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# Determination of relationships between thermal conductivity and material properties of rocks

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**Abstract**: Energy transfer between the adjacent parts of rocks in underground mines is widely influenced by the thermal conductivity of rocks. The relationships between the thermal conductivity and some material properties of rocks such as the uniaxial compressive strength, unit mass, tensile strength, cohesion, Young's modulus, point load strength, Schmidt rebound hardness, Shore scleroscope hardness and toughness strength were investigated. The statistical analysis of the data obtained in laboratory tests shows that the thermal conductivity increases with increasing the uniaxial compressive strength, unit mass, tensile strength, cohesion, Young's modulus, point load strength, Schmidt rebound hardness and Shore scleroscope hardness, and decreases with increasing the toughness strength.

**Key words**: thermal conductivity; material properties; underground mines

## 1 Introduction

Energy transfer arising from the temperature difference between the adjacent parts of a body is called heat conduction. The amount of heat to be transferred through any body depends upon a number of factors, such as the particle shape, porosity, temperature range, solid constituents, moisture content, uniaxial and/or triaxial pressure exerted on the rock *etc.* [1, 3-8]. With this behavior the thermal conductivity has a profound effect on the work safety and ventilation conditions such as the cooling load *etc.* in deep underground mines.

## 2 Theories

In general the thermal conductivity of rocks and its modification with regard to the pressure and moisture content can be calculated using Fourier's Law as given below:

$$\frac{dQ}{dt} = -kA\frac{dT}{dx} \quad (1)$$

$$\frac{dQ}{dt} = -(k_0 + \lambda P^n)A\frac{dT}{dx} \; [8] \quad (2)$$

$$Q = -(k_0 + \lambda_{cp}P^{n_{cp}})C_p^{\beta_{cp}}At\frac{dT}{dx} \; [4] \quad (3)$$

$$Q = -(k_{0w} + \lambda_w P^{n_w})w^{\beta}At\frac{dT}{dx} \; [6] \quad (4)$$

where $dQ/dt$ is the time rate of heat transfer; $A$ the area of the body whose heat is to be transferred; $dT/dx$ the temperature gradient; $k$ the thermal conductivity of the material; $k_0$ the thermal conductivity of the rock under normal conditions, W/(m·°C); $\lambda$ and $n$ are the rock-dependent constant parameters in uniaxial compression; $P$ is the applied uniaxial pressure, MPa; $\lambda_{cp}$, $n_{cp}$ and $\beta_{cp}$ are the therock-dependent constant parameters in triaxial compression; $C_p$ is the confining pressure, MPa; $k_{0w}$ the thermal conductivity of the rock in moist conditions without any pressure, W/(m·°C); $\lambda_w$, $n_w$ and $\beta$ are the rock-dependent constant parameters in moist conditions; $w$ is the moisture content (mass fraction in %).

As can be seen in formulae (2)-(4) and **figure 1**, the thermal conductivity of rocks increases digressively with increasing the rock pressure in the elastic region of deformation. Its increase becomes linear with a positive slope in the elasto-plastic region of the related rocks [8]. On the other hand, rocks show also different values regarding the uniaxial compressive strength, unit mass, tensile strength, cohesion, Young's modulus, point load strength, Schmidt rebound hardness, Shore scleroscope hardness and toughness strength. Additionally the thermal conductivity of the rocks under three-dimensional pressure increases to some definite extent as the thermal conductivity coefficient in uniaxial pressure [4]. In case of the existence of some moisture content in the rocks, the thermal conductivity shows an increasing behaviour to some extent [6].

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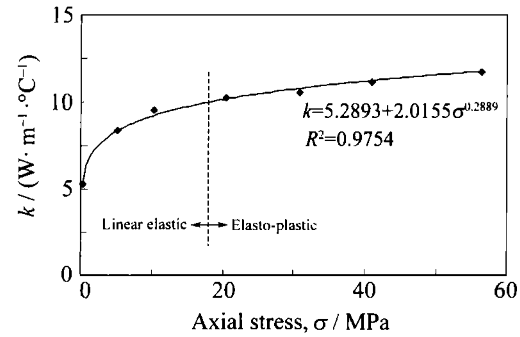


**Figure 1 Variation of the thermal conductivity ($k$) with the pressure for conglomerate [8].**

This study has aimed to determine the relationship between the thermal conductivity at normal temperature ranges without pressure application and the material properties of rocks mentioned above. To this aim different rocks such as monzonite, sandstone, conglomerate, black limestone, yellow travertine, marbles (Afyon sugar, Mugla white, Afyon sky-blue, Akkoy beige and Zile beige), gypsum, tuff, serpentinite (Mesh texture), Divrigi marble, pyroxenite, and diabase have been selected from different mines. Both the thermal conductivity coefficient and other material properties have been measured in the laboratory of the mining department at Cumhuriyet University.

## 3 Experimental

### 3.1 Experimental equipment

In order to measure the thermal conductivity of rock specimens, a steady state technique as shown in **figure 2** has been applied with or without pressure. This device has been developed by Görgülü, Durutürk and Demirci [8]. The other material properties of rocks such as the uniaxial compressive strength, unit mass, tensile strength, cohesion, Young's modulus, point load strength, Schmidt rebound hardness, Shore scleroscope hardness and toughness strength were determined according to the suggested methods by ISRM (International Society for Rock Mechanics) [2].

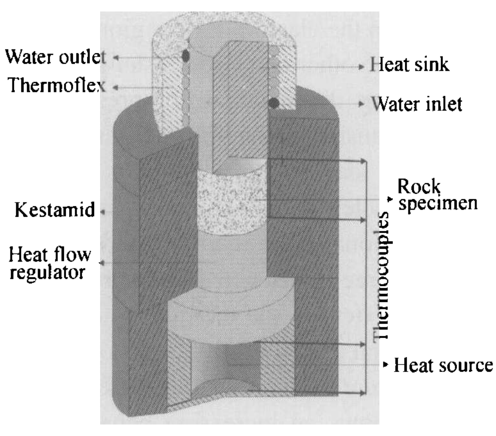


**Figure 2 Thermal conductivity measuring device [8].**

### 3.2 Specimen preparation and test procedure

In order to analyze the relationships between the thermal conductivity and the material properties of rocks, the rock specimens such as monzonite, sandstone, conglomerate, black limestone, yellow travertine, marbles (Afyon sugar, Mugla white, Afyon sky-blue, Akkoy beige and Zile beige), gypsum, tuff, serpentinite, Divrigi marble, pyroxenite, and diabase were taken from different formations. The description of those rock samples is given in **table 1**. The mechanical and physical properties of the rock specimens were determined according to the suggested methods by ISRM [2]. In order to measure the thermal conductivity the rock specimens were prepared in core shape (the diameter is about 54 mm) and cut in the form of slices with a thickness of 40 mm.

Within the scope of this work, the heat energy was supplied by a heat source kept constant at 100°C which was controlled digitally during the testing. At this temperature range, the heat flux through the test device was calculated and used for the determination of the conductivity. The heat source temperature reached 100°C and temperature measurements were carried out subsequently by using the multi-channel temperature read-out system. The calculation of the thermal conductivity for the rock specimens was carried out according to the Fourier Law by using the temperatures obtained from these tests.

## 4 Results

The material properties of the rocks determined from the laboratory tests are listed in **table 2**. In order to show the relationships between the thermal conductivity and the other material parameters there have been some statistical analysis on the basis of the data given in table 2.

**Figure 3** shows the relationship between the thermal conductivity and the uniaxial compressive strength of the rocks. It can be seen from this figure that the thermal conductivity of the rocks increases with increasing the uniaxial compressive strength of

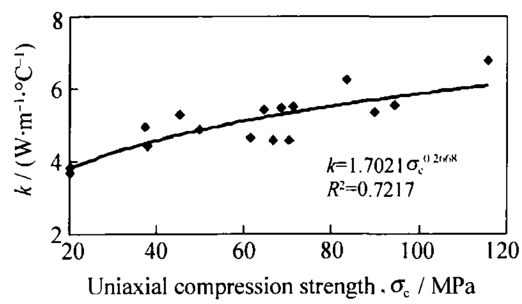


**Figure 3 Relationship between the thermal conductivity and the uniaxial compressive strength of rocks.**

the rocks. This increase shows a digressive behaviour. The relationships between the thermal conductivity and the tensile strength, point load strength, cohesion shown in **figures 4-6** have a similar behaviour as those in figure 3. The difference lies in the bigger sloping angle and lower correlation coefficient.

The relationship between the toughness strength and the thermal conductivity as given in **figure 7** shows a decreasing behaviour. This means the conductivity decreases with the increasing toughness. On the other hand, the relationships between the thermal conductivity and the unit mass, tangent Young's modulus, Schmidt rebound hardness, Shore scleroscope hardness show an exponential behaviour as given in **figures 8-11**.

**Table 1 Description of rock samples**

| Rock specimens | Minerals contains | Grain size / μm | Water content / % |
|---|---|---|---|
| Monzonite | Quartz, pyroxene, biotite, plagioclase | 250-2500 | 0.141 |
| Sandstone | Chlorite, calcite, biotite, quartz, feldspar, rock fragments. Cement: matrix in clay and silt size | 100-1500 | 0.327 |
| Conglomerate | Igneous, metamorphic and sedimentary rock fragments, chlorite, calcite, biotite, quartz, feldspar, opaque minerals. Cement: carbonate and matrix bond | Fine | 0.264 |
| Limestone | Calcite | >10 | 0.007 |
| Yellow travertine | Calcite | 250-500 | 0.766 |
| Afyon sugar | Calcite | 500 | 0.020 |
| Mugla white | Calcite, dolomite | 250-1000 | 0.020 |
| Zile beige | Calcite | >10 | 0.041 |
| Akkoy beige | Calcite | >10 | 0.078 |
| Afyon sky-blue | Calcite | 250-1500 | 0.041 |
| Gypsum | Gypsum | 10-250 | 8.942 |
| Tuff | Basaltic volcanic glass, pyroxene phenocrysts, plagioclase | — | 0.194 |
| Serpentinite | Serpentine minerals | — | 0.289 |
| Divrigi marble | Quartz, calcite, chlorite, pyrite | 25-750 | 0.138 |
| Pyroxenite | Serpentinized-chloritized | 50-600 | 0.333 |
| Diabase | Pyroxene, olivine, apatite, opaque minerals | — | 0.139 |

**Table 2 Thermal conductivity coefficients and the material properties of the rocks**

| Rock specimens | $k$ / (W·m$^{-1}$·°C$^{-1}$) | Uniaxial compressive strength / MPa | Unit mass / (g·cm$^{-3}$) | Toughness strength / MPa | Tensile strength (Brazil)/ MPa | Cohesion / MPa | Young's modulus / MPa | Point load strength / MPa | Shore scleroscope hardness | Schmidt rebound hardness |
|---|---|---|---|---|---|---|---|---|---|---|
| Monzonite | 5.3868 | 89.65 | 2.640 | 5.32 | 9.26 | 38.56 | 39.04 | 10.25 | 99.1 | 72.0 |
| Sandstone | 5.5668 | 94.00 | 2.761 | 4.27 | 7.50 | 26.00 | 34.92 | 6.50 | 80.2 | 62.1 |
| Conglomerate | 5.2893 | 45.00 | 2.564 | 4.02 | 4.20 | 19.57 | 31.6 | 4.30 | 74.3 | 54.0 |
| Limestone | 5.4952 | 68.34 | 2.708 | 3.74 | 6.82 | 26.17 | 35.81 | 5.93 | 74.5 | 59.8 |
| Yellow travertine | 4.4423 | 37.80 | 2.411 | 9.15 | 5.18 | 19.16 | 29.55 | 5.72 | 51.7 | 47.1 |
| Afyon sugar | 4.5753 | 66.44 | 2.708 | 10.19 | 5.93 | 25.93 | 35.16 | 6.78 | 59.9 | 57.2 |
| Mugla white | 4.6755 | 61.14 | 2.709 | 9.14 | 6.56 | 25.82 | 28.79 | 5.69 | 59.2 | 56.1 |
| Zile beige | 5.4373 | 64.32 | 2.693 | 3.44 | 7.27 | 19.84 | 35,37 | 5.65 | 69.9 | 61.0 |
| Akkoy beige | 5.5249 | 71.08 | 2.689 | 3.22 | 5.97 | 20.60 | 33.84 | 5.76 | 73.7 | 60.4 |
| Afyon sky-blue | 4.8981 | 49.74 | 2.697 | 4.61 | 5.02 | 17.32 | 34.7 | 5.44 | 52.9 | 57.9 |
| Gypsum | 3.6890 | 19.97 | 1.962 | 8.09 | 2.56 | 9.36 | 19.26 | 1.52 | 29.7 | 33.5 |
| Tuff | 3.8637 | 20.12 | 1.454 | 5.24 | 2.87 | 9.78 | 21.2 | 1.75 | 44.3 | 38.8 |
| Serpentinite | 4.6049 | 69.95 | 2.615 | 6.34 | 6.74 | 25.02 | 33.42 | 6.09 | 58.2 | 52.3 |
| Divrigi marble | 6.7842 | 115.44 | 3.112 | 2.81 | 11.09 | 47.19 | 43.4 | 11.94 | 108.2 | 78.2 |
| Pyroxenite | 6.2511 | 83.08 | 3.061 | 3.25 | 8.44 | 31.44 | 39.35 | 8.12 | 89.0 | 69.4 |
| Diabase | 4.9728 | 37.25 | 2.768 | 7.86 | 4.98 | 13.75 | 27.81 | 5.31 | 65.3 | 49.9 |

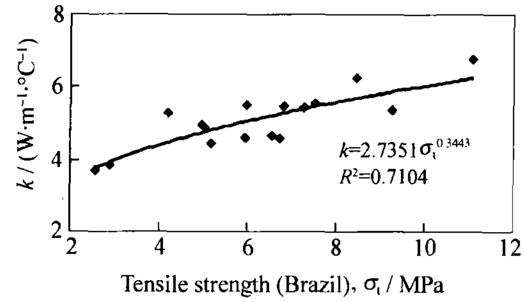


**Figure 4 Relationship between the thermal conductivity and the tensile strength of rocks (Brazil).**

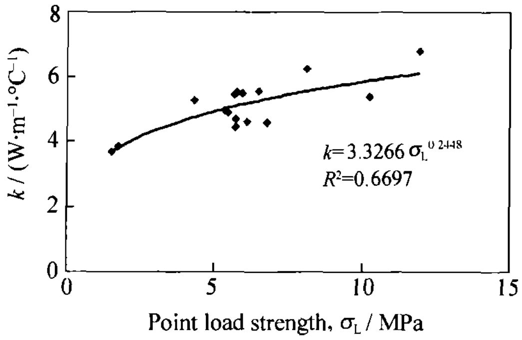


**Figure 5 Relationship between the thermal conductivity and the point load strength of rocks.**

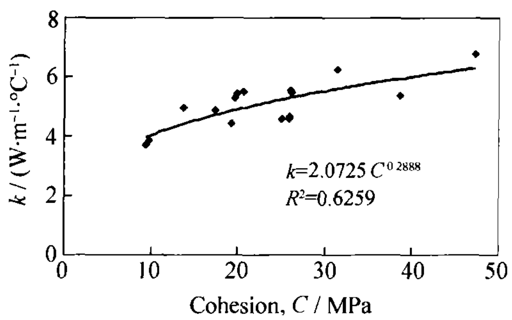


**Figure 6 Relationship between the thermal conductivity and the cohesion of rocks.**

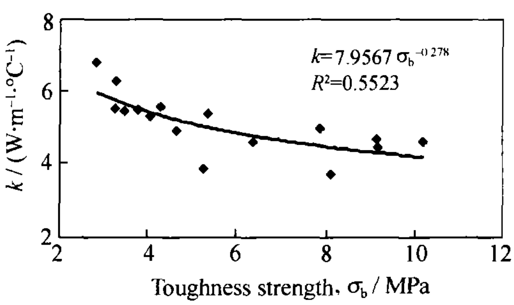


**Figure 7 Relationship between the thermal conductivity and the toughness strength of rocks.**

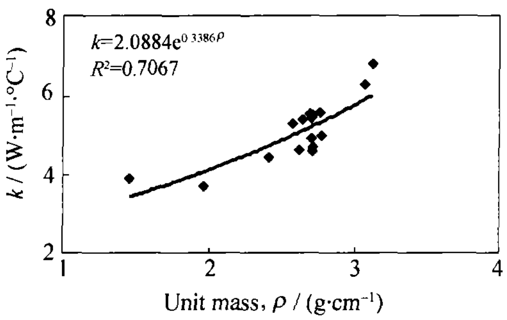


**Figure 8 Relationship between the thermal conductivity and the unit mass of rocks.**

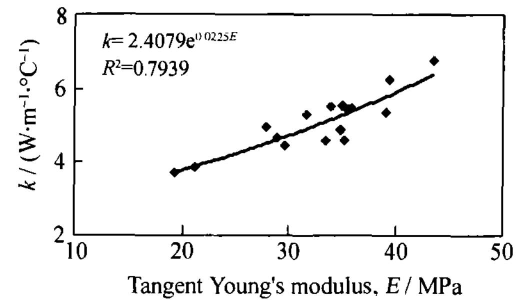


**Figure 9 Relationship between the thermal conductivity and Young's modulus of rocks.**

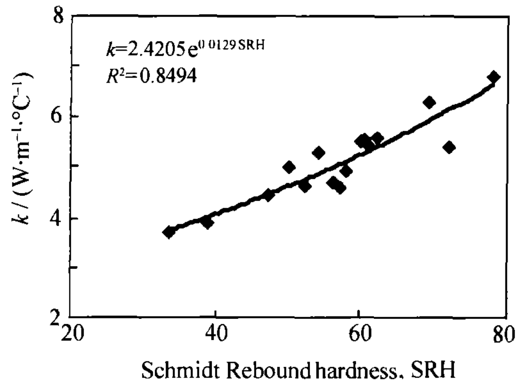


**Figure 10 Relationship between the thermal conductivity and the Schmidt Rebound hardness of rocks.**

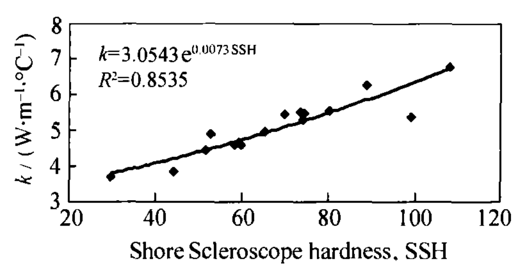


**Figure 11 Relationship between the thermal conductivity and Shore scleroscope hardness of rocks.**

## 5 Conclusions

The thermal conductivity of rocks have a profound effect on ventilation conditions and work safety in deep underground mines. This study aimed to show the relationships between the thermal conductivity and other material properties of rocks gives the following conclusions:

(1) There exists a definite relationship between the thermal conductivity and other material properties of the rocks.

(2) The thermal conductivity increases with increasing the uniaxial compressive strength, unit mass, tensile strength, cohesion, Young's modulus, point load strength, Schmidt rebound hardness and Shore scleroscope hardness and decreases with increasing the toughness strength.

(3) The correlation coefficient between the thermal

conductivity and the material properties of the rocks lies in the range of 0.6-0.9.

These conclusions predicated on laboratory show that it is possible to make some statements about the thermal conductivity on condition that some material properties of rocks are known in advance with a limited reliability.

## Acknowledgment

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