Thermal shock-induced physical changes of granitic rocks of a radioactive waste disposal site

A Németh and Á Török

Department of Engineering Geology and Geotechnics, Budapest University of Technology and Economics, Budapest, Hungary

torok.akos@emk.bme.hu

Abstract. Medium- and low-level radioactive waste is stored in the subsurface galleries of a granitic formation in Southern Hungary. The main lithology is monzogranite. The present study focuses on the thermal behavior and characteristics of intact rocks and thermally exposed specimens. Cylindrical specimens were heated to 250°C, and 500°C in an electric oven in laboratory conditions. Physical properties (density, ultrasonic pulse velocity) and non-destructive strength tests such as Duroskop rebound value were measured on samples kept at 22°C and on samples exposed to heat. The test procedures followed the guidelines given in EN. Tests show that the bulk density was reduced after the 250 °C treatment but slightly increased due to additional heat up to 500 °C. The ultrasonic pulse velocity rapidly decreases with temperature from 22°C to 500°C. The Duroskop rebound values also show a negative correlation with temperature. Color changes are also observed since the grey specimens became increasingly brownish with increasing temperature. The test results demonstrate that with increasing temperature, the tested monzogranite becomes less dense, and micro-cracks reduce the surface strength.

1. Introduction

Granite is considered one of the best target rocks for radioactive waste disposal. One of the critical damages linked to the mechanical strength loss of granite is the thermal shock. The study of thermal effects on rock properties is an increasing research field with publications on the thermal behavior of several lithologies, including limestone [1, 2], sandstone [3], and granite [4,5]. Besides the mechanical changes, mineralogical changes and other physical transformations are linked to increasing temperature in granite [6,7].

In this paper, the thermal behavior of monzogranitic cylindrical specimens is presented. The samples were obtained from exploratory core drillings of a radioactive waste disposal site in Hungary. At the site, low and intermediate level radioactive waste is deposited in the National Radioactive Waste Storage Facility of Hungary. The study aims to outline the physical changes caused by temperature in the monzogranite. The density, ultrasonic pulse velocity, and strength of samples were tested at room temperature and after thermal shocks of 250°C and 500°C in order to outline the thermal behavior of the host rock of the disposal site. A non-destructive strength testing device, the Duroskop, was applied to rapidly measure the strength loss of monzogranite.

2. Materials and methods

The low- and intermediate-level radioactive waste is disposed of at the National Radioactive Waste Storage Facility in Bátáapáti (South Hungary) (figure 1). The disposal chambers are located below the surface at a depth of 200-250 m. More than 1.7 km-long access tunnels lead to the disposal chambers.
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(figure 1). The host rock forms a part of the Carboniferous Mórágy Granite Formation [8]. This granitic larger rock body is located in Southern Hungary in the major structural geological unit Tisia. At its southern part in the Eastern-Mecsek Mountains, it forms the so-called Mórágy Crystalline Block. The block is bordered by faults. The lithology is variable, and it includes porphyric monzogranite and monzonite, with some xenoliths. The light-colored monzogranites enclose darker grey monzonite bodies.

![Figure 1. Location of Hungary's national radioactive waste repository in Bátaapáti and the access tunnel to the disposal chambers.](image)

The tested specimens belong to light grey monzogranite. The prevailing minerals are K-feldspar (larger crystals), quartz, and biotite (figure 2). The maximum crystal size of K-feldspars is 6 cm. No orientation or particular alignments of the crystals was observed.

![Figure 2. Tested samples before heat treatment (22°C)](image)

The laboratory tests involved physical parameters carried out on regularly shaped cylindrical specimens (figure 2). The cylindrical specimens were cut from core drillings using the cutting disc. Altogether 18 samples were prepared. The physical parameters were tested following the guidelines...
given by European Norms: bulk density (EN 1936:2007), the propagation speed of the ultrasonic wave (EN 14579:2005) [9,10]. A PUNDIT device was used to determine the P-wave velocity of cylindrical specimens. In terms of bulk density testing and ultrasonic wave propagation test, the testing principles of European standards and ISRM suggested methods are very similar. In the ISRM method, the dimensions of a rectangular shape are given, while EN also allows testing cylindrical test specimens [9, 10, 11]. A non-standardized test was applied for the surface strength test: the Duroskop. This tool was first used for testing the surface hardness of metals. Lately, it has also been used for testing rock specimens [12,13]. Duroskop has a small pointed mass (2 mm) that rebounds from the surface, and it is a powerful tool for measuring small surfaces and minor changes in surface strength. The Duroskop also detects rebound value similarly to the Schmidt hammer. A comparison of the two measurement methods is examined [14]. The rebound readings of the instrument are on a scale from 0 to 70. It is a portable tool, but a frame was used for testing cylindrical specimens in the laboratory (figure 3).

The heating experiments were performed in an electric oven. The heating rate is set to 20 °C/min, which is sufficient to generate a homogeneous thermal field. The temperature increased linearly to 250 °C and 500 °C and was kept constant for 240 minutes. The cooling was 5 °C/min until the room temperature was reached (figure 4). The samples were kept at room temperature during the tests.

![Duroskop rebound measurement](image)

**Figure 3.** Duroskop rebound measurement

![Heating experiments with temperature changes](image)

**Figure 4.** Heating experiments with temperature changes
### 3. Results and Discussion

The mean bulk density of the standard specimens was 2715 kg/m³, which was reduced due to thermal experiments by 1.3% at 250°C, followed by a slight increase at 500°C (table 1).

**Table 1.** Test results mean values and standard deviations (std) of at least 6 measurements each

| Thermal treatment | Bulk density (std.) [kg/m³] | P wave velocity (std) [km/s] | Duroskop (std) [-] |
|-------------------|-----------------------------|-----------------------------|-------------------|
| 22°C              | 2714.9 (16.4)               | 5.27 (0.19)                 | 50 (1.9)          |
| 250°C             | 2678.1 (34.0)               | 4.49 (0.15)                 | 49 (1.7)          |
| 500°C             | 2694.7 (27.1)               | 3.32 (0.19)                 | 47 (2.4)          |

The color of the specimens also changed with increasing temperature. The color change is already observed at samples that were subjected to 250°C, but at samples that experienced 500°C, an intense browning is visible. The color change is apparent when close-up views are presented. Brown spots and mottles appear on the sample surface at 250°C, while at 500°C, nearly the entire surface becomes brownish (figure 5).

![Figure 5](image.png)

**Figure 5.** Color changes of samples before and after heat treatment: a) Sample no. 2 at 22°C; b) Sample no. 2 after 250°C heat treatment; c) Sample no. 11 at 22°C and d) Sample no. 11 after 500°C heat treatment.

The density change trends are not uniform, as is seen on the box plots of densities (figure 6). The most significant scatter was recorded at samples experiencing 250°C thermal shocks. Nevertheless, the trend is not uniform after a decrease in density at 250°C, a relatively minor increase was measured at 500°C compared to values measured at 250°C.
Figure 6. Simple boxplot of bulk densities of specimens measured at 22°C, 250°C, and 500°C

The P wave velocity clearly shows a rapidly decreasing trend linked to thermal shocks. The mean values from 5.27 km/s were reduced to 4.49 km/s and then to 3.32 km/s at 250°C and 500°C, respectively (table 1). This decreasing trend is uniform and well visualized on the boxplot (figure 7). The loss of ultrasonic pulse velocity is linked to the mineral transformations and, more probably, to the generation of micro-cracks. In former papers [5, 15], it has also been described that micro-cracks are formed during the heating of granitic rocks.

Figure 7. Simple boxplot of P-wave velocities of samples measured at 22°C, 250°C, and 500°C

The Duroskop rebound values of the fresh samples are 50, with a low standard deviation. As documented by the rebound values, the surface strength slightly decreased with temperature to 49 and 47 at 250°C and 500°C, respectively (table 1). The mean values show these changes, but the individual measurements show some scatter when the entire data set is evaluated (figure 8). These scatters
attributed to different minerals at the surface of samples that behave differently under elevated temperatures.

![Boxplot of Duroskop values by Heat-treatment groups](image)

**Figure 8.** Simple boxplot of Duroskop rebound values measured at 22°C, 250°C, and 500°C

The Duroskop, with its small contact point and measuring area, is more sensitive to minor differences of the surface than the Schmidt hammer [14] that has the same testing principle. The Duroskop is considered a sensitive tool for small surface hardness testing. On the other hand, the drawbacks of the measurement are related to the fact that when different large crystals are found within the tested sample, individual readings can only refer to the strength of a mineral. In such examples, it is necessary to record many readings that can represent the mineralogy of the entire surface. Therefore, in this study, 12 readings were recorded on a small surface of an area of 17 cm². With a Schmidt hammer with a higher impact surface, fewer readings generally characterize the surface strength [16, 17].

Nevertheless, the general decreasing trend in surface strength indicates the mechanical changes related to heat. These mechanical changes loss in strength was already measured in several granites [5, 15, 18]. The mechanical parameters also reflect temperature regimes; namely, it is possible to assess the temperature to which the granite was exposed [7, 15].

These test results showed that non-destructive material testing provides a helpful tool for separating the granitoid rocks exposed to various temperatures. The ultrasound propagation velocity (P-wave) is the best method to assess the conditions of heat-affected monzogranite from the test results.

4. Conclusions
The tested samples belong to grey monzogranite forming the main host rock of the National Radioactive Waste Storage Facility of Hungary. The cylindrical samples were exposed to heat, and the temperature caused a color change that is more prominent in samples exposed to 500°C and appears in brown discoloration. A decrease in density at 250°C followed by a minor increase at 500°C, but heated samples have lower densities than the non-heated ones. Ultrasonic pulse velocity is an excellent tool to detect heat-related micro-structural changes. P-wave velocity reduction due to high temperature is significant since the measured mean values reduced from 5.27 km/s to 4.49 km/s (250°C) and 3.32 km/s (500°C). Duroskop is a valuable tool to assess surface strength changes linked to elevated temperatures, but it seems that it is a less sensitive device than an ultrasonic pulse velocity tester in tracking temperature changes. It is very sensitive to smaller-scale surface strength changes, and larger individual crystals can influence the Duroskop rebound values.
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