THERMAL CONDUCTIVITY OF ROCKS

A Thesis Submitted

By

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For

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To

The Faculty of Science,

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To

My Brother & Children

and

Memory of My Father.

C O N T E N T S

A C K N O W L E D G M E N T

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AIM OF THE WORK

There has been a considerable rise of interest, recently in the equilibrium heat flux across the earth's crust, both over the continents and over the ocean floors. The equilibrium heat flux is of great importance to an understanding of many physical problems connected with the earth's interior. The measured flux, however, is affected by a number of factors which depend mainly on the geological history of the earth. To find the flux occuring locally, it is necessary to determine the temperature gradient and the thermal conductivity of the rocks in the area. If the dimensions of the area are small compared with the dimensions of the earth and if there is no horizontal variation of constituents, the heat flow may be considered linear and the flux is given by the product of the temperature gradient and the thermal conductivity. To account for the effects of the geological history of the area a correction, generally to the temperature gradient, can be applied to arrive at a value for the equilibrium heat flux. Unfortunately, even the corrected values are considered approximations only, because the geological history of an area is, in general, not known with sufficient accuracy.

Furthermore, in such an investigation, it appears that there is a need for a large number of results from different areas all over the world. When these gathered results are plotted on a world map and isoplan lines are drawn, it may be hoped that some general picture of the pattern heat flow will be represented.

The fundamental implications of the results so far obtained are comprehensively reviwed in articles by Bullard (1952) and Jacobs (1954).

It is now a fact that the temperature in a mine or a borehole increases with depth, the temperature gradient ranges normally between 10 °C and 50 °C per kilometer. The gradient is due to a flow of heat from within the earth which can be estimated if the temperature gradient and the thermal conductivity are known.

Measurements of temperature gradient can be made in boreholes, mines and tunnels on land with very simple equipment. The temperature gradient in the sediment beneath the ocean floor has been measured along a probe 3 to 5 m. long forced into the soft sediment. Usually thermocouples or thermistors are used in such measurements at sea.

The thermal conductivity measurement of Limestone in El-Max region at Alexandria is the main concern of this work. The author hopes that the results obtained in this work will stimulate further thermal conductivity measurements of other types of rocks in the area as well as temperature gradient measurements. The future collected data will pave the way towards a future determination of the equilibrium heat flux in the region of Alexandria.

CHAPTER I

LABORATORY METHODS OF THERMAL CONDUCTIVITY MEASUREMENTS

Introduction :

The first experiments to determine the thermal conductivity of rocks were not connected with an investigation into the flow of heat from the crust of the earth; they were conducted merely to collect geophysical data.

Rock conductivities may be determined in two fundamentally different ways : by measurements in situ and by measurements in the laboratory. In both cases a troublesome contact resistance between the specimen and the temperature-measuring device has to be eliminated. The first determinations were made using in situ methods which were superseded, at least temporarily, by laboratory techniques introduced by Herschel and Lebour (1873) which at that time were less laborious. In more recent times it has been realized that in certain cases the small rock specimens used in the laboratory are not representative of a large mass of the rock. For this reason, attention has again turned to in situ methods using boreholes or short probes in the sides of tunnel walls.

The disadvantages of laboratory methods may be summed up as follows :

(a) They require additional apparatus and time for the preparation of the discs.

(b) They are selective in the sense that discs can only be prepared from fairly sound rock and that cores may not be recovered at all from highly altered or sheared zones.

(c) They use specimens that are frequently too small to be representative of even the sound rock.

(d) They do not take into account the effect of open veins or joints in the rock, which may well be important.

(e) They are used at pressures that are different from the pressures prevailing in situ.

All these disadvantages are considerably reduced by the measurement of the conductivity of the rock in situ in a borehole.

Steady-State Methods :

Until recently the apparatus for the measurement of thermal conductivity of solid materials of lower conductivity than metals such as soils and clays has generally been of one type namely, the steady-state hot-plate method. This consists of a small cylindrical prism of the sample, the ends of which are bound by metal slabs of higher conductivity. Heat is supplied at a known rate to one of the slabs and taken away at the other, so that the specimen is a part of the path of uniform flow of heat. Under these conditions, the temperature difference on both sides of the specimen is measured and the conductivity can readily be calculated. Several hours may be required for the determination of the conductivity of a specimen with this method because of the long time necessary for the attainment of equilibrium.

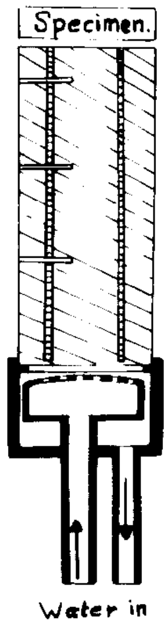
For the absolute measurement of thermal rock conductivities, the steady-state hot-plate method can be applied. In this method, a heater and an ice mixture are placed on both sides of a disc-shaped specimen. The determination of the thermal conductivity by this method, however, requires, also a relatively long time of the order of several hours.

Recent improvements by Beck (1957) have reduced this long time somewhat. The Beck steady-state method for the rapid measurement of thermal conductivity had reduced the time required for the thermal conductivity measurement to a matter of minutes.

It was shown by Beck that if the time required for steady condition is estimated theoretically it was found that almost all the time lag is due to apparatus design and that a suitably constructed divided bar apparatus should reach the steady-state within ten minutes. This comparatively short time interval is suitable not only because of the time saved, but also because little accurate work has been done on the variation of the thermal conductivity of porous rocks with changes in water content, it is not possible to do this by methods involving long time lags since they give in-accurate results due to evaporation and migration of water.

In this method a disc of rock is introduced between two cylindrical metal bars, usually brass and heat is supplied to the remote end of one bar while the remote end of the other is cooled with thermostatically controlled water. By measuring the temperature of the bars after steady-state has been reached the thermal conductivity of the specimen is determined in terms of the conductivity of the bars. The effect of the thermal contact resistance between the bars and the specimen is eliminated by making measurements with three or more discs of different thickness.

In general, the bars are arranged vertically with an electrical heater, at the top end of the upper bar, situated under a platform on which weights are placed to make the contact resistance as uniform as possible. In the electrically heated divided bar, heat is supplied at a constant rate so that when the total thermal resistance is altered by changing a specimen then, because the bottom end is controlled thermostatically, the temperature has to change at various points along the system and in particular at the heater end of the bar. The main time lag occurs for in many apparatus a comparatively small heater supplying approximately one cal. cm^{-2} $sec.^{-1}$ has to heat a large mass of metal. Furthermore, the thermal insulation around the metal bars also causes a time delay since this too has to reach equilibrium. It is interesting to note also that when using a set of three or more discs of rock, it is generally assumed that during the measurements the contact resistance and the rock specimens are at a given mean temperature to a first approximation. This is true provided that the thermal resistances of all the specimens to be measured are nearly equal. However it can readily be seen that if changing a specimen causes the total thermal resistance to increase then, assuming the upper end to be supplied with heat at a constant rate and the bottom end controlled thermostatically, and that the mean temperature of the upper end rises while that of the lower end remains constant the mean temperature of both the specimen and the contact resistance will increase. This effect is partly reduced in practice because heat is not supplied at a constant rate to the divided bar section of the apparatus. If one specimen is replaced by another of higher thermal resistance then the rate of supply of heat will fall since the heater



(Fig. I)