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THERMAL CONDUCTIVITY AND DIFFUSIVITY MEASUREMENTS BY THE TRANSIENT TWO LINEAR AND PARALLEL PROBE METHOD

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ABSTRACT

A new transient method for simultaneous thermal conductivity and diffusivity measurements is described. It employs two linear and parallel probes to be inserted in the material under test. One probe is used as a linear heating source while the other one as a temperature sensor. By recording the rate of the temperature rise of this second probe and applying the line heat source theory, developed by Carslaw and Jaeger (1959), thermal conductivity and diffusivity are determined in few minutes with very low temperature gradients applied to the sample. These properties make the method particularly suitable for applications in nonhomogeneous, damp and porous materials, like concrete, rock and soil.

The reliability of the method has been verified by comparing the experimental results obtained in some reference materials with the measurements performed on the same samples by other known and standardized methods.

Some applications concern the effects of the moisture content on the thermal properties of concrete and correlations between dry sand density and thermal conductivity: experimental results are presented and discussed.

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INTRODUCTION

Thermal conductivity and diffusivity of structural materials like concrete, rock and soil are of importance in many engineering applications ranging from energy conservation scheme to techniques for forecasting structural displacements of large structures.

Concrete, rock and soil are heterogeneous, damp and porous solids, so that the measurement of their thermal properties by conventional methods is subjected to large errors.

For example one of the main problems that must be overcome during the experimental determination of the thermal conductivity in such damp and porous materials is associated with the moisture content changes arising as far as a thermal gradient is applied to the material. The ways to prevent this effect consist in reducing as much as possible the run time of the test and the thermal gradient applied to the sample. The second solution can involve the use of temperature sensors with a very high sensitivity so that the first solution is more usually adopted.

To this aim in the last years transient measurement methods have been extensively studied as in comparison with steady state techniques they are less time-consuming.

THE TRANSIENT THERMAL PROBE METHOD

The most widely used transient method for measuring the thermal conductivity is the thermal probe method.

It is based on the theory developed by Carslaw and Jaeger (1959) referred to an infinite linear heat source buried in an infinite homogeneous medium.

Briefly, it states that the temperature rise T at a radial distance r from the heating source is given by

$$T(r,t) = - \frac{q}{4\pi\lambda} E_i \left(- \frac{r^2}{4Dt}\right) \qquad (1)$$

where E_i is an exponential integral, q is the power input for unit length of the heat source, λ and D are the thermal conductivity and thermal diffusivity, respectively.

By expanding the exponential integral in a power series, it is possible to show that for small values of r and long time t equation (1) becomes

$$T(t) = \frac{q}{4\pi\lambda}\left(\ln t + \ln \frac{4D}{r^2} - C\right) \qquad (2)$$

where C is the Euler's constant.

This expression shows that the temperature rise against the natural logarithm of the time is a straight line whose slope is proportional to the thermal resistivity of the material to be tested.

THE THERMAL PROBE

Figure 1 shows the details of the thermal probe that we have used as a linear heat source.

It is made up of stainless steel sheath which can have a diameter of 1 mm and a length of 70 mm or a diameter of 4 mm and a length of 300 mm. Inside it there are a karma resistive wire as heating element arranged for the whole length of the probe and a NTC thermistor as temperature sensor placed at middle height.

The electrical wires inside the probe are insulated electrically by an alumina tube. An epoxy resin is used to fill the voids inside the tube and to seal its ends.

After that the probe is buried in the sample and allowed to come to thermal equilibrium with it, temperature readings for 400 sec are performed to evaluate a possible thermal drift of the sample. Then the power q is switched on and temperature rise readings against the time are carried out and corrected according to the thermal drift coefficient previously obtained.

In order to have a good thermal contact between probe and solid samples, a silicon grease is used at their interface.

Fig. 2 shows a typical graph of the temperature rise of the probe against the time in comparison with the ideal line heat source response.

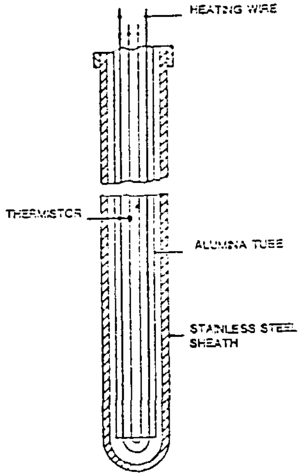

Fig. 1 - Details of a thermal probe.

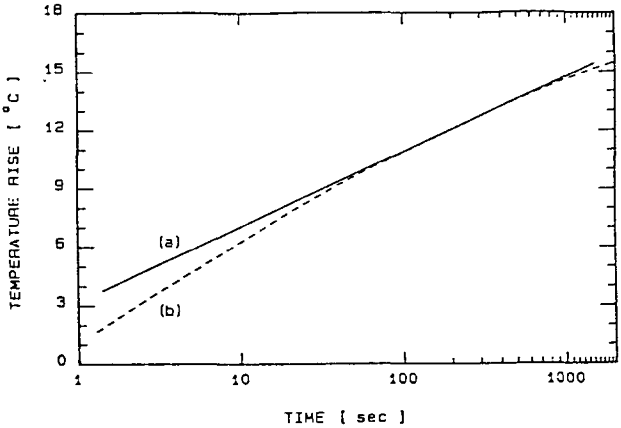

Fig. 2 - Comparison between the ideal (a) and real (b) line heat source response.

Some differences are evident at short and long heating times. They depend on the finite dimensions of the probe, on the thermal interface between probe and material and on the thermal properties of the material to be tested.

These effects can mask the right interval of time where equation (2) must be applied. In order to overcome this limitation the following more reliable method, based on the same theory, has been developed.

THE TWO LINEAR AND PARALLEL PROBE MEASUREMENT METHOD

Differentiating equation (1) with respect to time we obtain:

$$\frac{dT}{dt}(r,t) = \frac{q}{4\pi\lambda t} \exp\left(-\frac{r^2}{4Dt}\right) \qquad (3)$$

This function is plotted in fig. 3.

Taking into account the maximum value m and the related time t_m, it is possible to show that the thermal conductivity and diffusivity can be evaluated by the following expressions:

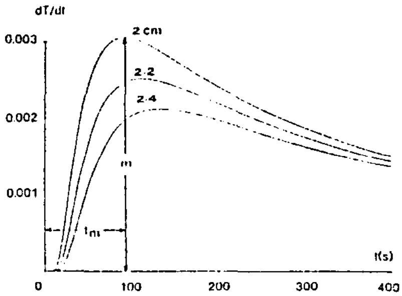

Fig. 3 - Plot of dT/dt versus time t.

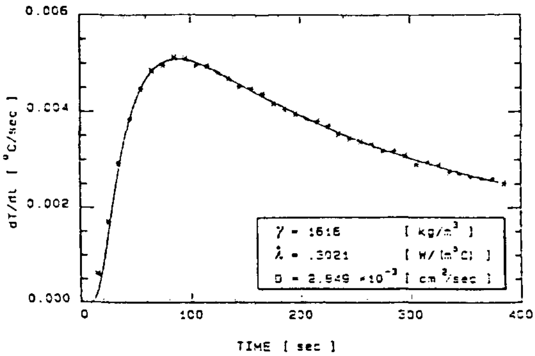

Fig. 4 - Example of a test performed in a dry sand sample.

$$\lambda = \frac{q}{4 \pi e \quad m \quad t_m} \qquad D = \frac{r^2}{4 t_m} \qquad (4)$$

The experimental plot of equation (3) is obtained by using a second probe, as temperature sensor, inserted into the material to be tested at a well known distance r from the heating probe and parallel to it.

In fig. 4 a typical test result carried out on a dry sand sample is presented.

The finite dimensions of the probe introduce a finite thermal capacity in series with the interface thermal resistance between probe and material under test. Their effects give arise to a thermal transient t_0 whose duration is properly evaluated and taken into account during each test by a particular approach reported in [2].

The main advantages of this new method are:

- simultaneous measurement of thermal conductivity and diffusivity;
- short run time of the test (from 400 sec to 1000 sec in dependence on the thermal diffusivity of the sample);
- low thermal gradient applied to the sample.

In order to verify its reliability, some solid materials have been tested. The relative thermal conductivity measurements have been compared with the results obtained on the same samples by the standardized hot-guarded plate method for thermal conductivity measurements.

The results reported in fig. 5, show a quite good agreement between the thermal conductivity measurements performed by the hot-guarded plate method and the corresponding measurements performed with the method proposed in this work.

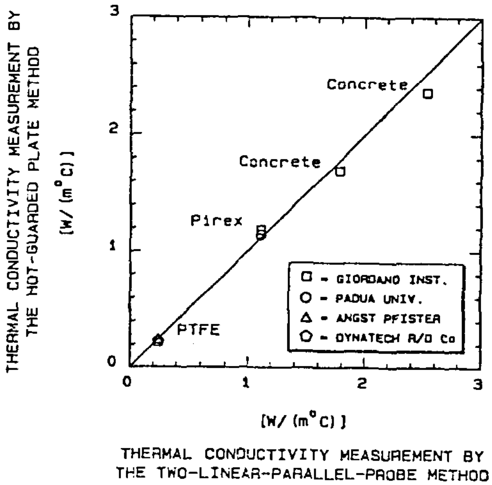

Fig. 5 - Comparison between the two linear and parallel probe method and the hot-guarded plate method.

Finally, a lot of tests performed on concrete samples, prepared in laboratory and kept at a constant temperature and moisture content, have shown that the thermal conductivity and diffusivity measurements are reproducible within $\pm$ 2-3% /4/.

APPLICATIONS

The main applications of the two linear and parallel probe method concern the evaluation of the thermal properties of concrete, rock and soil samples and their dependence on some other parameters of the materials.

As an example, fig. 6 shows the thermal conductivity measurements results performed in different concretes against their moisture content.

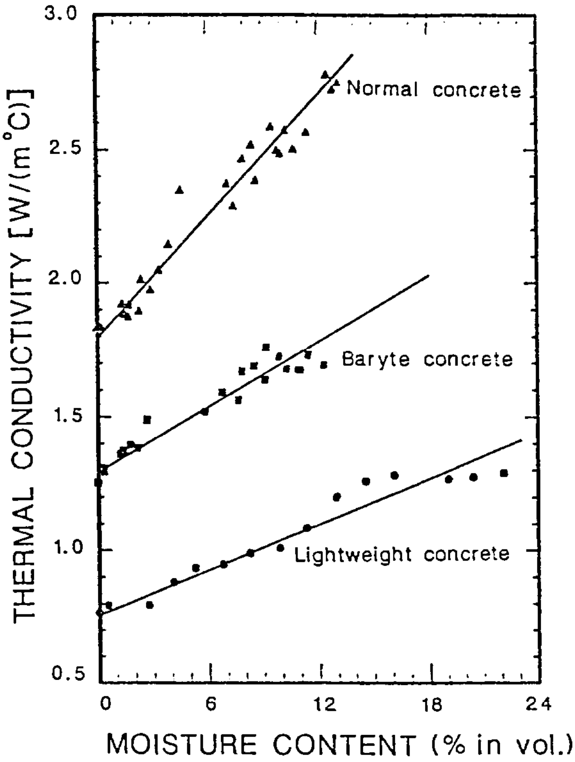

Fig. 6 - Thermal conductivity against the moisture content of concrete.

They put in evidence that the thermal conductivity increases in a quite linear way with the moisture content of concrete. The same experimental tests have shown that the thermal diffusivity seems to be independent of the moisture of concrete. Its value ranges from 0.005 cm^2/sec to 0.009 cm^2/sec in dependence on the type of concrete /3/.

As regards the applications carried out in dry sand, in fig. 7 the thermal conductivity measurements of two different sands against the dry density are reported: the results exhibit the increase of the thermal conductivity with the sand density.

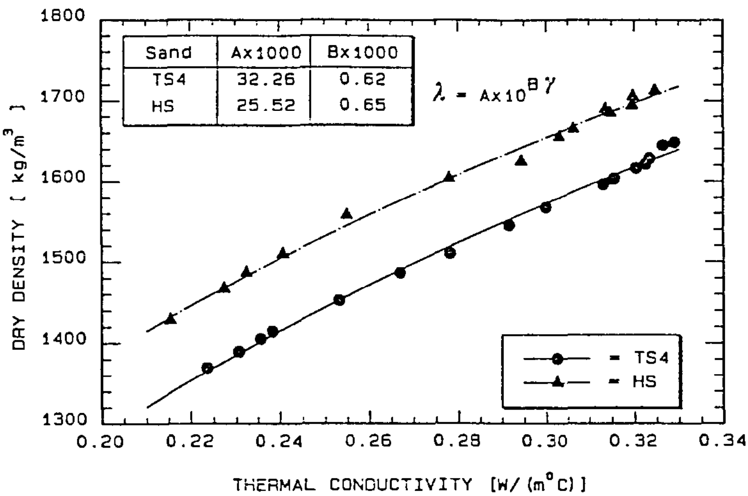

Fig. 7 - Thermal conductivity against the dry bulk density of sand.

CONCLUSIONS

A new transient method for simultaneous thermal conductivity and diffusivity measurements is proposed. It is based on the linear heat source theory.

Some applications have shown the influence of the density on the thermal conductivity of the sand and put in evidence the effects of the water content on the thermal properties of concrete.

They have also shown that the method is particularly suitable to be applied in damp and porous solids where water migration can arise if steady-state methods are used.

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