

## INVESTIGATION OF THERMAL PROPERTIES OF SOME BASALT SAMPLES IN EGYPT

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### Abstract

This work aims in studying the temperature dependence of the thermal properties (thermal diffusivity,  $k$ , specific heat,  $C_p$  and thermal conductivity,  $\lambda$ ) of some basalt group samples, collected from different regions in the eastern desert of Egypt. The thermal properties of these samples were measured in the temperature range from r.t. to 900 K. The average values of the thermal conductivity of these investigated samples lie in the range from  $0.4 \cdot 10^{-3}$  to  $2.01 \cdot 10^{-3}$  cal cm<sup>-1</sup> s<sup>-1</sup> K<sup>-1</sup>. This means that these samples are considered as thermal insulating materials. The thermogravimetric analysis (TG) confirmed that these investigated samples are dry rocks. X-ray fluorescence (XRF) and X-ray diffraction (XRD) confirmed that these rock samples have a crystalline phase, the peaks of XRD have a small change in their location as a result of heat treatment. This behaviour was attributed to the oxidation and firing of some minerals after the heat treatment.

**Keywords:** basalt, thermal properties

### Introduction

Temperature plays the most important role among the various influences on the thermophysical properties in the earth's crust [1]. The need for accurate and simultaneous measurements for any two of these parameters (thermal diffusivity  $k$ , specific heat  $C_p$  and thermal conductivity  $\lambda$ ) is preferable due to the lack of data in literature for basalt. The investigation of the temperature dependence of the thermal conductivity gives information on the heat transfer mechanisms for studied rocks, because the different mechanisms in general will cause different functions known from theoretical studies of the heat transport process [2, 3]. Thus, one can try to fit the experimental results to these functions to find the acting heat transfer mechanisms. In the past, the limited accuracy of the measuring results was given by one of the fit functions. But now the progress by computer supported measuring methods and data processing improved such possibilities. The knowledge of the acting heat transfer mechanisms is not only a theoretically interesting problem, but also an important practical consequence in so far

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as it enables us to extrapolate the results outside the direct experimentally studied temperature range [4]. Also data on the thermal transport properties (thermal diffusivity,  $k$  and thermal conductivity,  $\lambda$ ) of middle and lower crustal rocks are essential for obtaining accurate results of lithospheric geothermal modellings. These properties are functions of ambient temperature [5–13]. Direct measurements of thermal properties of lower crustal samples are often limited by the small size or altered condition of lower crustal xenoliths in kimberlites and lamproitic dykes. Obviously, such a few number of investigations cannot give a statistically valid picture for a widespread and important class of rocks such as basalts. In comparison with many other rocks, basalt have relatively simple structural properties (negligible anisotropy, small number of mineral constituents, often-even grains, and simple grain shape).

## Experimental work

The investigated basalt bulk samples ( $B_1, B_2, B_3, B_4$ ) in our work were obtained from different regions of the Eastern Desert of Egypt.

$B_1$ : was obtained from Lahamy Valley in the Eastern Desert, South of the Red Sea between South of Marsa Alam and Abo Gssoun.

$B_2$ : was obtained from Lahamy Valley in the Eastern Desert, South East of the Red Sea between North East of Marsa Alam and Abo Gssoun.

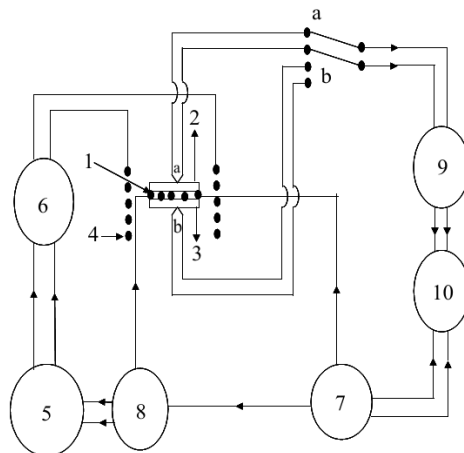
$B_3$ : was obtained from Gabal Muweilih located about 7 km South of Asphalt Qift-Qusair Road central of Eastern Desert.

$B_4$ : was obtained from Gabal EL-Sukkary located about 12 km South West of Marsa Alam, central of Eastern Desert.

The bulk samples were cut into disks by means of an impregnated diamond-slitting disk. After slitting, the sample faces was polished and lapped parallel. The samples were prepared in the shape of disks 25 mm diameter and 3–6 mm thickness to be suitable for the thermal investigation.

## Measurements

The thermal properties measurements are carried out using the plane temperature wave technique. The block diagram of the experimental setup is shown in Fig. 1 [14]. An appropriate heat source with small heat capacity (1) is sandwiched between identical samples (2, 3). The outer surface of each sample is provided by thermocouple  $a$  and  $b$ . The samples are mounted in a special holder such that it lies in the uniform heat zone of calibrated spiral heater (4). The electric power is supplied to (4) from AC voltage stabilizer (5) via variac transformer (6). The temperature is achieved through the electric relay circuit (7). The voltage applied to the perturbation heater (1) from the variac transformer (8). When the thermal equilibrium is attained, the thermocouple's time independent component is compensated by means of the potentiometric circuit (9). The time dependent component and the on-off signals of the perturbation heater's power are displayed on sensitive recorder (10).



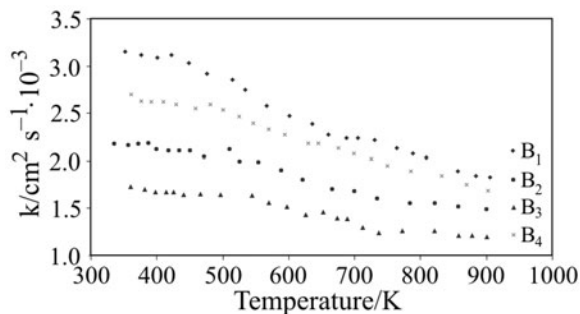
**Fig. 1** The block diagram of the thermal properties circuit. 1 – perturbation heater, 2, 3 – two identical samples a and b thermocouple, 4 – spiral heater, 5 – AC voltage stabilizer, 6 – variac transformer, 7 – electric relay circuit, 8 – variac transformer, 9 – potentiometric circuit and 10 – sensitive recorder

X-ray fluorescence (XRF) and X-ray diffraction (XRD) confirmed the explanation of the results before and after heat treatment. XRF analysis was performed with an applied research laboratory (ARL 8680 S) in central lab of cement factory, Assiut, Egypt. The structural analysis was performed using an X-ray chart diffractometer (Philips Holland model PW 1710) [15–17]. The results were supported with the thermogravimetric analysis (TG) [18, 19], using D08T-12 TG 01 (Shimadzu, Japan).

## Results and discussion

### Thermal diffusivity (*k*)

The temperature dependence of the thermal diffusivity (*k*) in the temperature range from 300 to 900 K for the investigated basalt samples are shown in Fig. 2. The behaviors of thermal diffusivity results are similar and show a wide scatter of about 4%,



**Fig. 2** Temperature dependence of thermal diffusivity (*k*)

which is achieved by the used apparatus, as shown in [20–23]. Each experimental point represents the average of two calculated values measured at the same temperature. The temperature dependence of the thermal diffusivity ( $k$ ) can be adequately represented by an empirical equation in the form:

$$k=1/(A+BT) \quad (1)$$

In general  $k=\alpha T^{-n}$ ,  $1.05 \leq n \leq 1.15$ ,  $\alpha$ , constant. Thus Eq. (1) was fitted to the results for temperatures up to 500 K by linear regression [1, 24], where  $A$  and  $B$  are fitting parameters correspond approximately to the electronic and the lattice contributions, respectively. The thermal diffusivity is related to the thermal conductivity by the equation:

$$\lambda=C_p kd \quad (2)$$

where  $C_p$  is the specific heat capacity and  $d$  is the density of the sample. It can be noticed that the values of the thermal diffusivity of the samples ranges from  $1.2 \cdot 10^{-3}$  to  $3.15 \cdot 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ .

These values lie approximately within the range of insulating materials. The agreement between our results and those in literature is quite satisfactory [4, 21, 25, 26]. The main behavior of these results is a decrease of the thermal diffusivity with temperature, but each sample is characterized by its own values. It is interesting to notice that the thermal diffusivity of fine-grained sample (Basalt) is lower than that of coarse-grained group (granite) [27]. This may be ascribed to that the fine grained samples have a lower mean free path of phonon-phonon scattering than that of coarse grained samples. The variation of  $k(T)$  of the basalt samples in the studied temperature range is approximately in accordance with the theory of heat transport mechanism in dielectrics [2, 3]. The difference of the thermal diffusivity values between these basalt group samples may be attributed to the small difference in density and the mineral composition Table 2 among these samples [27]. Moreover, the increase of number of phonon-phonon collisions (Umklapp-process) leads to decrease the mean free path of the phonon-phonon scattering which, consequently leads to decrease the thermal diffusivity, Fig. 2.

#### *Specific heat ( $C_p$ )*

The temperature dependence of the measured specific heat,  $C_p$  of the specimens from 300 to 900 K is shown in Fig. 3. It is found that the values of the specific heat of our samples are very small, discrepancy ranged from 0.145 to 0.248 cal  $\text{g}^{-1} \text{K}^{-1}$ . Each experimental point represents the average of two values measured at the same temperature. We notice that from 300 to 500 K the measured  $C_p$  values increase rapidly with increasing temperature for all basalt samples. This behaviour is in agreement with the TG results, Fig. 4 where a mass loss of about 3.296 mass% as shown in Table 1.

In fact, the loss of the sample mass contributes to the increase of its specific heat according to the relation:

$$C_p= Q/m\omega\theta f(\varphi,B_i) \quad (3)$$

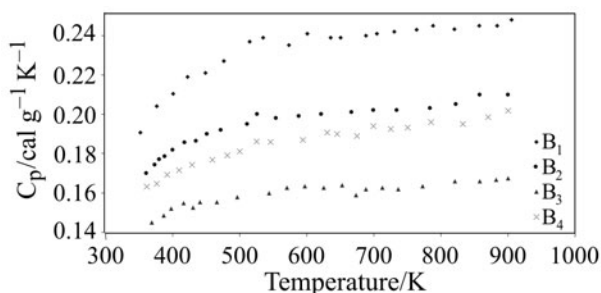


Fig. 3 Temperature dependence of specific heat ( $C_p$ )

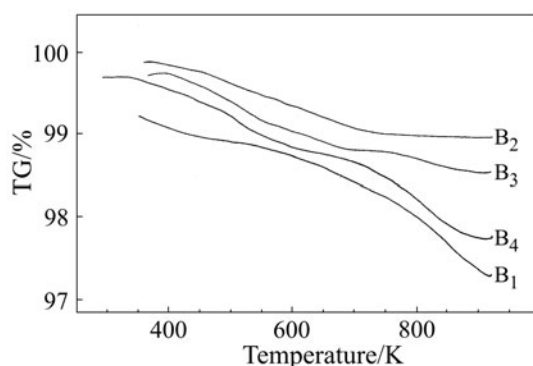


Fig. 4 Thermogravimetric analyses (TG) at a heating rate  $20 \text{ K min}^{-1}$

where  $Q$  is the absorbed heat power,  $m$  is the mass of the sample,  $\omega$  is the angular frequency of the heat source,  $\phi$  is the measured amplitude of the temperature oscillations and  $f(\phi, B_i)$  is a correction function, which is nearly equal to unity [28].

The rapid increase of  $C_p$  in the first region from 300 to 500 K (Fig. 3) may be attributed to the dehydration of the specimen rather than to chemical or physical changes. This can be indicated by the mass loss of the investigated samples (Table 1) and TG analysis (Fig. 4). In the range from 500 to 900 K (Fig. 3). It is shown that the measured  $C_p$  values increase slightly with temperature. This behaviour is in accordance with Dulong–Petit law [29]. In the case of rocks, the contribution of the electrons to the specific heat is weak and the lattice contribution cannot be easily represented by the specific heat function (Debye) due to the complex lattice vibration. On the other hand, the molecular theory and the Neuman–Kopp rule,

Table 1 Mass loss of the investigated samples

Sample	Total mass loss/mass%	Average mass loss
B <sub>1</sub>	2.434	3.296%
B <sub>2</sub>	1.244	
B <sub>3</sub>	2.536	
B <sub>4</sub>	6.971	

$$C_p = \sum_{i=1}^N g_i c_i$$

cannot be used to calculate the specific heat of the rocks because of the different contents in the composition of rocks [7]. The lack of experimental results and information about specific heat and other physical constants of these rocks in the literature preclude quantitative comparisons. In addition, the different types of rocks mineral composition make these comparisons very difficult.

#### Thermal conductivity ( $\lambda$ )

The dependence of the thermal conductivity on temperature of the investigated samples from 300 to 900 K is shown in Fig. 5. The values of thermal conductivity of these samples ranged from  $0.4 \cdot 10^{-3}$  to  $2.01 \cdot 10^{-3}$  cal cm<sup>-1</sup> s<sup>-1</sup> K<sup>-1</sup>. Our temperature range is not sufficient to reveal positively any radiative heat transfer effects, if present in these rocks. For the thermal conductivity, the analogous equations were assumed  $\lambda = \alpha' T^{-m}$ ,  $1.05 \leq m \leq 1.15$ ,  $\alpha'$ , constant. In rock samples in most cases, the temperature dependence is essentially lower. Therefore a constant term was added [1]. The obtained experimental results can be adequately represented by the equation;

$$\lambda(T) = 1/(C + DT) \quad (4)$$

where  $\lambda$  is the thermal conductivity,  $C$  and  $D$  are fitting parameters and  $T$  is absolute temperature. This function is useful in the temperature range 300 to 900 K where phonon thermal conductivity is the dominating heat transfer mechanism. In general, the temperature dependence of thermal conductivity can, roughly, be classified into two broad groups: rocks with either low or high quartz content. High content of quartz results in a high value of conductivity at room temperature. Rocks having low content of quartz exhibit much smaller room temperature value of conductivity [4].

As indicated in Fig. 5, in the temperature range from 300 to 500 K the thermal conductivity is slightly decreased for all basalt samples with percent of decrease 0.174%. From 500 to 900 K, the thermal conductivity showed also a slight decrease with increasing temperature for all studied basalt samples with percent of decrease

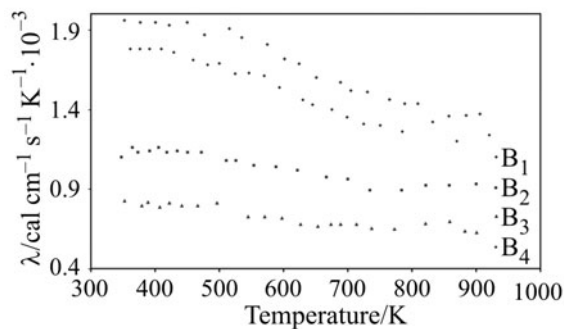


Fig. 5 Temperature dependence of thermal conductivity ( $\lambda$ )

0.387 relatively higher. The slight decrease of the thermal conductivity in all investigated samples is caused by temperature independent scattering processes. It is reasonable to interpret these processes as being associated with the presence of intergranular boundaries [24]. Moreover, the thermal conductivity resulted from phonon lattice contribution can be explained as; by increasing temperature the number of phonon–phonon collisions ‘Three-phonon Umklapp processes’ [30, 31] increases which leads to a decrease in the mean free path of phonons. This leads to the slight decrease in thermal conductivity according to the relation:

$$\lambda_{\text{ph}}=1/3cvl \quad (5)$$

where  $c$  is the heat capacity per unit volume,  $v$  is the average phonon velocity and  $l$  is the phonon mean free path. Also this decrease of thermal conductivity with temperature may be attributed to the fact that in the process of heating, the samples were subjected to some composition changes. Such changes are the increase of  $\alpha$ -quartz content at the expense of plagioclase transformation of iddingsite in magnetite and biotite in chloritized mineral [21]. It is indicated that the silicon dioxide ( $\text{SiO}_2$ ) as shown in Table 2, is the largest fraction in the composition, which contains different types of low thermal conductivity components such as Hyalite, chert and  $\alpha$ -quartz [32–35].

It is also found that rock composition contains calcium oxide of relatively high thermal conductivity, so that the variation of the values of thermal conductivity among basalt group samples depend on the variation in the mineral composition of these samples. All of these results indicate that the transfer of energy is mainly due to the phonon lattice component of the thermal conductivity. The contribution of the electrons to the thermal conductivity is relatively weak.

**Table 2** X-ray fluorescence (XRF) of rock minerals. Composition of the investigated samples

Sample	B <sub>1</sub> /mass%	B <sub>2</sub> /mass%	B <sub>3</sub> /mass%	B <sub>4</sub> /mass%
SiO <sub>2</sub>	43.77	47.01	47.94	47.23
Al <sub>2</sub> O <sub>3</sub>	16.3	16.4	11.19	15.25
Fe <sub>2</sub> O <sub>3</sub>	8.59	8.55	9.33	8.12
CaO	8.42	9.18	10.21	5.78
MgO	6.92	6.95	10.62	3.64
K <sub>2</sub> O	0.56	0.17	0.0	0.13
Mn <sub>2</sub> O <sub>3</sub>	0.0	0.0	0.21	0.18
Na <sub>2</sub> O <sub>3</sub>	2.75	2.48	1.8	3.86
P <sub>2</sub> O <sub>3</sub>	0.0	0.0	0.06	0.1
SO <sub>3</sub>	0.00	0.0	0.00	0.0
TiO <sub>2</sub>	0.0	0.0	0.92	1.03
L.O.I*	12.69	9.26	7.72	14.58

\*L.O.I is the abbreviation of loss of ignition.

X-ray diffractograms before thermal measurements, are shown in Fig. 6 (B<sub>1</sub>b), (B<sub>2</sub>b), (B<sub>3</sub>b), (B<sub>4</sub>b). It is obvious that, the X-ray diffractograms after thermal measurements of basalt group samples, exhibit some peaks with small changes in their location and more pronounced than those obtained before thermal measurements. This can be attributed to the oxidation and firing of some minerals during thermal treatment. Heat treatment means the effect on chemical composition after and before thermal measurements. This means that the heat treatment does not largely affect the thermal conductivity. This is due to that silicon dioxide, aluminum oxide, iron oxide

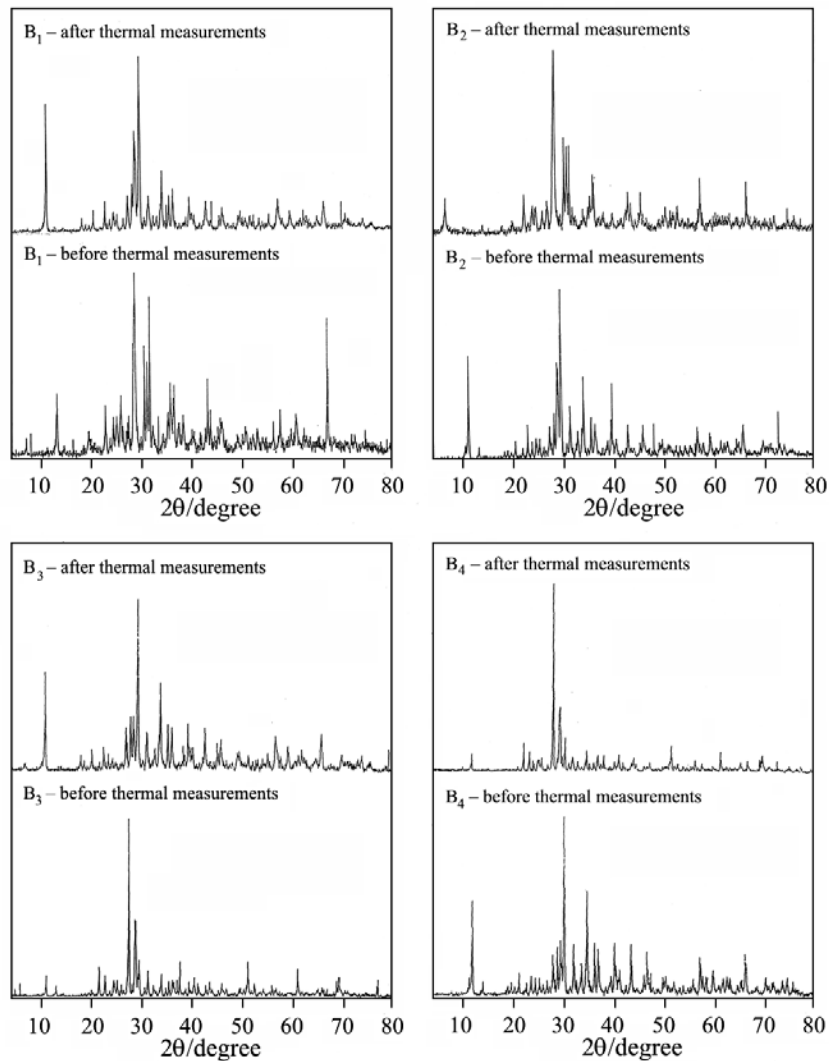


Fig. 6 X-ray diffractograms after and before thermal measurements



and calcium oxide represent the majority of the component, that they play an essential part in the thermal conductivity values.

From thermogravimetric analysis (TG) as shown in Fig. 4, for these samples, it is shown that in the beginning of the temperature rise a very small mass loss is recorded in all curves of basalt groups, which is ascribed to the evolution of the few percentage of free water from the samples. As the temperature increases the structurally bound water start to release from the samples at about 500 K which leads to the mass loss of the samples. As the structurally bound water releases the component of the lattice phonon conduction of thermal conductivity decreases, which leads to slight decrease in thermal conductivity, as shown in Fig. 5. The total mass loss through the thermal treatment of basalt samples is indicated in Table 1. These quite low percentages of mass loss (~3 mass%) of these investigated samples indicated that all of these samples are considered dry rock samples. Thus, TG results are in agreement with the thermal conductivity behaviour of the investigated basalt samples.

## Conclusions

The following conclusions can be drawn:

- The discontinuity in  $k(T)$  curves indicates that these samples have a chemical composition change expected in the biotite component. The increase of number of phonon-phonon collisions 'Umklapp-Process' leads to the rapid decrease of thermal diffusivity.
- Within the whole range considered for  $T$ , the values of the specific heat of these samples ranged from 0.145 to 0.248 cal g<sup>-1</sup> K<sup>-1</sup>.
- The thermal conductivity ( $\lambda$ ) of the studied samples ranged from,  $0.4 \cdot 10^{-3}$  to  $2.01 \cdot 10^{-3}$  cal cm<sup>-1</sup> s<sup>-1</sup> K<sup>-1</sup>. These values lie approximately in the range of insulating materials. The variation in the values of the thermal conductivity between these basalt samples depends on the variation in the mineral composition of these samples. As a result, the transfer of energy is mainly due to the phonon or lattice component of the thermal conductivity. The contribution of the electrons to the thermal conductivity is relatively weak.
- From the TG results it is concluded that all basalt samples have a few percentages of two kinds of water. The first is the free water, which release at the first region of the studied temperature range. The second is the structurally bound water, which releases through the second region. There is a small percentage of mass loss through this range of temperature (RT-900 K). This means that, these samples are considered as dry rock samples.
- XRD indicates that these samples contain some crystalline phases, which have a very small change in their location after the heat treatment.

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