ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Assessment of the strength and deformation of granite exposed to temperature cycles

C.V. Cedeño-Burgos, C. Kazemi, C. Hidalgo-Signes, M.E. Garrido & V. Martínez-Ibáñez
Universitat Politècnica De València, Valéncia, Spain
ccedeo@doctor.upv.es

Á. Rabat
Universidad de Alicante, Alicante, Spain

Abstract

The effects of thermal cycles on granite are a field of interest in mining, civil engineering, and geothermal energy. However, research on the behaviour of granites subjected to thermal cycling still needs to be explored. In this study, granite samples were subjected to 5 thermal cycles at target temperatures of 200, 300, and 400 °C and rapid quenching by immersion in water at 70 °C, what we consider a more realistic cooling temperature in geothermic. After each thermal cycle, uniaxial compressive strength and ultrasonic pulse transmission tests were performed to determine the elastic moduli static and dynamic. Also, ultrasonic P- and S-wave tests were performed. A significant reduction in the physical and mechanical properties was observed with increasing temperature and number of cycles. A temperature of 400 ºC was of paramount importance, where the dynamic elastic modulus showed a decrease of 63. 8%, the static elastic modulus of 47.8 %, and the uniaxial compressive strength showed a decrease of 17.1 %; at 200°C, a slight increase of UCS was experienced due to thermal expansion of minerals, closing pores and healing microcracks. This research indicates the existence of severe thermal damage in granites when subjected to thermal cycles in the range of 300-400 ºC. We consider a cooling method at tempered water to 70 ºC closer to the real ranges of temperatures existing in geothermal exploitation; it is more realistic than cooling to ambient temperature as in most existing research, so we consider this methodology a novelty in this field.

Keywords

Thermal cycles, Granite, Uniaxial Compressive Strength, Dynamic elastic modulus, Static elastic modulus.

ISRM

NBG

1 Introduction

Experimenting thermal cycling and high temperatures in rocks is relevant to evaluate their durability in construction, understand their weathering in geology, optimize their extraction in mining and analyze their behavior in geothermal system. It is essential to study the effects of temperature cycling, as it affects their strength and durability. Testing granites exposed to temperatures in ranges of 100-300, 300-400, 400-600, and 600-800 °C, Qiang et al. (2015) deduced that there is a transition from brittle to a ductile state of granite affecting its strength. Alm et al. (1985) conducted mechanical tests on granites exposed to temperatures between 100-600 °C for 3 hours, reported an increase of micro-cracks, which can significantly influence the elastic and fracture mechanical properties. Chen et al. (2012) argued that, at a heating temperature above 400 °C, peak stress and elastic modulus decreased while the peak strain increased. In experiments conducted by Dwivedi et al. (2008) it rocks were heated at different temperature ranges between 25 °C and 700 °C, and it was concluded that stress and strain increased rapidly when samples were subjected to temperatures above 500 °C.

The research works cited above agree that applying high temperatures to granite decreases its physical-mechanical parameters. These hypotheses were verified using strength tests, deducing temperature ranges where these values are critical, and the thermal damage is irreversible. Also, there is different research about rock exposure to thermal cycles. Understanding the behavior of rocks under the effects caused by thermal cycles allows creating safer infrastructures, extracting resources efficiently and optimizing geothermal systems, promoting sustainability; predicting the behavior of the material helps to reduce risks during extraction and handling operations, to cite the most relevant advantages of this study.

In this work, we present new results on the variation of physical and mechanical properties of a granite exposed up to 5 heating cycles. We use target temperatures of 200, 300 and 400 ºC, then cool samples on water tempered to 70 ºC. Non-destructive (ultrasound P- and S-wave velocity) and destructive (uniaxial compressive strength) tests are performed to assess the variation in the properties of granites.

2 Materials and methods

2.1 Specimen preparation

The rock used in this study is a granite extracted from a quarry in Quintana de la Serena in the Extremadura region (Spain). This igneous rock has a granular texture composed of feldspar and quartz. One of its primary uses is in the construction industry, as its low cost, properties, and appearance make it a favorite material for construction. It is present in many works, from monuments and pavements to large constructions such as bridges and dams. Currently there are large mineral reserves of this granite and others like it throughout the northwest area of the country.

In this research, eighty cores were drilled from granite blocks, with dimensions of 300×140×100 mm, provided from a mentioned quarry. The specimens for laboratory tests are cylindrical, with a diameter of 54 mm and slenderness of 1:2.5. The tests were conducted according to ISRM Suggested Methods (Hatheway, A. W., 2009).

2.2 Thermal cycles

Seventy-five samples were separated into three groups of twenty-five samples for target temperatures of 200, 300 and 400 ºC. For each target temperature, groups were divided into sub-groups of 5 samples, and each sub-group was subjected to 1 to 5 cycles. Thermal treatment was applied in an electric muffle and consisted of heating samples at a rate of 10 ºC/min, and then the target temperature was maintained constant for 1 hour. Temperatures were controlled using thermocouples on the surface and in the core of the sample, and data was recorded through TC-08 Data Logger and PicoLog 6 software.

Samples were cooled rapidly through immersion in water tempered at 70 ºC. We consider this cooling method at tempered water to 70 ºC to be closer to the real ranges of temperatures existing in geothermal exploitation; it is more realistic than cooling to ambient temperature as in most existing research, so we consider this methodology a novelty in this field. Once the thermal treatment was finished, samples were dried at 50 °C for twenty-four hours. Thermal treatment was not applied to the remaining group of five samples, and the laboratory tests on this group were considered a pattern for the intact samples.

The factors that depend on the efficiency of the instruments, such as temperature control, heating rate, cooling, type of heat source and accuracy of the sensors, can influence the variation of results such as thermal expansion, microfractures and material resistance, a risk that is run when experimenting in the laboratory; therefore we have been very careful and strict in the control of these factors, making adjustments and permanent calibrations of the equipment, so that they are in optimal conditions and work under the methodology of the thermal test proposed for all samples.

2.3 Laboratory testing

P- and S-wave velocities were measured in every sample and the dynamic elastic modulus was calculated. To do so, signal emitting-receiving equipment Proceq Pundit Lab+ coupled with a computer and 150 kHz transducers were used. Moreover, the uniaxial compressive strength (UCS) and static tangent Young's Modulus (E_{st}) were determined using a four-column press machine Mecánica Científica SA model 28.5200 with a capacity of 2 MN and strain gauges Tokyo Measuring Instruments Lab PF-30-11($120.3 \pm 0.5\ \Omega$, $k = 2.13 \pm 1$).

The compressive load was continuously applied at a constant load rate of 1.0 kN/s until specimen failure. The tangent Young's modulus and the corresponding Poisson's ratio were determined from values of 50% of the specimen's ultimate load. The tests were performed according to the methods recommended by ISRM, and the equipment used is represented in (Fig. 1).

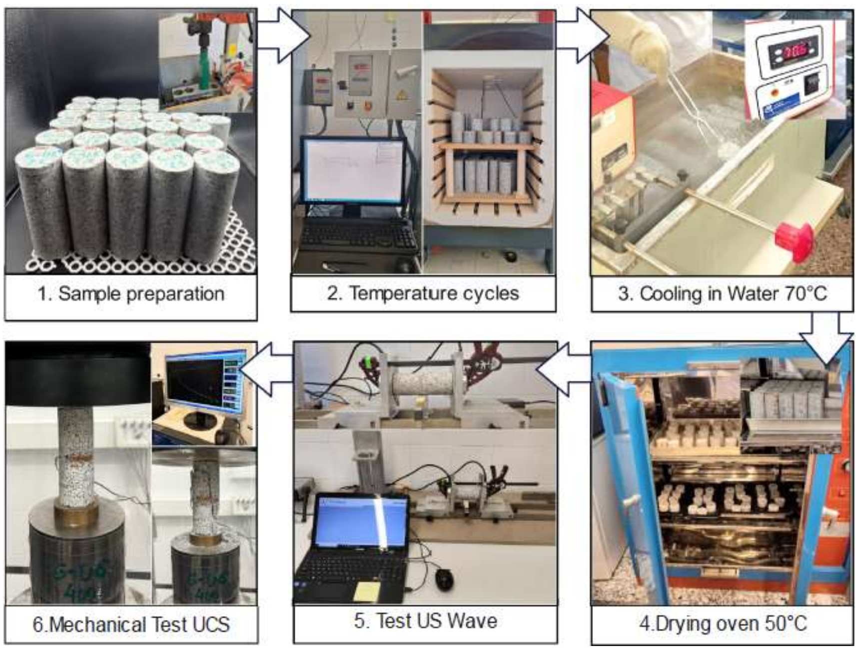

Fig. 1 Experimental workflow and laboratory equipment used in research.

3 Results and discussion

This work studies the variation of the strength of granite subjected to high temperature cycles; by means of UCS, US tests, the static and dynamic strength moduli are determined to evaluate the thermal damage as the exposure cycles increase. There are previous works focused on the effects of thermal cycling, this research shows a relevant interest in simulating geothermal scenarios where the rock is usually found in nature.

Regarding the physical properties, ultrasonic tests showed a notable decrease in the velocity of both P- (Fig. 2) and S-waves (Fig. 3) when increasing temperature and cooling cycles. The induced thermal damage increases internal micro-cracks and porosity, which is the leading cause for slowing down the propagation of the ultrasonic waves (Fan et al. 2017; Gautam et al. 2018).

In (Fig. 2), the variation of the P-wave velocity records has an almost constant slope, with few differences between the cycles applied at 200 and 300 ºC; the differences between cycles 4 and 5 at 400 ºC are more noticeable and show a greater decrease in the wave velocities through the rock.

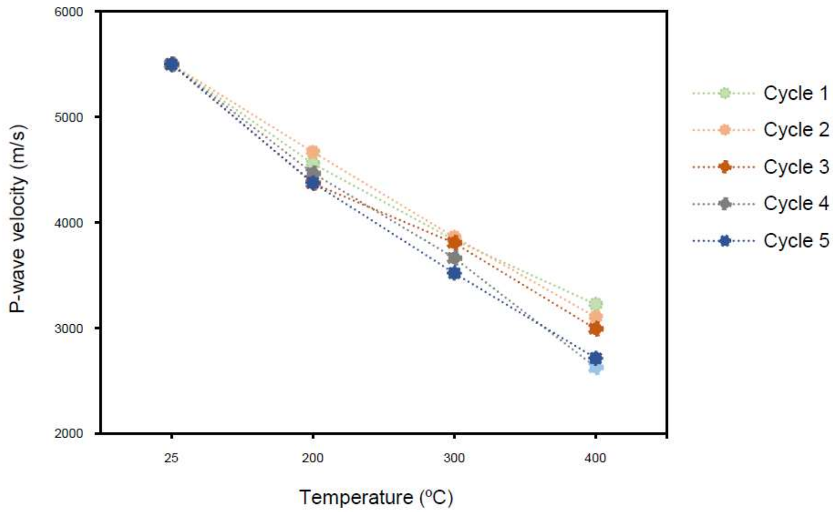

Fig. 2 P-wave velocity variation as a function of temperature and number of thermal cycles.

In (Fig.3), the S-wave velocities also decrease after applying several temperature cycles, the slope between them is not constant, but tends to a more noticeable decrease from cycle 3 to cycle 5 at temperatures of 300 and 400 ºC respectively; this behavior of reduction of the velocities can predict a directly proportional relationship with the number of cycles.

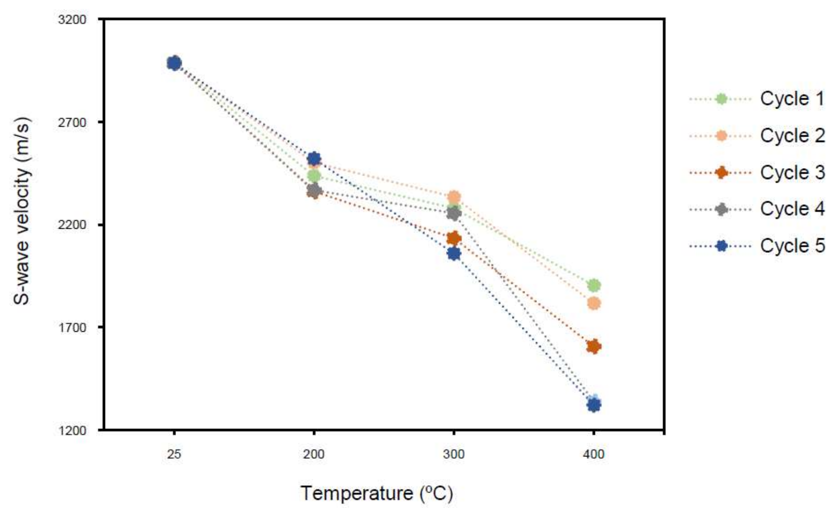

Fig. 3 S-wave velocity variation as a function of temperature and number of thermal cycles.

The dynamic elastic modulus (Ed) also decreased due to temperature and thermal cycles (Fig. 4). This parameter registered a reduction of 30.1 % at 200 °C, 43.1 % at 300 °C and 63.8 % at 400 °C in the fifth cycle when compared to intact samples. The relationship between temperature (∘C) and dynamic elastic modulus (GPa) shows that increasing temperature causes the dynamic elastic modulus (Ed) to decrease, indicating that the material loses stiffness with heat, its behavior appears similar between cycles, but small variations are noted, the fifth cycle (blue) appears to have the largest reduction in elastic modulus (Ed). Overall, the graph suggests that the material becomes less stiff with increasing temperature and that this effect may intensify with the number of cycles.

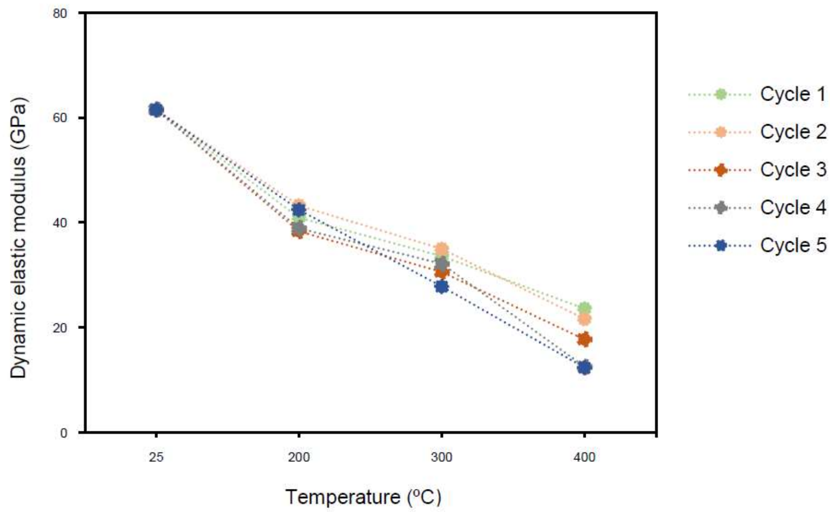

Fig. 4 Dynamic elastic modulus as a function of temperature increase and number of thermal cycles.

Initially, it is shown in (Fig.5) that the resistance remains stable or even increases slightly in as in cycle 2 at 200 °C showing a momentary increase in resistance, which could indicate a hardening or consolidation process at intermediate temperatures, from higher temperatures (300-400°C), the resistance decreases significantly. The fifth cycle (blue) shows the greatest reduction in strength at high temperatures, indicating a possible progressive deterioration of the material. In general, the material loses strength as the temperature increases, especially in later cycles. The behavior may be related to microstructural changes in the material, such as recrystallization or weakening of internal bonds. The slight improvement in some cycles at intermediate temperatures could be due to sintering processes or internal stress relief.

Also, UCS tends to decrease with temperature and thermal cycles. The reduction of this variable in the fifth cycle was 1.4 % at 300 °C and 17.1 % at 400 °C compared to pattern samples. However, a slight increase of 0.3 % was observed in UCS at 200, probably due to the rearrangement of the particles of the material at this specific temperature, (Alm et al., 1985) It indicates that some of the calculated parameters show a maximum value for the specimens thermally treated at 100°C than in the untreated ones, showing a similar behavior to that experienced at 200°C in our research, presenting a temporary increase in resistance in the early temperature cycles; factors such as the origin of the rock, discontinuities, moisture content, porosity or other external agents may differentiate this effect but it is undoubtedly a remarkable reference.

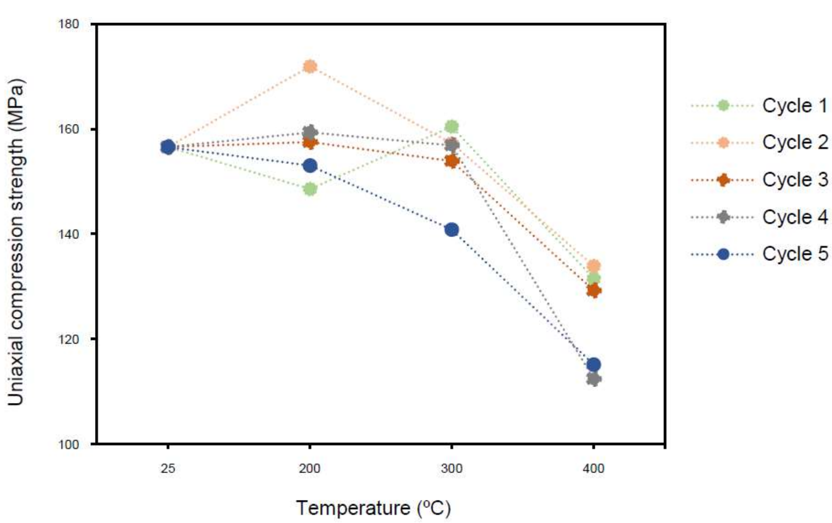

Fig. 5 Uniaxial compressive strength in response to temperature increase and thermal cycling.

The static elastic modulus (Est) (Fig.6) decreases in all the cycles as the temperature increases, it is appreciated in cycle 3 at 300°C (brown) a value a little far from the trend that could be due to consolidation effects of the material, at this point the elastic modulus is higher compared to the other cycles, however, it is corrected with the increase of temperature and number of cycles, In the last cycle 5 (blue) the reduction of the elastic modulus is more pronounced at 400°C indicating progressive degradation of the material, due to changes in its microstructure, the variability between cycles suggests thermal fatigue effects or micro cracks that affect the mechanical response and the momentary increase of the modulus in certain cycles could be due to hardening processes at intermediate temperatures.

The static elastic modulus (E_{st}) also experienced a decrease with temperature and number of cycles. The reduction in the fifth cycle was 10.7 % at 200 °C, 22.2 % at 300 °C and 47.8 % at 400 °C compared to pattern samples.

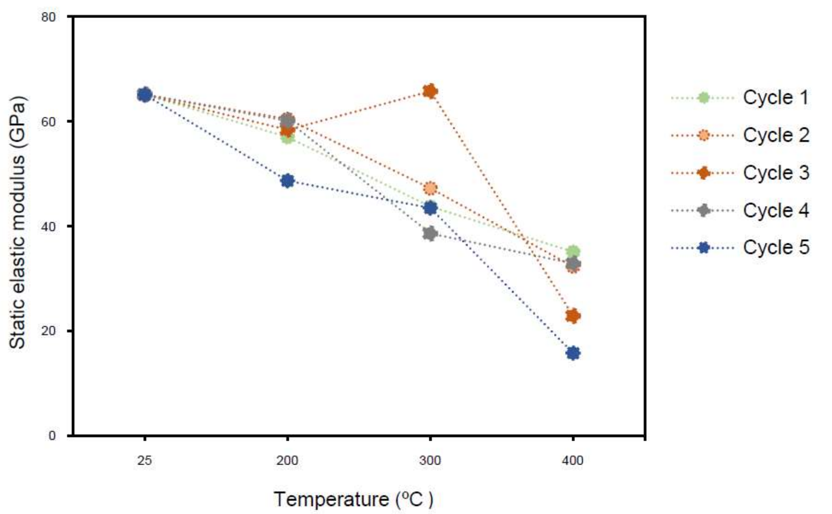

Fig. 6 Behavior of the static elastic modulus as a function of temperature increase and number of thermal cycles.

The values of the dynamic elastic modulus (E_d) and static elastic modulus (E_{st}) showed similarity in magnitude and behavior with a tendency to decrease with temperature and number of thermal cycles.(Chen et al., 2012) in his research he mentions that as the heating temperature increases, the maximum stress and the elastic modulus of the heated granite decrease, while the maximum deformation increases; we consider that the cooling mode has an important relevance, since cooling the heated specimens by immersing them in water adds an additional impact to the thermal damage already caused during exposure to high temperatures.

4 Conclusions

In this research, samples of granite blocks from Quintana de la Serena were subjected to up to 5 thermal cycles. Samples were heated to temperatures of 200, 300, and 400 °C, and then cooled with tempered water at 70 °C. Non-destructive (ultrasound P- and S-wave velocity) and destructive (uniaxial compressive strength) tests were performed to assess the variation in the physical and mechanical properties of this rock. The main conclusions are presented below:

1) The P- and S-wave velocities considerably reduced after thermal cycles at all temperatures, and these results are attributed to the induced thermal damage that increased internal micro-cracks and porosity.

2) Thermal cycles caused a notorious degradation of the physical and mechanical properties of granite. A temperature of 400 °C showed the most critical, with a loss of 63.8 % in dynamic elastic modulus and 47.8 % in the static elastic modulus. Uniaxial compressive strength decreased by 17.1 %.

3) Samples showed a slight increase in the mechanical properties at 200 °C which we attribute to the rearrangement of the particles of the material at this specific temperature.

The methodology used in this study tries to recreate the existing conditions in the geothermal field. The progressive exposure to changes in temperature and number of cycles generate internal micro cracks due to differential thermal expansion and contraction of the minerals that compose it. This research in its general scope contemplates the observation of chemical and mineralogical phenomena that occur at the microstructural level. At this time, the research works on this way and the results will be published shortly notably reinforcing what is exposed here, in terms of the mechanical behavior of this granite expose to temperatures cycles.

Acknowledgements

The authors acknowledge the Department of Geotechnical and Geological Engineering of Universitat Politècnica de València, the Department of Civil Engineering of Universidad de Alicante, and the Department Explotación y Prospección de Minas of Universidad de Oviedo for their continuous support. This investigation was funded by the Ministry of Science and Innovation of Spain through Grant MCINN-23-PID2022-142015OB-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe."

References

Alm, O., Jaktlund, L. L., & Shaoquan, K. (1985). The influence of microcrack density on the elastic and fracture mechanical properties of Stripa granite. *Physics of the Earth and Planetary Interiors*, *40*(3), 161–179. https://doi.org/10.1016/0031-9201(85)90127-X

Chen, Y.-L., Ni, J., Shao, W., & Azzam, R. (2012). Experimental study on the influence of temperature on the mechanical properties of granite under uni-axial compression and fatigue loading. *International Journal of Rock Mechanics and Mining Sciences*, *56*, 62–66. https://doi.org/10.1016/j.ijrmms.2012.07.026

Dwivedi, R. D., Goel, R. K., Prasad, V. V. R., & Sinha, A. (2008). Thermo-mechanical properties of Indian and other granites. *International Journal of Rock Mechanics and Mining Sciences*, *45*(3), 303–315. https://doi.org/https://doi.org/10.1016/j.ijrmms.2007.05.008

Fan, L. F., Wu, Z. J., Wan, Z., & Gao, J. W. (2017). Experimental investigation of thermal effects on dynamic behavior of granite. Applied Thermal Engineering, 125, 94-103. https://doi.org/10.1016/j.applthermaleng.2017.07.007.

Gautam, P. K., Verma, A. K., Jha, M. K., Sharma, P., & Singh, T. N. (2018). Effect of high temperature on physical and mechanical properties of Jalore granite. Journal of Applied Geophysics, 159, 460–474. https://doi.org/10.1016/J.JAPPGEO.2018.07.018

Hatheway, A. W. (2009). The complete ISRM suggested methods for rock characterization, testing and monitoring; 1974–2006. *Environmental & Engineering Geoscience* 2009; 15 (1): 47–48. doi: https://doi.org/10.2113/gseegeosci.15.1.47

Qiang, S., Weiqiang, Z., Xue, L., Zhang, Z., & Tianming, S. (2015). Thermal damage pattern and thresholds of granite. *Environmental Earth Sciences*, *74*. https://doi.org/10.1007/s12665-015-4234-9