:

$$\lambda = C_\lambda \frac{Q}{4\pi(T_2 - T_1)} \ln\left(\frac{t_2}{t_1}\right) \quad (2)$$

With:

$$Q = \frac{RI^2}{L} = \frac{UI}{L} \quad (3)$$

By posing

$$S_h = \frac{T_2 - T_1}{\ln(t_2) - \ln(t_1)} = \frac{T_2 - T_1}{\ln\left(\frac{t_2}{t_1}\right)} \quad (4)$$

λ then becomes the following:

$$\lambda = C_\lambda \frac{Q}{4\pi S_h} \quad (5)$$

We note:

Q : linear power supplied to the medium (W/m);

R : resistance of the thermal probe (Ω);

I : constant current flowing through the heating resistor (A);

L : length of the heating element (m);

λ : thermal conductivity (W/(m·°C));

C_λ : correction factor;

t_1 and t_2 : measurement time (s);

T_1 and T_2 : temperatures corresponding respectively to times t_1 and t_2 ;

S_h : slope of the linear regression.

The methodology for in situ measurements is identical to that for laboratory measurements. During in situ tests, the section of track in which the measurements are to be taken must be isolated from traffic. In situ measuring campaigns are carried out during the dry season.

4. Results and Discussions: Calibration phase

The calibration tests carried out on charcoal powder and on dry gully sand made it possible to plot the curves in **Figures 6-9** ([22]-[25]). **Figure 6** and **Figure 7** present the curves showing the evolution of the temperature as a function of time relative to the tests carried out on dry gully sand and on charcoal powder.

By observing the two curves in **Figure 6** and **Figure 7**, it was noticed that during the heating phase the temperature increased exponentially until it stabilized. On the other hand, during the resting phase it also decreased exponentially. The evaluation of λ is made by considering the exponential part, that is, the time interval [0 s; the 390 s] for dry rill sand and [0 s; the 720 s] for charcoal powder.

Figure 8 shows the representation of temperature as a function of time in the exponential domain, the computational domain of λ dry rill sand and charcoal powder ([26]-[33]).

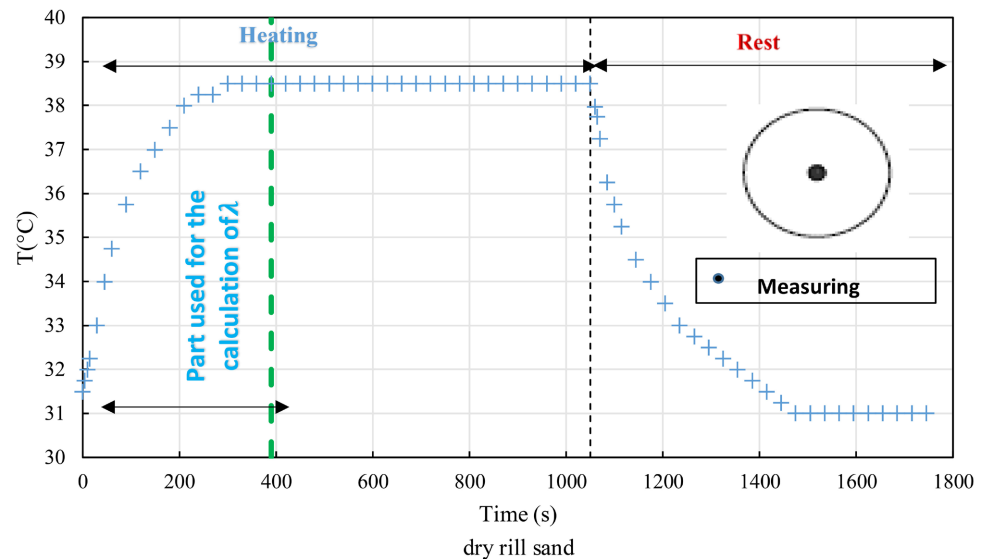


Figure 6. Evolution of temperature as a function of time.

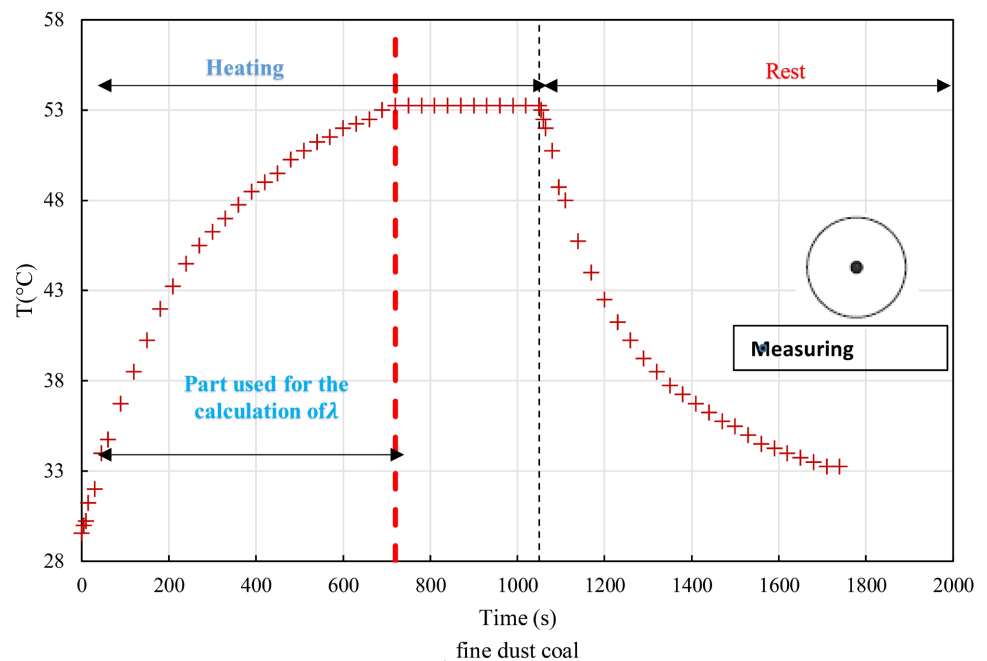


Figure 7. Evolution of temperature as a function of time.

Figure 9 shows the temperature variation in the plane $(T, \ln(t))$ of the heating phase. In particular, Figure 9(c) and Figure 9(d) represent the quasi-stationary part observed at the level of each material. The stationary part is included between the two vertical dotted lines (---) on the curves of Figure 9(a) and Figure 9(b) respectively for dry rill sand and for charcoal powder. This quasi-stationary part is defined by the set of successive points approximately forming a straight line. After identifying this part, a linear regression of the different points made it possible to obtain the straight lines of equations $y = 2.318x + 26.614$, $R^2 = 99.85\%$ for dry rill sand and $y = 5.804x + 1.3563$, $R^2 = 99.75\%$ for charcoal powder.

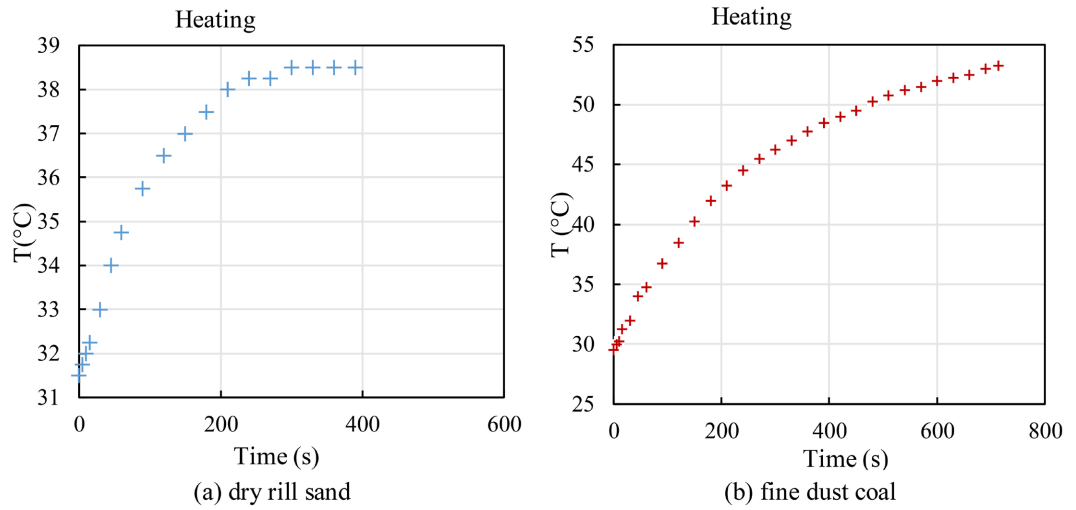


Figure 8. Evolution of temperature as a function of time in the exponential domain.

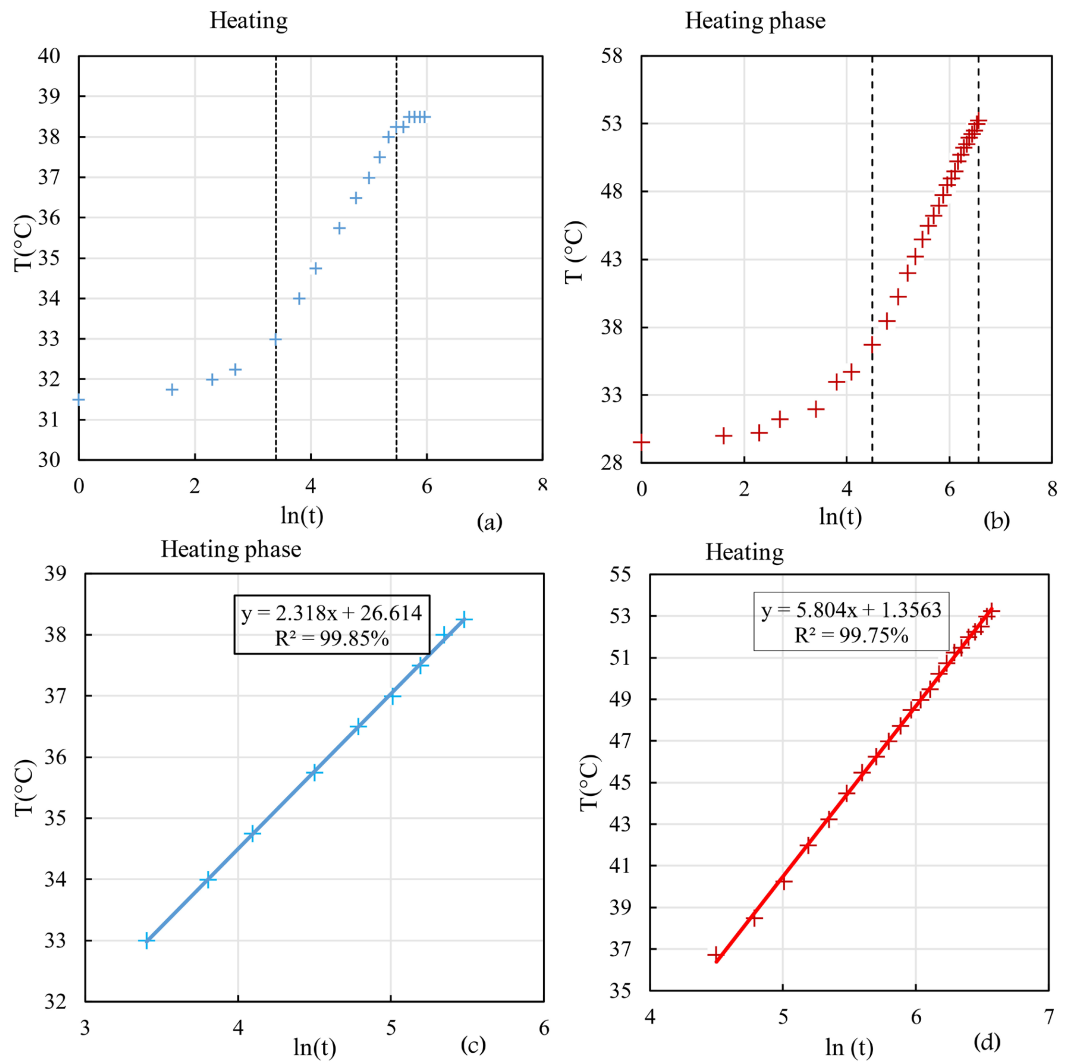


Figure 9. Temperature variation in the plane $(T, \ln(t))$: (a) and (c): Dry rill sand; (b) and (d): Fine coal dust.

From the equations of the linear regressions, the slopes of the two materials are obtained. Thus, from these slopes, the thermal conductivity of each of the two materials is determined. **Table 2** shows the slopes of the linear regressions of the two materials.

Table 2. Slopes of the linear regressions of the two materials.

Materials	Slopes S_h
Dry rill sand	2.3182 \approx 2.318
Charcoal dust	5.804

- The linear electric power is given by:

$$Q = \frac{RI^2}{L} = \frac{UI}{L} \quad (6)$$

Let

$$Q = \frac{12 \times 0.1}{0.1} \quad (7)$$

Which gives $Q = 12$ W/m

Considering dry rill sand, we have $S_h = 2.318$

So, we have:

$$\lambda = \frac{12}{4 \times \pi \times 2.318} = 0.412 \text{ W}/(\text{m} \cdot ^\circ\text{C}) \quad (8)$$

So the conductivity of dry rill sand is $\lambda = 0.412$ W/(m·°C).

By analogy, we obtain the thermal conductivity of charcoal powder. Let $\lambda = 0.165$ W/(m·°C).

Then, the calibration coefficient C_λ for each material is determined from Equation (1).

So for dry rill sand, we have:

$$C_\lambda = \frac{0.400}{0.412} = 0.97 \quad (9)$$

For charcoal powder, we have:

$$C_\lambda = \frac{0.16}{0.165} = 0.97 \quad (10)$$

We note that the calibration coefficients calculated for the two materials are identical. Therefore we retain that $C_\lambda = 0.97$.

Table 3. Comparative table of values measured and those taken from the literature.

N°:	Material	Thermal conductivity (W/(m·°C))	
		Measured values	Literature values
1	Dry gully sand	0.412	0.400
2	Charcoal powder	0.165	0.16

To summarise, **Table 3** below shows the thermal conductivity values measured and those given in the literature, for dry gully sand and charcoal powder respectively.

5. Conclusions

This study has enabled the development of a device for measuring the thermal conductivity of unbound granular materials. It is a simple and very practical device for laboratory and in situ testing. This device is composed of an acquisition box, a power variator, a thermal probe equipped with a temperature sensor, and a computer. The calibration coefficient determined from measurements carried out on dry gully sand and charcoal powder is 0.97, a correction factor to be applied to all thermal conductivity values obtained from said device.

The cost of producing the device is 400,000 FCFA or around US\$690. Equipment marketed by manufacturers via the Alibaba website (<https://french.alibaba.com/product-detail/DRH300-Guarded-hot-plate-thermal-conductivity-60651067350.html>) costs between US\$6200 and US\$9000, *i.e.* at least 9 times the cost of the present device.

Although DS18B20 sensors have good accuracy ($\pm 0.5^{\circ}\text{C}$ within the specified range), they are subject to self-heating leading to possible drift over time, hence the need for periodic checks or recalibration.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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