Mechanical behavior of granitic rocks under elevated temperatures: implications for underground radioactive waste disposal safety and tunnelling

Andor Németh
Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Engineering Geology and Geotechnics, Budapest, Hungary

Ákos Török
Budapest University of Technology and Economics, Faculty of Civil Engineering, Department of Engineering Geology and Geotechnics, Budapest, Hungary

ABSTRACT: The study focuses on heat-induced physical property changes ingranitic rocks, which are vital for the stability of underground spaces such as tunnels or radioactive waste disposal chambers. Monzogranite from Bátaapáti Radioactive waste repository was tested at different temperatures (22 °C, 250 °C, 375 °C, 500 °C, 625 °C, 750 °C) for P and S-ultrasound velocities, bulk density, Duroskop rebound, uniaxial compressive strength, and modulus of elasticity. Analysis revealed temperature-related physical deterioration via test results. Significant changes occurred above 500 °C, and physical deterioration of the monzogranite was drastic at 750 °C. This data could predict the heating temperature in granitic rocks under unknown conditions, aiding the design and global monitoring systems.

Keywords: radioactive repository, granite, heat treatment, mechanical properties.

1 INTRODUCTION

Nuclear waste disposal sites are essential for managing long-term radioactive waste from various sources (Neumann 1988). Due to their stability and low permeability, research has focused on granitic rock formations. Radioactive materials remain hazardous for thousands of years, necessitating careful planning and engineering to prevent their release into the environment (Chapman & Hooper 2012). Deep geological repositories, often in granitic rock, utilize natural barriers for containment. Several countries have implemented or are considering such repositories (Guatam et al., 2019). Understanding rock physical properties under elevated temperatures is vital for long-term repository performance. Heat-induced changes affect stability, thermal behavior, and mineralogical alterations in the host rock of the repositories. Various testing methods have explored heat-related mineralogical alterations and mechanical deterioration of natural stones (Chakrabarti et al. 1996; Vázquez et al. 2015) and geological environments (Shang et al. 2019). This study aims to show temperature effects on rock physical properties, aiding repository design and suggesting proper temperature monitoring. The findings hold relevance for global underground repositories in granitic environments.

2 MATERIALS AND METHODS

The National Radioactive Waste Storage Facility in Bátaapáti, South Hungary, stores low- and intermediate-level radioactive waste. It's situated in the Mecsek Mountains and features subsurface galleries at depths of 200-250 meters. A 1.7 km tunnel leads to disposal chambers where waste is stored. The host rock is the Mórágy Granite Formation, a Carboniferous intrusive crystalline body (Peregi and Gulácsi 2009, Kis et al. 2023) (Figure 1/A-B).

When oxidized, the monzogranite rock type dominates, ranging from light grey to reddish-brown. It has fine to coarse-grained textures with a slight directional pattern (Balla and Gyalog 2009). This study focuses on porphyritic monzogranite, which contains biotite, amphibole, quartz, plagioclase, and feldspar megacrysts (Figure 1/C-D).

Figure 1. The geological environment of the Bátaapáti National Radioactive Waste Repository in Hungary. A) The underground subsurface gallery B) End of the tunnel under excavation C) A boulder of the examined monzogranite host rock D) Mineralogical assemblage of the porphyritic monzogranite lithotype.

During sample preparation, cylindrical test specimens (of diameter: 4.7 cm, height-diameter ratio: 2:1) were prepared from pre-drilling materials. All in all, 36 samples were divided into 6 heat treatment groups. Visual inspection and bulk density checks ensured sample homogeneity.

Laboratory testing involved drying, measuring, and subjecting specimens to non-destructive tests at room temperature. Then, sample groups were individually heated at various temperatures for 4 hours (from 250 °C to 750 °C, by 125 °C group steps), cooled slowly to room temperature, and subjected to non-destructive and destructive tests.

Non-destructive tests included bulk density (EN 1936:2006), P- and S-wave velocity (EN 14579:2005), and Duroskop surface strength measurements (Török 2018). Destructive tests encompassed uniaxial compressive strength (EN 1926:2006) and elastic modulus measurements (EN 14580:2005). Non-destructive tests were conducted multiple times per sample per temperature, while destructive tests were performed once on every specimen.

The conducted tests are generally used in international rock physical research. The results of these tests provide essential input for geological engineering designs and rock physical modeling, influencing tunnel design and monitoring.

3 RESULTS AND DISCUSSION

The initial control groups of monzogranite displayed a typical slightly reddish, dark grey color. After heat treatment, color changes became apparent, with yellowish-brown patches emerging at lower temperatures and shifting towards pale yellowish-brown hues. Substantial color and mineral appearance alterations occurred at higher temperatures (625 750 °C). It is previously indicated that color changes indicated thermal decay in granite rocks, offering insight into material property alterations (Gomez-Heras et al. 2016; Németh et al. 2021). Heat-induced microcracks developed at lower temperatures but at elevated temperatures (750 °C) can be seen macroscopically on the surface of the specimens (Figure 2).

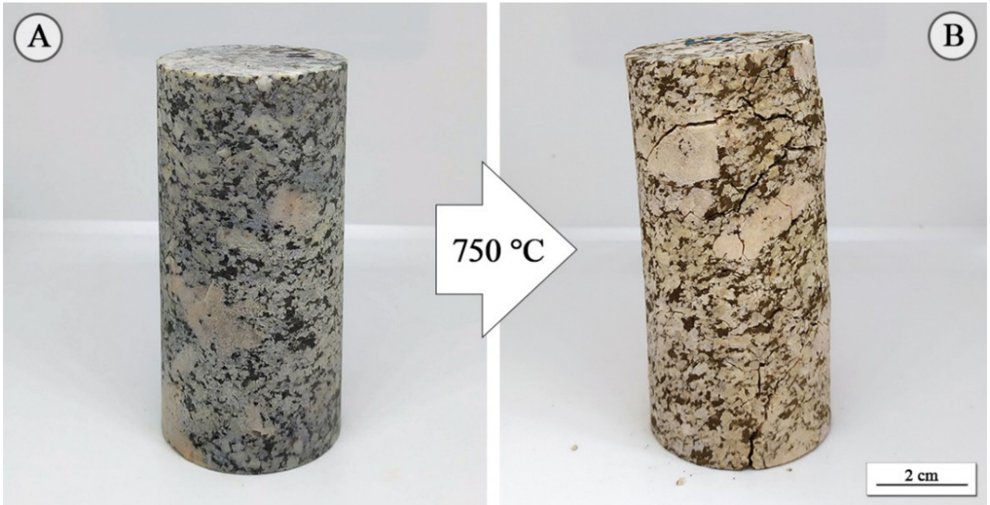

Figure 2. An examined monzogranite sample A) before and B) after heat treatment. Note the significant color change of the minerals and the macro-cracks appearing in the sample after 750 °C of heat treatment.

The non-destructive and destructive test results following heat treatment are reported in Table 1. The descriptive statistical results clearly show that significant rock physics changes occur between each heat treatment group.

Table 1. Summary of test results.

Temperature group	P-wave velocity	S-wave velocity	Bulk density	Duroskop value	Uniaxial compressive strength	Elastic modulus
[°C]	[km/s]	[km/s]	[kg/m3]	[-]	[MPa]	[GPa]
22 °C	5.28 (0.26)	3.1 (0.12)	2715.98 (23.65)	50.89 (0.37)	106.72 (17.02)	28.05 (5.82)
250 °C	4.57 (0.13)	2.81 (0.09)	2678.14 (34.01)	49.39 (0.44)	86.48 (22.23)	23.79 (9.20)
375 °C	4.01 (0.12)	2.6 (0.11)	2711.76 (11.50)	51.18 (0.45)	79.32 (6.00)	22.62 (2.55)
500 °C	3.39 (0.10)	2.19 (0.08)	2694.72 (27.14)	47.13 (0.67)	93.57 (19.10)	21.02 (3.26)
625 °C	1.44 (0.11)	0.95 (0.07)	2637.70 (4.50)	32.56 (1.00)	70.55 (11.03)	10.64 (1.29)
750 °C	0.55 (0.10)	0.33 (0.05)	2493.30 (106.11)	19.1 (5.88)	41.09 (21.42)	4.66 (3.01)

results in: mean (std. dev.) form

Increasing heat treatment temperature led to a significant reduction in both P-wave and S-wave velocities. This decline was consistent across the temperature range. However, the rate of decrease accelerated between 500 °C and 625 °C for both wave velocities (Figure 3). The decrease in wave propagation velocity is mainly associated with developing micro (and at high-temperature macro) cracks in the rock (Fan et al. 2017; Siegesmund et al. 2018). Reasons include linear and differential thermal expansion of minerals (Fan et al. 2017) and possible mineral transformation of quartz at 573°C (Singh et al. 2012; Fan et al. 2017; Siegesmund et al. 2018).

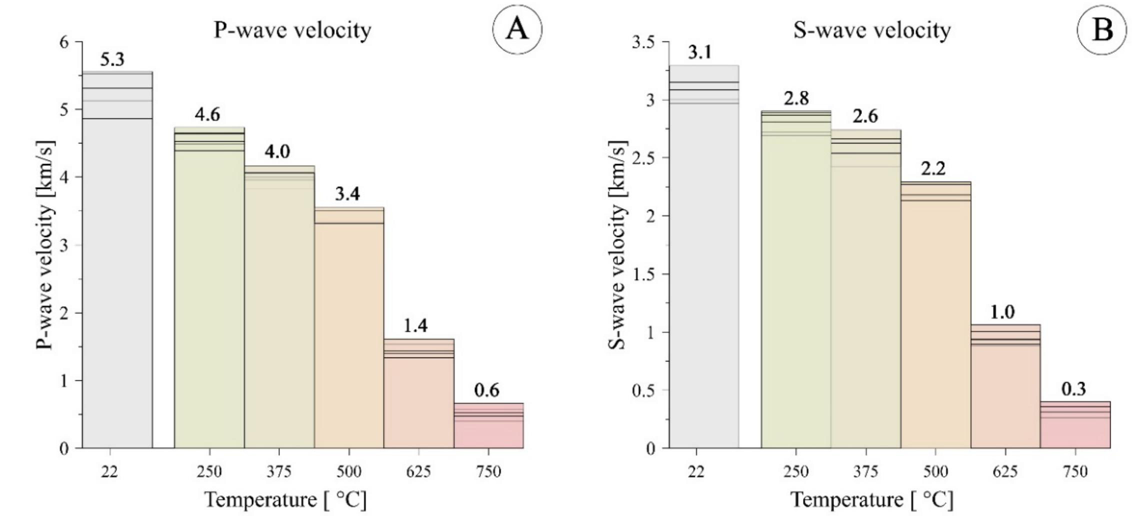

Figure 3. A) P-wave velocity and B) S-wave velocity histograms of the examined heat-treated monzogranite groups. Results on top of the histograms show group mean parameters.

The bulk density of monzogranite decreased notably with higher temperatures. While it slightly increased from 250 °C to 375 °C, it generally decreased. Changes in bulk density were due to variations in mass and volume. A steady decrease in mass and substantial volume increase occurred from room temperature up to 750 °C, except for a slight decrease at 375 °C (Figure 4/A).

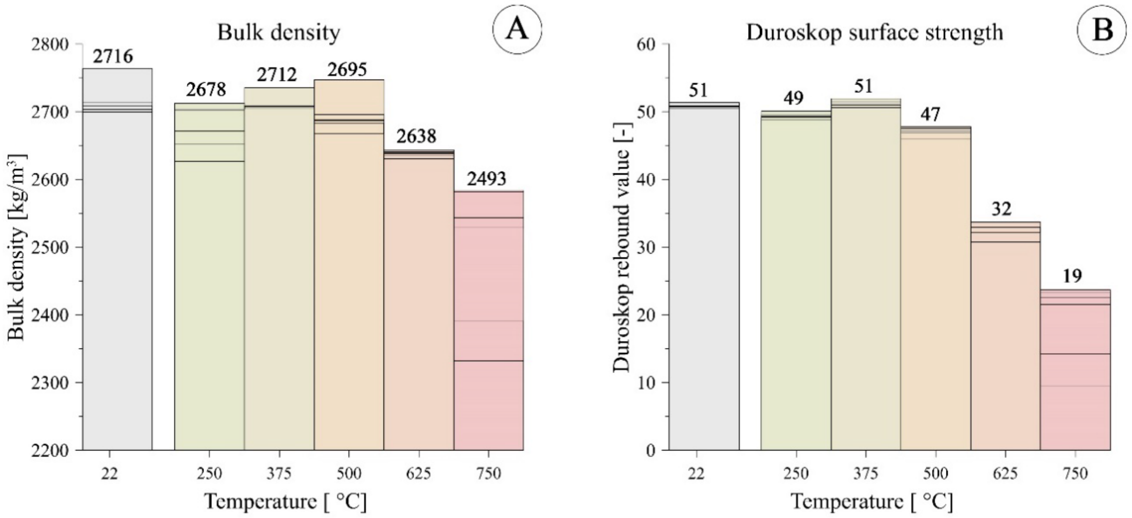

Figure 4. A) Bulk density and B) Duroskop histograms of the examined heat-treated monzogranite groups. Results on top of the histograms show group mean parameters.

The increase of the density parameters at such a temperature range is mainly associated with crystal water removal and micro-crack closure (Poros et al. 2008; Szabó et al. 2008) and hardening of the granite (Wang et al. 2020).

Duroskop rebound values followed a similar trend as bulk density. Although generally decreased from 22 °C to 750 °C, the trend wasn't uniform with temperature increase (Figure 4/B). This phenomenon could be in connection with bulk density values.

Uniaxial compressive strength of monzogranite declined significantly as temperature increased; heat treatment-induced thermal expansion and relaxation, crack propagation, and ultimately fragmentation at high temperatures of 750 °C cause internal strength loss, and the monzogranite becomes weaker (Siegesmund et al. 2018). A slight increase at 500 °C occurs, hence the hardening of the granite (Wang et al. 2020). (Figure 5/A).

The elastic modulus of monzogranite declined significantly as temperature increased (Figure 5/B). The loss of elasticity of the Mórágy granite after 500 °C is marked by the development of mineral alteration (quartz inversion) and the propagation of crack propagation due to thermal expansion. High rigidity occurs at high (625 °C and 750 °C) temperatures.

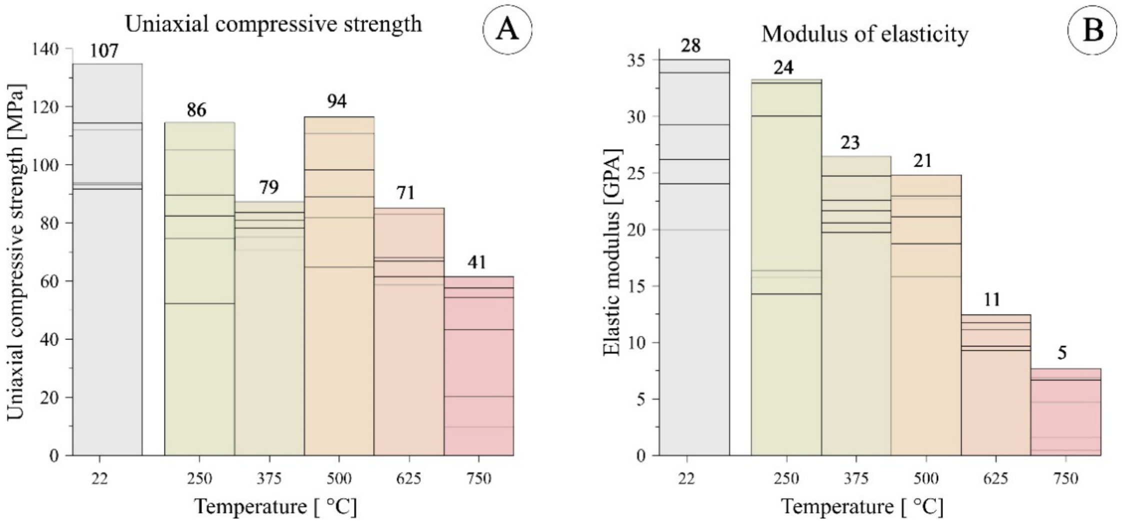

Figure 5. A) Uniaxial compressive strength and B) Modulus of elasticity histograms of the examined heat-treated monzogranite groups. Results on top of the histograms show group mean parameters.

4 CONCLUSION

Rock physics tests on Bátaapáti monzogranite samples (22 °C to 750 °C) revealed significant changes in ultrasound velocities, bulk density, Duroskop strength, uniaxial compressive strength, and elasticity. Results indicate a temperature-driven model. Except for the linear trend changes in ultrasound propagation velocities and elastic modulus from room temperature to 500 °C, rock physics mean parameters showed a relative increase between 250 °C and 500 °C. This hardening phenomenon suggests a nonlinear trend; however, after 500 °C, a consistent decrease indicated a direct relationship between heat treatment and mechanical degradation of the monzogranite. At high temperatures of 750 °C, the monzogranite suffers severe deterioration. These findings have implications for design and monitoring systems in monzogranite environments.

ACKNOWLEDGMENTS

The support for the New National Excellence Program 2022 (ÚNKP-22-3-II-BME-40) scholarship is acknowledged. The research was also partly funded by project no. TKP-6-6/PALY-2021 with support from the Ministry of Culture and Innovation of Hungary from the National Research, Development, and Innovation Fund, financed under the TKP2021-NVA funding scheme.

REFERENCES

Neumann, P.A.: The geological disposal of nuclear waste. J. Environ. Radioact. 6, 92–94 (1988).

https://doi.org/10.1016/0265-931X(88)90071-9
Chapman, N., Hooper, A.: The disposal of radioactive wastes underground. In: Proceedings of the geologists'association, vol. 123, pp. 46–63 (2012). https://doi.org/10.1016/j.pgeola.2011.10.001
Gautam, P.K., Verma, A.K., Singh, T.N., Hu, W., Singh, K.H.: Experimental investigations on the thermal properties of Jalore granitic rocks for the nuclear waste repository. Thermochim. Acta 681, 178381 (2019). https://doi.org/10.1016/j.tca.2019.178381
Vázquez, P., Shushakova, V., Gómez-Heras, M.: Influence of mineralogy on granite decay induced by temperature increase: experimental observations and stress simulation. Eng. Geol. 189, 58–67 (2015). https://doi.org/10.1016/j.enggeo.2015.01.026
Chakrabarti, B., Yates, T., Lewry, A.: Effect of fire damage on natural stonework in buildings. Constr. Build. Mater. 10, 539–544 (1996). https://doi.org/10.1016/0950-0618(95)00076-3
Shang, X., Zhang, Z., Xu, X., Liu, T., Xing, Y.: Mineral composition, pore structure, and mechanical Characteristics of pyroxene granite exposed to heat treatments.Minerals 9, 553 (2019). https://doi.org/10.3390/min9090553
Peregi, Z., Gulácsi, Z.: Mórágy Granite Formation, Lower Carboniferous. In Geology of the North-Eastern Part of the Mórágy Block: Balla, Z., Gyalog, L., Eds.; MagyarÁllami Földtani Intézet: Budapest, Hungary, Chapter 3.1.1.3, pp. 338–359 (2009)
Balla, Z., Gyalog, L.A.: Geology of The north-eastern part of the Mórágy Block: Explanatory notes to the geological map series of the northeastern part of the Mórágy Block (1:10 000); Magyar Állami Földtani Intézet: Budapest, Hungary; vol. 15–17, pp. 58–69 (2009)
EN 14580:2005 Natural stone test methods - Determination of static elastic modulus (2005)
EN 1926:2006 Natural stone test methods - Determination of uniaxial compressive strength (2007)
EN 14579:2005 Natural Stone Test Methods-Determination of Sound Speed Propagation (2005).
EN 1936:2006 Natural Stone Test Methods. Determination of Real Density and Apparent Density, and of Total and Open Porosity (2007).
Török, Á.: Non-destructive surface strength test—duroskop a forgotten tool; comparison to Schmidt hammer rebound values of rocks. In Proceedings of the IAEG/AEG annual meeting, San Francisco, CA, USA, 17–21 September 2018; vol.6, pp. 129–135. (2018). https://doi.org/10.1007/978-3-319-93142-5_18
Gomez-Heras, M.; Figueiredo, C.; Varas-Muriel, M.; Maurício, A.; Alvarez de Buergo, M.; Aires-Barros, L.; Fort, R. Digital Image Analysis Contribution to the Evaluation of the Mechanical Decay of Granitic Stones Affected by Fire. In Fracture Failure of Natural Buildings Stones; Kourkoulis, S.K., Ed.; Springer: Dordrecht, The Netherlands, 2006. http://doi.org/10.1007/978-1-4020-5077-0_26
Németh, A., Antal, Á., Török, Á.: Physical alteration and color change of granite subjected to high temperature. Appl. Sci. 11, 8792 (2021). https://doi.org/10.3390/app11198792
Fan, L.F., Wu, Z.J., Wan, Z., Gao, J.W.: Experimental investigation of thermal effects on the dynamic behavior of granite. Appl. Therm. Eng. 125, 94–103 (2017). https://doi.org/10.1016/j.applthermaleng.2017.07.007
Siegesmund, S., Sousa, L., Knell, C.: Thermal expansion of granitoids. Environ. Earth Sci. (2018). https://doi.org/10.1007/s12665-017-7119-2
Singh, V., Tathavadkar, V., Denys, B.M., Venugopal, R.: Application of quartz inversion phenomenon in Mineral processing—a case study of siliceous manganese ores. Min. Eng. 32, 8–11 (2012). https://doi.org/10.1016/j.mineng.2012.03.010
Poros, Z.S., Molnár, F., Koroknai, B., Lespinasse, M., Maros, G.Y., Benkó, Z.S.: Application of studies on fluid inclusion planes and fracture systems in the reconstruction of the fracturing history of granitoid rocks III: results of studies in drillcores from the radioactive waste depository site at Bátaapáti (Üveghuta). Bull. Hung. Geol. Soc. 138, 361–382 (2008)
Szabó, B., Benkó, Z.S., Molnár, F.: The application of studies on fluid inclusion planes and fracture systems in reconstructing the fracturing history of granitoid rocks II. Fracture systems of the Mórágy Granite. Bull. Hung. Geol. Soc. 138, 193–227 (2008)
Wang, F., Frühwirt, T., Konietzky, H.: Influence of repeated heating on physical-mechanical properties and damage evolution of granite. Int. J. Rock Mech.Min. Sci. 136, 104514 (2020). https://doi.org/10.1016/j.ijrmms.2020.104514
Kis, A., Weiszburg, T.G., Dunkl, I, Koller, F., Váczi, T., Buda Gy. Interpretation of wide zircon U–Pb age distributions in durbachite-type Variscan granitoid in the Mórágy Hills. Miner Petrol (2023). https://doi.org/10.1007/s00710-023-00817-2