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# Measurement of thermal properties of select intact and weathered granulites and their relationship to rock properties

D. Ramakrishnan[1], Rishikesh Bharti[1], M. Nithya[1], K. N. Kusuma[1], and K. D. Singh[1]

## ABSTRACT

Understanding the thermal properties of granulites, a group of high-grade metamorphic rocks representing composition of lower crust of the Earth, is necessary to arrive at effective crustal heat flow modeling. However, the thermal conductivity and diffusivity of intact and weathered granulites and parameters that influence them are poorly known. The above properties for a few felsic, mafic, and intermediate granulites and associated soils from the Southern Granulite Terrain, India were investigated using a cost-effective, self-fabricated setup. The results generated by this technique were precise, reproducible, and comparable with other published procedures and values. Because the samples analyzed were of intact in situ specimens, the thermal conductivity and diffusivity could be directly used in practical applications. Among several parameters, it was observed that $SiO_2/MgO + Fe_2O_3$ ratio, grain size, and bulk density were the principal factors to influence the conductivity and diffusivity of fresh felsic- and mafic-granulites. For weathered rocks/soils, moisture content, coefficient of uniformity, and fine fractions controlled the thermal properties.

## INTRODUCTION

Estimation of primary and derived thermal properties of soils and rocks is of immense use in various fields such as mineral investigation (Facer et al., 1980; Zoloterav, 1989; Prensky, 1992; Mwenifumbo, 1993), planetary exploration (Johnson and Lorenz, 2000; Jakosky et al., 2006; Edwards et al., 2009; Piqueux and Christensen, 2009), petrophysics and hydrocarbon exploration (Beck, 1976; Vasseur et al., 1995; Schön, 1996; Nasipuria et al., 2006; El Sayed, 2011), geotechnical engineering (Selvadurai and Nguywn, 1997; Jougnot and Revil, 2010), geothermal energy harvesting (Feldrappe et al., 2008; Fuchs and Forster, 2010), lithological discrimination (Bosch et al., 2002) and nuclear waste disposal (Nguyen and Selvadurai 1995; Millard et al., 2004). Further, vertical and spatial variations in the earth's temperature and heat flow are extensively used in crustal heat flow models (Beardsmore and Cull, 2001). This demands data on the thermal conductivity of upper, middle, and lower crustal rocks. Often, properties of outcropping rocks have been applied for upper crust. For middle and lower crust, P-wave velocity to heat conduction relationship is used. However, the general validity of the relationship is controversial (Cermak et al., 1990; Huenges, 1997; Joeleht and Kukkonen, 1998). This naturally necessitates study on the thermal behavior of granulites also for efficient heat flow modeling. However, information on the thermal properties of felsic, intermediate, and mafic-granulites are poorly known (Rudnick and Fountain, 1995; Joeleht and Kukkonen, 1998; Ray et al., 2006). This study is an attempt to increase understanding of the thermal properties of granulites belonging to Southern Granulite Terrain (SGT), India.

Considerable efforts have been made in the past to develop techniques to determine important thermal properties; namely, the conductivity (K), diffusivity (α), specific heat capacity (c), and inertia (I) under field and laboratory conditions. This led to investigations of the thermal properties of rocks and soils using various methods such as the steady-state divided-bar technique (Birch, 1950; Beck, 1957), needle-probe method (DeVries and Peck, 1958; Von Herzen and Maxwell, 1959), quick thermal conductivity meter (Ito et al., 1977) and several other transient-, steady-state, and modulated methods (Woodside and Messmer, 1961; Morabito, 1989; Middleton, 1993; Schilling, 1999; Abu-Hamdeh, 2003; Bautista et al., 2005; ASTM, 2008, 2009a, b). Each of the above techniques has its own merits and demerits. The needle-probe is more suited to unconsolidated sediments, whereas the divided bar is more appropriate to well-consolidated, low-porosity rocks.

The basis for most of the present-day steady-state methods is the procedure suggested by Beck (1957) wherein a constant known

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[1]Indian Institute of Technology Bombay, Department of Earth Sciences, Powai, Mumbai, India. E-mail: ramakrish@iitb.ac.in; rishi@iitb.ac.in; nithyam@iitb.ac.in; kusuma@iitb.ac.in; kdsingh85@iitb.ac.in.

quantity of heat is supplied to one face of a slab of test material. An analysis of the temperature change with time of the other face leads to the estimation of thermal constants of the tested material. Modifications to this method were suggested by Beatty et al. (1950) where one face of the test slab that was initially kept at constant temperature is suddenly brought into contact with an isothermal heat source at higher temperature. The temperature-time change of a heat sink of known thermal capacity in contact with the opposite side of the test slab is then recorded. The thermal constants of the test slab were deduced from this record.

In the present study, a setup was fabricated which can be used to estimate thermal conductivity and diffusivity by steady-state and transient techniques. While estimating the conductivity by steady-state, the procedure of Beck (1957) was adopted. The thermal diffusivity by transient method was estimated by following the procedures of Beatty et al. (1950). It is observed that this setup could be effectively used to evaluate thermal properties of rock slabs, and undisturbed or remoulded soil samples. Experiments conducted on different rocks slabs and soil samples indicate that the results are reproducible and comparable with published results. Further, an attempt is also made to relate the thermal diffusivity and conductivity with petro-, pedo-physical, and chemical properties such as moisture content, density, mineralogy, grain size distribution, and chemistry.

## MATERIALS AND METHODS

### Theory

One-dimensional heat transfer is reasonably well understood and the simplest concept (Figure 1). For low-heat-conducting materials like rocks and soils, 1D transient heat transfer equations (equations 1, 2, and 3) are widely used to estimate the thermal conductivity and diffusivity. The transient equations are based on the Carslaw and Jaeger (1959) criteria of heat transfer in a slab that is initially at start temperature, insulated at the surface $x = 0$, and has a constant heat flux introduced at the surface $x = a$ at time $t = 0$. The temperature at a distance $x$ within the slab at time $t_s$ ($t_s > t_0$) is given as:

$$T(x,t) = \frac{F\alpha t}{aK} + \frac{Fa}{K}\left(\frac{3x^2 - a^2}{6a^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}e^{-\alpha n^2\pi^2 t/a^2}\cos\frac{n\pi x}{a}\right), \qquad (1)$$

where $\alpha$ is thermal diffusivity ($m^2/s$), $K$ is thermal conductivity (W/m °C), and $a$ is the thickness of the slab/specimen (m). If

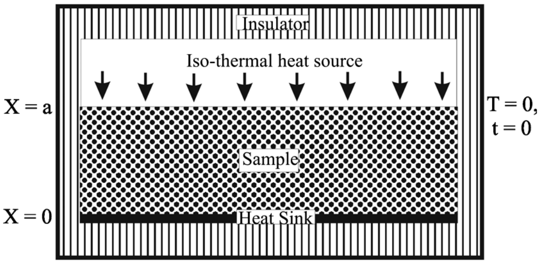


Figure 1. Diagram depicting the concept of 1D heat transfer in a rock slab.

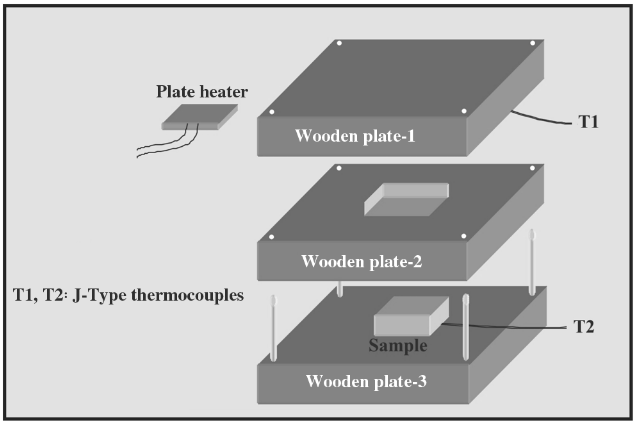
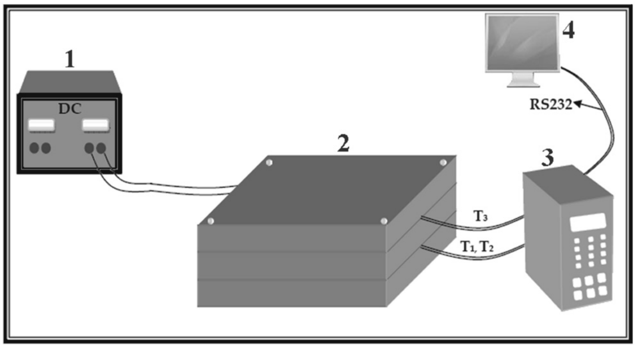


Figure 2. Schematic diagram showing part of an experimental setup comprising heat source, sample holder, and thermocouples.



1- D.C. Power supply, 2- Sample holder with heat source and sink, 3- Data logger, 4- Display

Figure 3. Schematic diagram depicting the instrument setup.

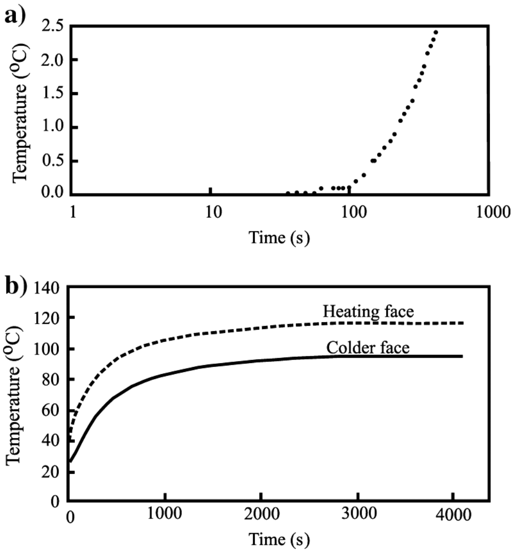


Figure 4. (a) Temperature, (T) time, (t) plot for heat conduction by transient technique for granite (sample H). (b) Temperature (T) time, (t) plot for heat conduction by steady-state technique for norite (sample B)

temperature is measured at the base of the slab ($x = 0$), the above expression is modified as

$$T(a,t) = \frac{F\alpha t}{aK} - \frac{Fa}{6K} + C, \tag{2}$$

where $C$ is the term for transient flow. For larger $t$, the term $C$ is negligible, and temperature $T$ versus time $t$ becomes linear with an intercept $t_i$ on $T = 0$ axis. The intercept can be expressed as

$$t_i = \frac{a^2}{6\alpha}. \tag{3}$$

From the experimental data on temperature versus time measurements, thermal diffusivity can be estimated using the above equations. Subsequently, conductivity can be estimated using the relation $\alpha = \frac{K}{\rho c}$, where $\rho$ is the density and $c$ is the specific heat capacity.

The steady-state method is based on the assumption of 1D heat flow inside the sample. Accurate measurement of the heat flux requires great care to minimize the sources of error. Before temperature measurements are taken, the whole setup (with thermocouples placed in the defined positions) is allowed to come into a state of thermal equilibrium. This method involves measurement of the temperature difference between the top and bottom of a sample when both are in steady-state (equation 4). The coefficient of thermal conductivity $K$ is a measure of the rate at which heat $Q$ flows through a material. It is expressed as

$$K = \frac{Q\Delta x}{A\Delta T}, \tag{4}$$

**Table 1. Major oxide geochemistry of investigated rock slabs.**

| Major oxides (wt.%) | A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | 8.3 | 16.1 | 13.4 | 17.9 | 3.0 | 15.8 | 16.4 | 12.4 | 15.9 |
| CaO | 3.9 | 9.7 | 9.1 | 10.3 | 7.6 | 8.5 | 3.5 | 1.6 | 3.6 |
| $Fe_2O_3$ | 8.8 | 6.3 | 1.5 | 8.5 | 23.7 | 9.9 | 4.3 | 5.8 | 6.2 |
| $K_2O$ | 4.5 | 0.4 | 4.8 | 0.6 | 0.0 | 0.7 | 0.9 | 1.4 | 1.2 |
| MgO | 1.4 | 14.7 | 0.2 | 1.2 | 16.9 | 1.8 | 1.3 | 0.8 | 2.1 |
| MnO | 0.2 | 0.2 | 0.0 | 0.2 | 0.2 | 0.1 | 0.0 | 0.1 | 0.0 |
| $Na_2O$ | 0.9 | 2.0 | 3.0 | 2.9 | 0.7 | 3.3 | 3.4 | 3.5 | 3.1 |
| $P_2O_5$ | 0.0 | 0.2 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 |
| $SiO_2$ | 71.8 | 49.6 | 67.7 | 58.0 | 47.3 | 59.4 | 69.8 | 74.0 | 67.2 |
| $TiO_2$ | 0.2 | 0.8 | 0.1 | 0.4 | 0.6 | 0.4 | 0.3 | 0.4 | 0.5 |
| Total | 100.0 | 100.0 | 100.0 | 100.1 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

(A) Quartz-garnet-biotite-sillimanite gneiss, (B) Norite, (C) Migmatite, (D) Pyroxene granulite, (E) Metamafite, (F) Carderite granulite, (G) Granulite, (H) Granite, (I) Intermediate charnockite.

**Table 2. Grain size gradation of analyzed soil samples.**

| | wt.% Retained | | | | |
|---|---|---|---|---|---|
| ASTM sieve designation | Sandy-clayey-loam-I[a] | Sandy loam-I[a] | Sandy clay loam-[a]II | Sandy-loam-II[b] | Clean sand[b] |
| 35 | 10.2 | 26.8 | 7.1 | 18.3 | 1.5 |
| 80 | 30.2 | 38.1 | 30.1 | 45.9 | 67.4 |
| 140 | 21.7 | 10.5 | 24.9 | 17.0 | 30.6 |
| 270 | 27.5 | 21.9 | 29.2 | 15.9 | 0.5 |
| > 270 | 10.4 | 2.8 | 8.8 | 2.9 | 0.0 |
| NMC (%) | 9.2 | 7.5 | 10.0 | 8.1 | 5.1 |
| Bulk density ($kg/m^3$) | 1392 | 1518 | 1649 | 1465 | 1537 |

[a] undisturbed.
[b] disturbed.

where $Q$ is heat flux ($\mathrm{W/m^2}$), $K$ is thermal conductivity ($\mathrm{W/m\,°C}$), $\Delta x$ is thickness of the sample (m), $\Delta T$ is temperature difference at steady-state (°C), and $A$ is total cross-sectional area of conducting surface($\mathrm{m^2}$).

## Experimental setup

The experimental setup in our study comprises three wooden plates (1, 2, and 3) of dimension $9 \times 9 \times 1$ inches that can be stacked together to form a compact airtight box with a nut and screw attachment (Figures 2 and 3). The uppermost wooden plate has an embedded heating source of dimension $3 \times 3$ inches, which can provide constant heat flux. A thermocouple attached to the heat source permits measurement of temperature on the heating face of the sample. A DC power supply is used to provide constant voltage and current to the heater. By changing the voltage (0–120V) and current (0–2A), heat flux delivered to the sample can be raised up to a temperature of 150°C. The middle plate has a central opening with thermal wool packing to accommodate sample slabs of dimension $3 \times 3 \times 1$ inches or NX cores (54 mm diameter) of 1 inch thickness. The lower plate has embedded thermocouples for measuring temperature on the other face of the sample. Both faces of the sample are moderately polished and given a very thin coating of thermal grease to ensure perfect contact of the specimen with heating source and to minimize thermal contact resistance.

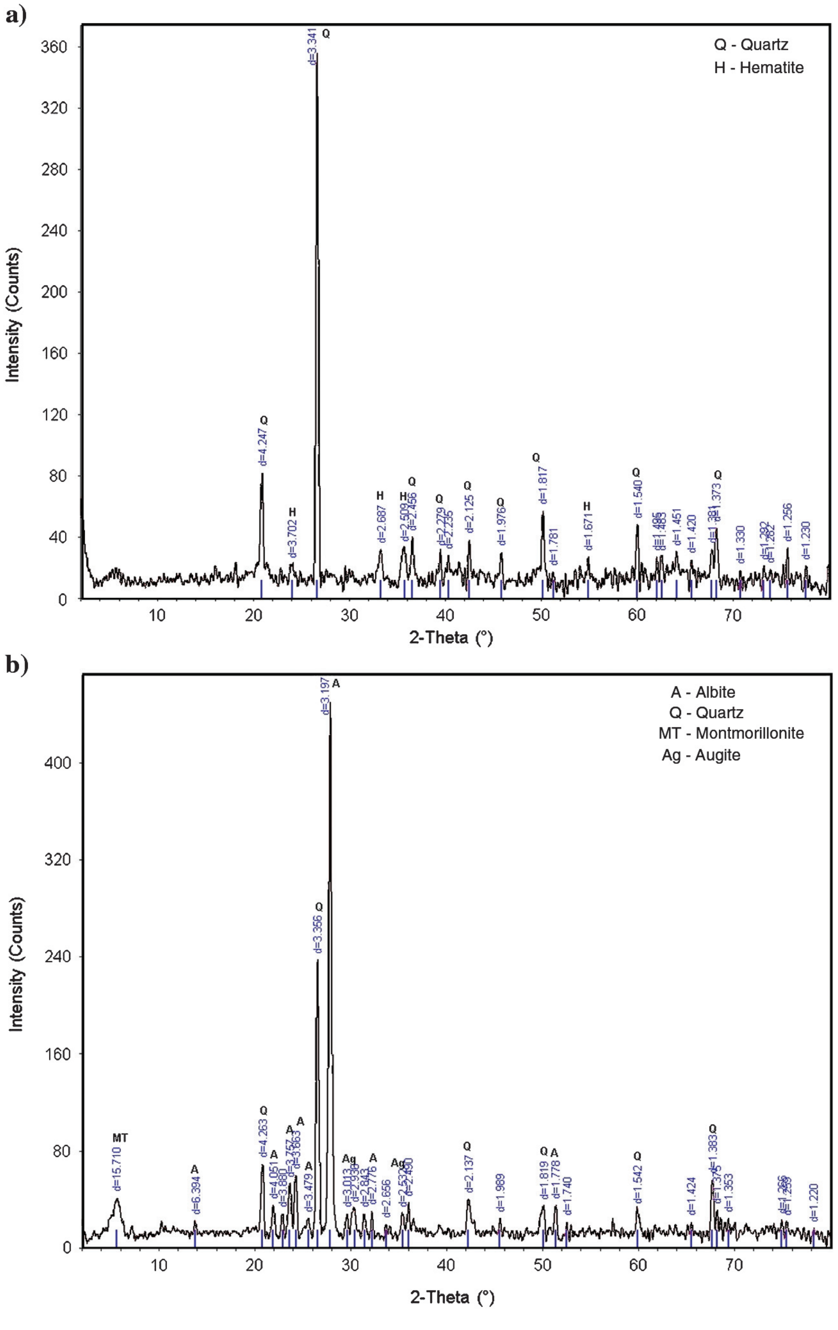


Figure 5. XRD spectra depicting (a) the mineralogy of SM and (b) SC class of soils.

A thin sheet (30 μm thickness) of aluminum foil was placed in between the sample and lower plate so as to produce a uniform basal temperature. The aluminum foil, which is a much better thermal conductor than the rock/soil sample, helps to instantly distribute the basal temperature around the thermocouple. The temperatures of the top and bottom of the sample were simultaneously measured with J-type thermocouples. The thermocouples were calibrated by comparison technique (ASTM, 2008b) and are sufficient to detect temperature changes of the order of 0.01°C. These thermocouples were connected to a data logger, and the temperature was logged at every 6 s interval.

## Sample preparation

In the case of rocks, crack/fracture-free samples were selected so as to avoid the complexities arising due to convection and radiative heat transfer (Clauser and Huenges, 1995; Gehlin and Hellström, 2003). For this purpose, blocks to be cut were immersed in water and allowed to dry at room temperature. These specimens were visually inspected for presence of fractures, which usually retain moisture for longer duration. Fracture-free specimens were subsequently cut into slabs as per the dimension mentioned earlier. The cut slabs were again subjected to the above procedure to check for possible fractures introduced during cutting. The defect-free samples were then slightly polished and coated with a thin film of thermal grease.

In the case of soils, the samples were extruded carefully from the undisturbed soil samplers and cut into slabs. This method is helpful to maintain the field moisture and density and can be easily followed in soils rich in plastic fines. For sand and nonplastic fines dominated soils, disturbed samples were collected from the field and remoulded to natural moisture content (NMC) and field bulk density, which were subsequently cut into slabs and coated with film of thermal grease. Transient and steady-state experiments were conducted at very low heat flux (45°C–50°C) to avoid movement of moisture and phase changes.

## Experimental procedure

The transient experiment was carried out by rapidly exposing the top surface of the sample to the heat source and measuring the temperature at the base of the sample block for approximately four minutes after introduction of the heat source. The four-minute measurement duration was found to be sufficient to obtain linear

**Table 3. Thermal conductivity and diffusivity of investigated rock slabs.**

| Sample no | Rock types | Density kg/m$^3$ | Sp. heat capacity J/kg °C | Thermal diffusivity $\times 10^{-7}$ m$^2$/s | Conductivity (steady-state) W/m °C | Conductivity (transient) W/m °C | Deviation W/m °C |
|---|---|---|---|---|---|---|---|
| A | Garnet-biotite-sillimanite gneiss | 2672.6 | 770 | 8.3 | 1.9 ± 0.1 | 1.7 ± 0.1 | 0.4 |
| B | Norite | 3165.1 | 670 | 8.0 | 1.9 ± 0.2 | 1.7 ± 0.2 | 0.6 |
| C | Migmatite | 3311.6 | 450 | 12.2 | 2.0 ± 0.1 | 1.8 ± 0.1 | 0.3 |
| D | Pyroxene granulite | 2784.9 | 849 | 8.0 | 2.1 ± 0.2 | 1.9 ± 0.3 | 0.7 |
| E | Metamafite | 3466.6 | 699 | 6.8 | 1.6 ± 0.2 | 1.7 ± 0.2 | 0.5 |
| H | Granite | 2804.1 | 600 | 10.2 | 1.9 ± 0.1 | 1.7 ± 0.1 | 0.4 |
| I | Charnockite | 3010.3 | 660 | 8.7 | 1.7 ± 0.1 | 1.7 ± 0.1 | 0.2 |

**Table 4. Thermal properties of investigated soils.**

| Soil type/class | Coeff. of uniformity Cu = $D_{60}/D_{10}$ | Bulk density kg/m$^3$ | Diffusivity $\times 10^{-7}$(m$^2$/s) | Steady-state conductivity W/m °C | Transient-state conductivity W/m °C | Max. difference W/m °C |
|---|---|---|---|---|---|---|
| Clayey-sand (SC) | 7.7 | 1478.8 | 5.3 | 1.3 ± 0.2 | 1.2 ± 0.2 | 0.5 |
| Sand (SW) | 3.2 | 1210.9 | 10.7 | 1.1 ± 0.1 | 1.2 ± 0.1 | 0.3 |
| Sandy loam (SC) | 3.7 | 1238.1 | 5.6 | 1.1 ± 0.1 | 1.0 ± 0.1 | 0.3 |
| Clayey-sandy-loam (SC) | 3.6 | 1492.6 | 4.3 | 1.1 ± 0.1 | 1.0 ± 0.2 | 0.4 |
| Sandy loam (SM) | 8.3 | 1465.9 | 7.6 | 1.3 ± 0.1 | 1.3 ± 0.1 | 0.2 |
| Clayey-sandy-loam (SC) | 3.6 | 1749.6 | 3.2 | 1.1 ± 0.1 | 0.9 ± 0.2 | 0.5 |
| Sandy loam (SM) | 8.7 | 1518.8 | 5.1 | 1.2 ± 0.1 | 1.2 ± 0.1 | 0.2 |
| Quartz sand (SW) | 3.4 | 1537.1 | 4.3 | 1.0 ± 0.1 | 1.0 ± 0.1 | 0.2 |
| Quartz fines | 2.7 | 1337.1 | 4.4 | N.A | 0.5 ± 0.1 | N.A |

behavior in a slab about 2.5 cm thick. The measured temperatures were reduced by subtracting the initial ambient/equilibrated temperature, so as to make the measurements relative to zero initial temperature. This reduced temperature to time graph was plotted; based on the linear segment, intercept time $t_i$ was identified (Figure 4A). The thermal diffusivity was determined from the intercept time using equation 3.

**Table 5. Statistical analysis showing influence of index properties on thermal conductivity and diffusivity.**

| Rock properties | Statistical parameters | Thermal conductivity (W/M °C) | Thermal diffusivity ($m^2/s$) |
|---|---|---|---|
| $SiO_2/MgO + Fe_2O_3$ | $R^2$ | 0.93 | 0.93 |
| | Df | 5 | 5 |
| | F | 7.6 | 50.9 |
| | Fc | 6.6 | 16.2 |
| | S | 0.05 | 0.01 |
| Density | $R^2$ | 0.63 | 0.80 |
| | Df | 5 | 5 |
| | F | 6.7 | 9.15 |
| | Fc | 6.6 | 6.6 |
| | S | 0.05 | 0.05 |
| Grain size | $R^2$ | 0.96 | 0.71 |
| | Df | 5 | 5 |
| | F | 37.1 | 9.45 |
| | Fc | 16.3 | 6.6 |
| | S | 0.01 | 0.05 |
| Soil index properties | | | |
| Soil moisture content (clayey soils) | $R^2$ | 0.89 | 0.94 |
| | Df | 4 | 4 |
| | F | 4.3 | 9.9 |
| | Fc | 3.8 | 7.7 |
| | S | 0.12 | 0.05 |
| Soil moisture content (sandy soils) | $R^2$ | 0.95 | 0.92 |
| | Df | 4 | 4 |
| | F | 38.08 | 18.5 |
| | Fc | 21.2 | 12.2 |
| | S | 0.01 | 0.025 |
| Coeff. of uniformity | $R^2$ | 0.81 | 0.95 |
| | Df | 4 | 4 |
| | F | 8.5 | 3.06 |
| | Fc | 7.7 | 2.71 |
| | S | 0.05 | 0.15 |
| % fines | $R^2$ | 0.80 | 0.93 |
| | Df | 4 | 4 |
| | F | 8.4 | 14.3 |
| | Fc | 6.7 | 10.9 |
| | S | 0.06 | 0.03 |

($R^2$) regression coeff, (Df) degree of freedom, (F) F-ratio, (Fc) F-critical value, (S) statistical significance.

For the steady-state measurement, a constant voltage and current was applied to the plate heater. The heat flux was maintained till the upper and lower faces of the sample reached steady-state (Figure 4B). Because it is possible to measure thermal gradient $\Delta T$ across the faces, thickness of the sample $\Delta x$, and area $A$, the thermal conductivity can be directly estimated using the equation 4.

## Calibration

The experimental setup was calibrated using quartz fines akin to the procedure adopted by Presley and Christensen (2010). For this purpose, transparent quartz grains from pegmatite were crushed, sieved, and oven-dried. Diffusivity and conductivity values were estimated on the fractions smaller than 63 μm at ambient pressure and temperature conditions, and compared with published results.

# RESULTS

## Characterization of rocks and soils

Because density, texture, fracture, chemistry, and mineralogy affect the thermal diffusivity and conductivity, an attempt was herein made to characterize these basic properties of the samples. The rocks chosen for present study include granite, charnockite, garnet-biotite-sillimanite gneiss, pyroxene granulite, metamafite, magnetite quartzite, norite, and migmatite. From the petrography studies it was evident that the chosen rocks were massive, granoblastic, and had no mineral lineation and foliation planes. Hence, this work offers the advantage of directly relating the thermal properties to above mentioned bulk properties. The major oxides chemistry of the rock slabs estimated by X-ray fluorescence technique is presented in Table 1. The granite, migmatite, charnockite, and garnet-biotite-sillimanite gneiss are typically coarse grained with high percentage of $SiO_2$ (67%–73%). The mafic rocks (namely norite, metamafite, and pyroxene granulite) exhibit a typical equigranular, interlocking texture with low percentage of $SiO_2$ (47%–57%). These rocks are composed of pyroxenes, plagioclase, olivine, and their altered secondary minerals. Depending on the molar proportions of A ($[Al_2O_3 + Fe_2O_3] - [Na_2O + K_2O]$), C ($[CaO] - 3.33[P_2O_5]$), and F ($[FeO + MgO]$), pyroxene granulites, norite, and metamafite can be grouped as mafic-granulites. Similarly, granite gneiss, migmatite, and garnet-biotite-sillimanite gneiss can be grouped as felsic granulites. The charnockite of the study area can be considered intermediate because the ACF values for this rock fall in between quartzo-feldspathic and basic group of rocks.

In the case of soils, the thermal properties are affected by mineralogy, grain size, bulk density, and moisture content. The grain size distribution, field moisture content, and bulk density are given in Table 2. The soil samples are dominated by sand fractions (62%–81%), with subordinate amount of fines (silt and clay). The natural moisture content and bulk density of these soil samples vary from 5% to 10% and, 1211 to 1649 $kg/m^3$, respectively. These soils fall in sand well-graded (SW), silty-sand (SM), and clayey-sand (SC) classes of unified soil classification scheme. The mineralogy of soils estimated by the X-ray diffraction (XRD) technique (Figure 5a and 5b) indicated that quartz is predominant in all the three types of investigated soils. Other characteristic minerals present in these soils include albite, hematite, augite, and montmorillonite.

## Estimation of thermal diffusivity and conductivity

In the case of transient measurements, the thermal diffusivity was measured and thermal conductivity was subsequently calculated using its relation with specific heat capacity and bulk density (Table 3). At room temperature, the thermal conductivities of $SiO_2$ rich rocks (67%–74%) range from 1.6 to 1.9 W/m°C, whereas conductivities of mafic rocks are slightly higher (1.7 to 2.2 W/m°C) than the silica-rich rocks. The experiments were repeated to check the consistency and it was clear that transient and steady-state methods yielded highly reproducible results within an error limit of ±0.3 W/m°C. The results estimated by transient and steady-state method deviate from 0.2 to 0.7 W/m°C. This error range is less than the values (0.2 ± 0.1 to 3.4 ± 3.0 W/m°C) published in literature for various rocks (Beardsmore and Cull, 2001). Because bulk density, grain size, and composition directly affect the physical path of heat flow (García et al., 1989), an attempt was made to establish interrelationship between these variables and thermal properties. For this purpose, F-ratio tests were carried out to determine the noise in the data before establishing any statistical relationship (Table 5). It is observed that grain size, $SiO_2/MgO + Fe_2O_3$ ratio, and bulk density influence thermal properties significantly (> 90%). Because scatterplots made among these parameters (Figure 6) depict a parabolic trend, we used a second-order polynomial fit for better approximation. Such higher-order polynomials are regularly used in literature to estimate the thermal properties of rocks and other materials (García et al., 1989; Enweani et al., 1995; Živcová et al., 2009). It is observed that an increase in mean grain size (Figure 6B) results in an increase in the thermal conductivity ($R^2 = 0.97$). The $SiO_2/MgO + Fe_2O_3$ content influence thermal conductivity and diffusivity ($R^2 = 0.93$) significantly (Figure 6a and 6d). Similarly, the conductivity-diffusivity relationship (Figure 6g) also exhibits good correlation ($R^2 = 0.75$). The bulk density-diffusivity relationship ($R^2 = 0.80$) was statistically better than the bulk density-conductivity ($R^2 = 0.63$) relationship (Figure 6c and 6f).

We adopted the above statistical procedures in relating soil thermal properties to influencing parameters (grain size distribution, percentage of fines, bulk density, and moisture content) also (Table 5, Figure 7). For all type of soils, the estimated F-ratios indicate that thermal properties are significantly (>95%) influenced by index properties. The sandy soils have a conductivity value ranging between 0.98 and 1.02 W/m°C. The sandy loam with a typical mineral assemblage of quartz, feldspar, and subordinate clay exhibit conductivity values ranging from 1.05 to 1.24 W/m°C.

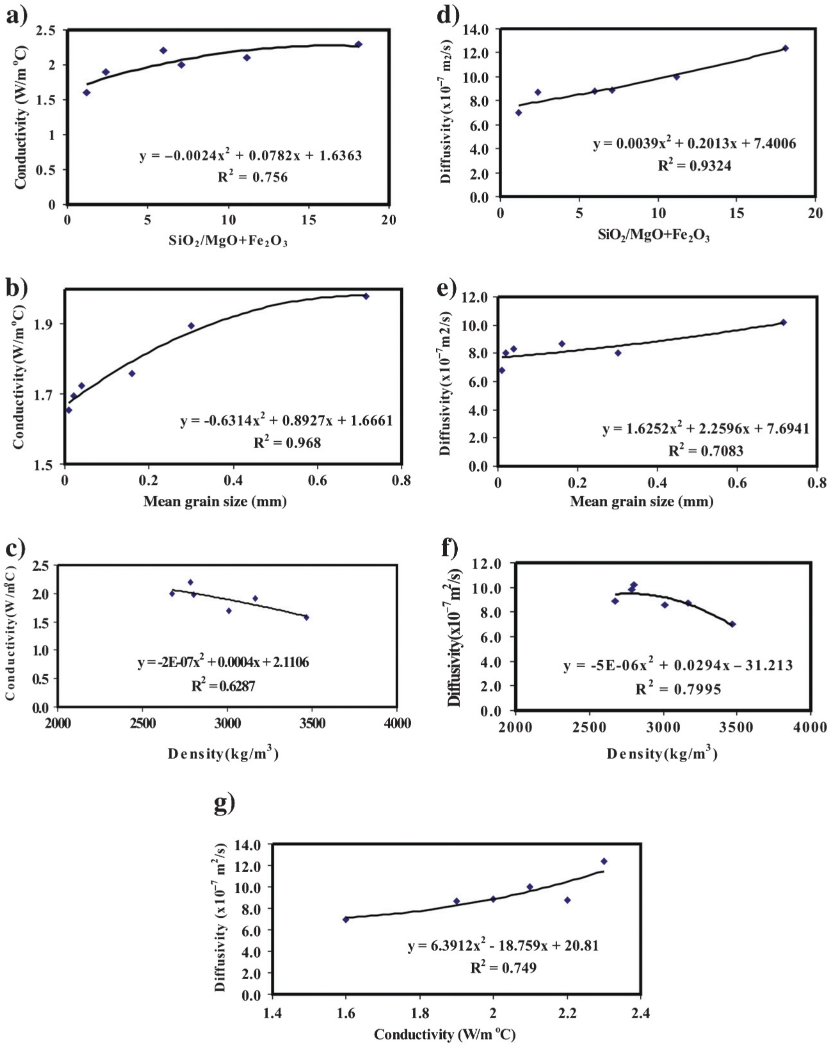


Figure 6. Scatterplots showing (a, b, c) the influence of chemistry, grain size, and bulk density on thermal conductivity and (d, e, f) diffusivity of rock slabs; and (g) the diffusivity-conductivity relationship.

The clayey-sandy-loam comprising the quartz, montmorillonite, and feldspar has conductivity values varying from 1.09 to 1.29 W/m °C. In this study, the coefficient of uniformity (Cu), a ratio between the diameter of grains corresponding to 60% ($D_{60}$) and 10% ($D_{10}$) of cumulative weight distribution was used as a measure of grain size distribution in samples. It is evident from Figure 7a and 7d that with increase in Cu, thermal conductivity and diffusivity increase ($R^2 = 0.81 - 0.95$). From Figure 7b and 7e it is observed that soil thermal properties are inversely related to percentage of fine (<63 μm) content. Overall relationship between fine content and conductivity is statistically good ($R^2 = 0.80$) at 95% significance level. The bulk density of soils seems to influence the diffusivity ($R^2 = 0.75$) more than the conductivity values ($R^2 = 0.37$).

To understand the effect of soil moisture on conductivity and diffusivity, experiments were conducted (on sandy and clayey soils) with increasing amount of soil moisture (Figure 8a and 8b; Table 6). In both cases, moisture content up to 20% by weight was increased, and beyond this moisture level the soil started flowing. It was evident from the results that conductivity and diffusivity of soils increased with an increase in soil moisture content. The increase in diffusivity was almost similar for sandy and clayey soils up to 10% moisture addition. Beyond this value, the rate of increase in diffusivity was higher in sandy soil (Figure 8a) than clayey soil. In both cases, the observed relationship is statistically significant.

## DISCUSSION

Thermal characters of granulites and associated soils are poorly understood because of limited data on basic thermal properties (conductivity and diffusivity) and influencing properties (mineralogy, chemistry, bulk density, grain size, and moisture content). For porous media, thermal properties of grains are often estimated by assuming that the heat transfer mechanism is conduction (Sass et al., 1971). However, convection and radiative heat transfer associated with secondary porosity (fractures) can adversely affect the estimates of bulk thermal properties of the rocks (Clauser and Huenges, 1995; Gehlin and Hellström, 2003). These observations indicate that the conductivities estimated for aggregates (Sass et al., 1971) have limited utility in applications involving the thermal

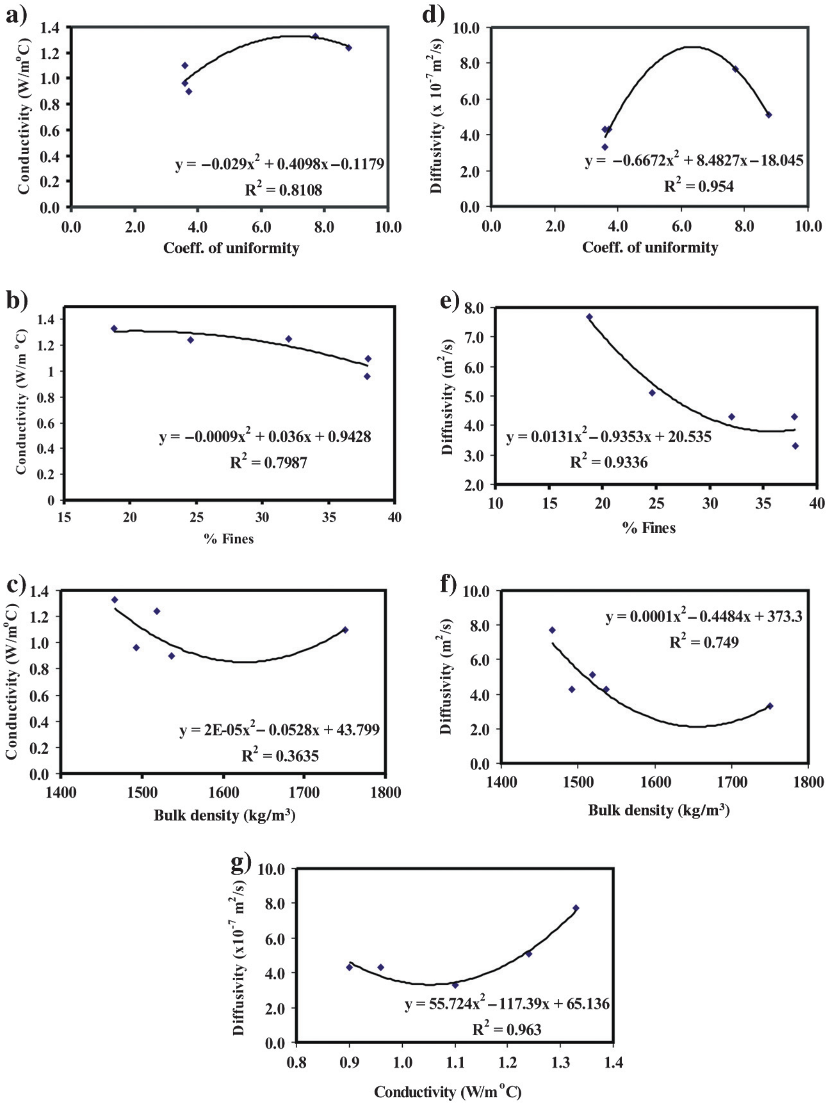


Figure 7. Scatterplots portraying (a, b, c) the control of grain size, fines content and density on thermal conductivity; (d, e, f) diffusivity for soils; and (g) the diffusivity-conductivity relationship.

properties of intact rocks. In this study, an attempt was made to estimate thermal diffusivity and conductivity of select intact rocks and soils using a cost-effective, self-fabricated setup. The estimated conductivity and diffusivity values for various granulites (Table 6) are comparable with published results (Horai and Baldridge, 1972; Cote and Konard, 2005; Ray et al., 2006; Kim et al., 2007). The results produced by this procedure are reproducible and error estimates are comparable to those of other published techniques (Beardsmore and Cull, 2001).

Because pressure and temperature influence thermal properties of rocks (Vosteen and Schellschmidt, 2003), the thermal conductivity values estimated at room temperature and pressure conditions can not be directly used in crustal heat flow modeling. However, it is evident from literature (Seipold, 1998; Kukkonen et al., 1999) that at elevated pressure (1000 MPa) and temperature (1150 K), conductivity and diffusivity of rocks decrease linearly by 12%–20% and 40%–55%, respectively. The thermal properties measured by the proposed technique can be extended to crustal heat flow related studies using the published predictive equations.

In relating the thermal diffusivities of rocks as a function of constituent mineralogy, Höfer and Schilling (2002) elucidated that thermal diffusivity is greatly influenced by amount of quartz, which has the highest thermal diffusivity among the major minerals. Pyroxene, amphibole, and garnet display intermediate diffusivities, and feldspars are of minor importance owing to their low diffusivity. Because basic and intermediate granulites do not have any free quartz, an attempt made here was to relate the bulk chemistry of rocks as a proxy for mineralogy. It was observed that conductivity and diffusivity are sensitive to $SiO_2/(MgO + Fe_2O_3)$ ratio (Figure 6a and 6d). This ratio also can be used to discriminate the felsic- and mafic-granulites (Miyashiro, 1974). The felsic rocks such as granite and migmatite with high percentages of quartz have a higher diffusivity values ($10.8 - 11.5 \times 10^{-7}$ $m^2/s$) than the mafic rocks dominated by pyroxenes, olivine, and feldspar ($7.74 - 9.95 \times 10^{-7}$ $m^2/s$). The second-order polynomial equation relating conductivity and diffusivity to $SiO_2/(MgO + Fe_2O_3)$ ratio shows $R^2$ values 0.76 and 0.93, respectively, at 95% significance levels. This indicates that in the case of basic rocks, where no free quartz exists, the specific heat capacity of Fe-Mg minerals plays a critical role in thermal diffusivity. Similar observations were also reported by Höfer and Schilling (2002) and Ray et al. (2006). Increases in the conductivity and diffusivity with increases in grain size could be attributed to reduction in thermal resistance over grain boundaries (Jessop, 2008).

For soils, it is evident that with increase in fines content, conductivity and diffusivity decrease (Figure 6, Table 4). This observation is akin to the results reported by Abu-Hamdeh (2003), wherein the increase in clay content was attributed to an increase in volumetric specific heat. In this study, soils rich in quartz are found to have lower conductivity (0.98 W/m °C) than the soils rich in ferro-magensium (pyroxene, amphibole, and hematite) minerals (1.05–1.29 W/m °C). Such anomalous behavior could be attributed to higher sensitivity of thermal properties to fine fractions and density changes than the quartz content (Smits et al., 2009). Further,

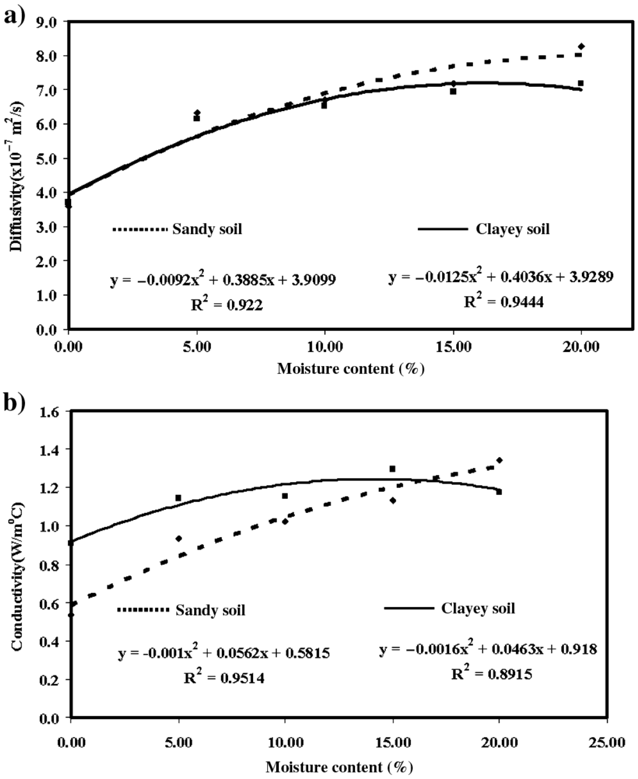


Figure 8. Relationship between (a) moisture content and diffusivity and (b) conductivity for clayey and sandy soils.

**Table 6. Thermal conductivity of investigated rocks vis-à-vis published results.**

| | Thermal diffusivity $\times 10^{-6}$ $m^2/s$ | | Thermal conductivity W/m °C | |
|---|---|---|---|---|
| Rock types | Representative value estimated | Published | Representative value estimated | Published |
| Granite | 1.02 | 0.93–1.787[c] | 1.71 | 1.5–2.5[a] |
| Charnockite | 0.87 | 1.25–1.85[b] | 1.72 | 2.13–2.81[b] |
| Garnet-biotite-sillimanite gneiss | 0.83 | 1.15[b] | 2.00 | 2.20[a] |
| Pyroxene granulite | 0.80 | 1.17–1.29[b] | 2.20 | 2.27–2.6[b] |
| Metabasite | 0.68 | N.A | 1.65 | 1.84[c], 2.20[a] |
| Norite | 0.80 | N.A | 1.91 | 1.7–2.5, 2.10–2.30[a] |
| Migmatite | 1.22 | N.A | 2.09 | 1.8–2.4[b] |

only quartz crystals common in sand fractions have high thermal conductivity, and quartz bound inside clay or silt particles do not behave similarly (Farouki 1986; Peters-Lidard et al., 1998). Because the investigated soils have a significant amount of fines (18%–38%), it was not possible to directly relate the quartz content estimated by XRD technique with thermal properties. Further, it was observed that moisture content seems to affect diffusivity and conductivity significantly (Figure 8a and 8b). This effect is more pronounced in sandy soils than in clayey sands (Tables 4 and 5). This phenomenon is mainly attributed to increase in specific heat and volumetric heat capacities of the soil-water mixture system (Abu-Hamdeh, 2003).

## CONCLUSIONS

In this study, we evaluated the thermal properties of granulite rocks and associated soils using a cost-effective method. This method allows estimation of thermal properties of rocks and soils, and also provides satisfactory results when compared with the published data. The conductivity values measured using this setup by transient and steady-state techniques for a suite of granulite rocks and associated soils commensurate well with an error in estimate up to ±0.3 W/m °C. These error values are comparable to the errors associated with other published techniques. It is suggested that by virtue of its cost effectiveness, the proposed technique is best suited for applications involving vast database generation. Further, this study has also revealed the role of chemistry, mineralogy, bulk density, grain size distribution, and moisture content on the thermal properties of intact granulites and their weathered products.

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