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Thermal Cycling Effects on Granite Pore Structure at Moderate Temperatures

M. E. Garrido, C. V. Cedeño, V. Martínez-Ibáñez, C. Hidalgo-Signes
Universitat Politècnica de València, València, Spain
egarrido@upv.es
0000-0001-7804-3922

D. J. Guerrero-Miguel
Universidad de Oviedo, Oviedo, Spain

Abstract

Thermally induced microfracturing has emerged as an effective method to enhance permeability of low-porosity crystalline rocks in Enhanced Geothermal Systems (EGS). Most existing studies focus on high-temperature treatments (>500 °C), which limits their applicability under field conditions, where moderate temperatures and controlled thermal shocks are preferred. This study examines the evolution of porosity and pore structure in granite subjected to repeated heating-cooling cycles at relatively low temperatures to assess the feasibility of inducing microfracture development in geothermal reservoir stimulation. Granite samples were heated to 200, 300, and 400 °C and then cooled by immersion in water to generate a steep thermal gradient. Different groups of samples were exposed to 1 to 5 thermal cycles. Total and open porosity, density, and ultrasonic wave velocity were determined to assess progressive thermal damage. In addition, mercury intrusion porosimetry was performed to characterize variations in pore volume, pore size distribution, and pore connectivity. X-ray diffraction (XRD) analysis was conducted to detect potential mineralogical changes resulting from repeated thermal exposure. The results show a progressive decrease in bulk density and ultrasonic velocities with increasing temperature and cycle count, indicating the accumulation of microstructural damage. Open porosity shows a significant increase, particularly at 300 and 400 °C, while total porosity shows more limited changes, suggesting that increasing the cycle count improves pore connectivity. The porosimetry results confirm a shift toward larger pore sizes and improved connectivity after five cycles, especially at higher temperatures, reflecting microcrack coalescence. XRD analyses show no peak displacements or new mineral phases, confirming that the observed changes are not associated with mineralogical transformations. Overall, this study demonstrates that thermal treatment at moderate temperatures effectively improves porosity and microfracture connectivity in these rocks, offering a practical and energy-efficient method for geothermal reservoir stimulation.

Keywords

Granite, Microcracking, Thermal cycling, Porosity, Geothermal reservoir stimulation.

1 Introduction

The increasing demand for low-carbon energy has intensified interest in Enhanced Geothermal Systems (EGS), which enable energy extraction from low-permeability rock formations. Improving permeability is essential to ensure efficient fluid circulation and heat extraction. Among stimulation techniques, thermal treatment has emerged as a promising method to induce microstructural damage and enhance fracture and pore connectivity. Thermal loading generates internal stresses due to differential thermal expansion of minerals, promoting microcrack initiation and propagation, particularly in granite, where mineral heterogeneity leads to stress concentration at grain boundaries (Griffiths et al., 2017).

Previous studies have shown that thermal cycling produces progressive damage in granite, characterized by microcrack development and degradation of elastic properties (Rong et al., 2021; Yin et al., 2021; Zhu et al., 2020). Ultrasonic velocities decrease as microfracture networks evolve, while pore structure changes, including increased connectivity, have been reported (Yu et al., 2021). These processes are critical for geothermal applications, where permeability is mainly controlled by pore and fracture connectivity rather than total porosity. Most experimental studies focus on high temperatures (>500 °C), whereas the effects of moderate temperatures remain less understood. Previous work has shown that treatments between 200 and 400 °C combined with rapid cooling can induce microfracturing without significant mineralogical changes (Tomás et al., 2025). However, the influence of repeated thermal cycles under these conditions is still poorly constrained.

This study investigates the effects of thermal cycling at moderate temperatures on the microstructural evolution of a low-porosity granite from western Spain, with emphasis on pore structure and connectivity. The objective is to improve the understanding of thermally induced damage mechanisms and their implications for permeability enhancement in geothermal systems.

2 Thermal treatment

The thermal treatment was designed to reproduce damage mechanisms relevant to geothermal environments, where temperature variations induce internal stresses and microcrack development. Samples were heated to 200, 300 and 400 °C, representative of moderate geothermal conditions, using a muffle furnace at a rate of 5 °C/min, followed by a 1-hour isothermal stage. Rapid cooling was then applied by immersion in water at 70 °C for 10 minutes to generate a controlled thermal shock.

To evaluate cyclic effects, specimens were grouped according to the number of heating–cooling cycles (1 to 5). Each group included five samples to ensure statistical consistency. Prismatic specimens were used for density and porosity measurements, while cylindrical specimens were prepared for ultrasonic pulse velocity tests. After each cycle, samples were oven-dried at 70 °C to eliminate residual moisture and ensure consistent measurements.

Microstructural characterization was performed using mercury intrusion porosimetry (MIP) and X-ray diffraction (XRD) on selected samples subjected to 1 and 5 cycles at each temperature, as well as on untreated reference samples, allowing evaluation of both initial and cumulative effects of thermal cycling on pore structure and mineralogical stability.

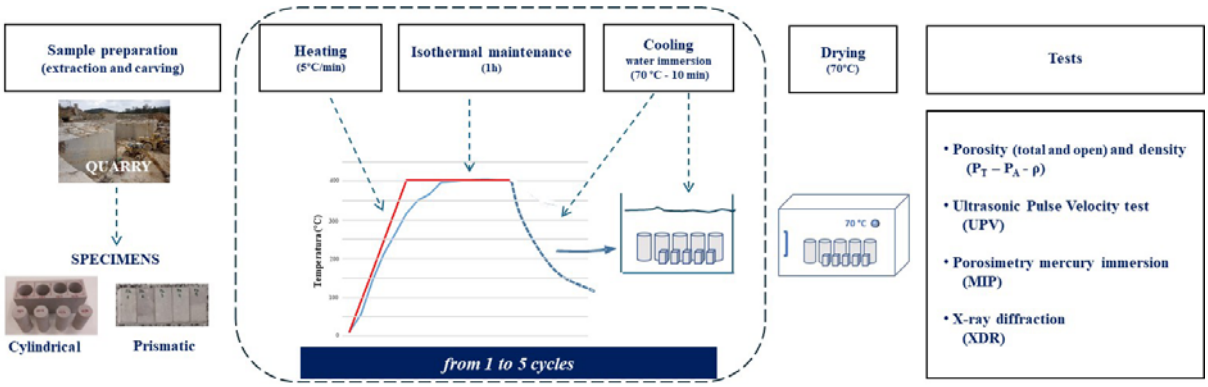


Fig. 1 Diagram of the applied thermal treatment and work methodology.

3 Results

3.1 Density and porosity

Bulk density (ρ_b) shows a slight but consistent decrease with the number of thermal cycles for all tested temperatures (Fig. 2a). This reduction is more pronounced at 400 °C, where the cumulative effect of repeated heating and cooling leads to a progressive loss of density. The observed trend suggests the development of internal microcracking and associated volumetric expansion, even though the absolute changes remain relatively small due to the low initial porosity of the granite. The evolution is not strictly linear, with minor fluctuations at intermediate cycles, which may be related to microstructural rearrangements or closure of pre-existing defects. Nevertheless, the overall decrease in bulk density confirms the progressive nature of thermally induced damage.

Open porosity (OP) exhibits a clear increasing trend with the number of thermal cycles, particularly at 300 and 400 °C (Fig. 2b). The increase becomes more pronounced after the initial cycles, suggesting that thermal loading enhances the opening and interconnection of pre-existing microcracks. Compared to total porosity, the changes in open porosity are more significant, highlighting that the main effect of thermal cycling is the improvement of pore connectivity rather than the generation of new pore volume. At lower temperatures (200 °C), the variations are more limited, suggesting that the induced damage is less intense. The progressive increase in open porosity with cycling confirms the cumulative effect of thermal stresses on the accessible pore network.

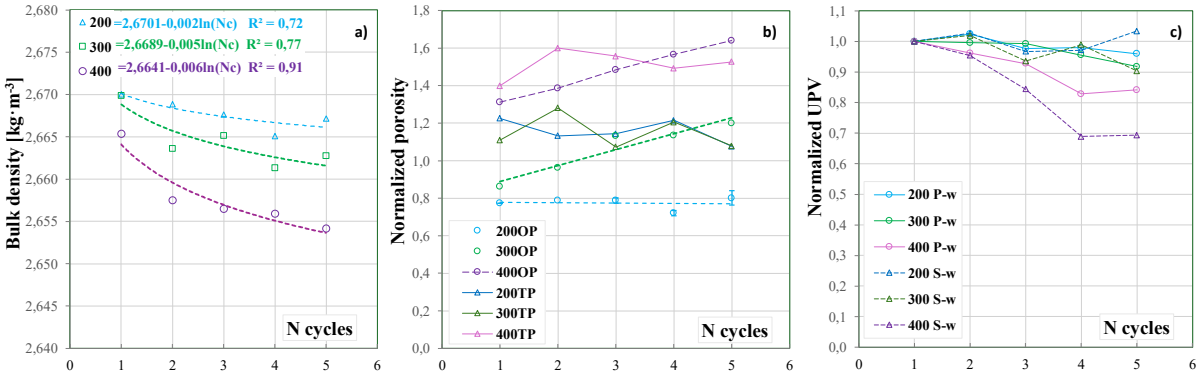


Fig. 2 Tests results: a) bulk density, b) open and total porosity and c) ultrasonic pulse velocity.

Fig. 2b also shows results of total porosity (TP). Its evolution is more moderate and less systematic compared to open porosity. Although a general increasing tendency can be observed with the number of cycles, particularly at higher temperatures, the variations remain relatively small. In some cases, slight decreases or fluctuations are observed at intermediate cycles, which may be attributed to temporary closure or rearrangement of microstructural features during the early stages of thermal loading. The limited increase in total porosity suggests that thermal cycling does not significantly generate new pore volume but rather redistributes the existing pore system. This behaviour is consistent with the low initial porosity of granite and the dominance of microcracking processes.

3.2 Ultrasonic pulse velocity

P-wave and S-wave velocities decrease with increasing number of cycles, reflecting the progressive accumulation of internal damage (Fig. 2c). The reduction is more significant at higher temperature and becomes more pronounced after successive cycles, indicating the cumulative effect of microcrack development. S-wave velocity shows a greater sensitivity to thermal damage than P-wave velocity, exhibiting a more marked decrease, which is consistent with the higher sensitivity of shear waves to discontinuities and crack density. In some cases, slight increases or stabilizations are observed at early cycles, possibly due to microcrack closure or stress redistribution. Overall, the decline in ultrasonic velocities confirms the progressive degradation of the elastic properties of the granite.

3.3 Characterization of the porous system

The results of mercury intrusion porosimetry (MIP) presented in Table 1 show the evolution of the pore system in granite as a function of both thermal cycling and temperature. The untreated samples (C0) are characterized by very low total porosity, with a pore system dominated by micropores and limited connectivity. After one thermal cycle (C1), only slight variations in total pore volume are observed across all temperatures (200, 300 and 400 °C), although changes in pore size distribution indicate the initiation of microcracking and a partial redistribution of the pore network.

The effect of temperature becomes more evident after five cycles (C5), where samples treated at 300 °C and especially 400 °C show a more pronounced increase in accessible pore volume and a clear shift toward larger pore diameters compared to those treated at 200 °C. This behaviour suggests that higher temperatures promote more intense microcrack propagation and coalescence. At 200 °C, the pore system remains relatively stable, with limited development of larger pores, indicating that thermal damage is still incipient. In contrast, at 400 °C, the broader pore size distribution and the presence of larger pores reflect the formation of a more heterogeneous and interconnected pore network.

Table 1. Ranges of MIP-derived parameters for granite samples.

T [°C]	Parameter	C0	C1	C5
25	Total porosity [%]	0.37 – 0.92	-	-
	Interparticle porosity [%]	0.14 – 0.37	-	-
	Intraparticle porosity [%]	0.00 – 0.78	-	-
	Apparent density [kg·m^{-3}]	2560 – 2645	-	-
	Modal diameter [µm]	0.008 – 0.059	-	-
200	Total porosity [%]	-	0.50 – 0.58	0.38 – 1.43
	Interparticle porosity [%]	-	0.16 – 0.40	0.15 – 1.43
	Intraparticle porosity [%]	-	0.10 – 0.42	0.01 – 0.23
	Apparent density [kg·m^{-3}]	-	2589 – 2662	2598 – 2693
	Modal diameter [µm]	-	0.007 – 0.030	0.012 – 0.048
300	Total porosity [%]	-	0.25 – 0.50	0.76 – 2.60
	Interparticle porosity [%]	-	0.20 – 0.28	0.37 – 1.78
	Intraparticle porosity [%]	-	0.05 – 0.21	0.39 – 0.82
	Apparent density [kg·m^{-3}]	-	2601 – 2649	2567 – 2682
	Modal diameter [µm]	-	0.006 – 0.173	0.006 – 0.007
400	Total porosity [%]	-	0.29 – 0.78	0.93 – 1.08
	Interparticle porosity [%]	-	0.06 – 0.29	0.33 – 0.46
	Intraparticle porosity [%]	-	0.00 – 0.71	0.47 – 0.75
	Apparent density [kg·m^{-3}]	-	2645 – 2665	2600 – 2674
	Modal diameter [µm]	-	0.007 – 4.747	0.006 – 0.050

3.4 Mineralogical analysis

XRD analyses reveal no significant mineralogical differences between untreated samples and those subjected to thermal cycling at 200, 300 and 400 °C, even after five cycles. The position of diffraction peaks remains unchanged in all cases, indicating the absence of phase transformations (Fig. 3b). However, slight variations in peak intensities are observed, particularly at higher temperatures and after multiple cycles. These changes are attributed to microstructural effects such as microcrack development, internal stress redistribution and preferred orientation. The results confirm that thermal damage in the studied granite is controlled by physical processes, with temperature and number of cycles enhancing microstructural heterogeneity without affecting mineralogical composition.

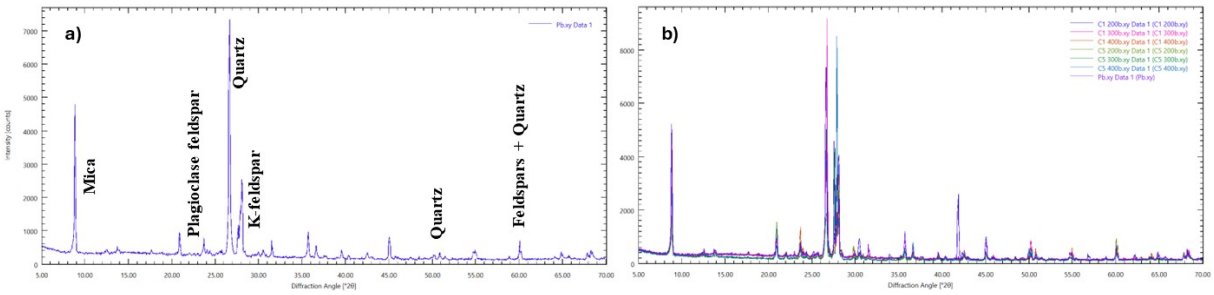


Fig. 3 XRD patterns: a) reference granite highlighting the main mineral phases. b) thermally treated samples.

4 Discussion

The combined analysis of bulk density, porosity, ultrasonic velocities and MIP results provides a consistent interpretation of thermally induced damage in granite. The decrease in bulk density, although limited, reflects volumetric expansion associated with microcrack development, as reported in previous studies (Gautam et al., 2020; Gómez-Heras et al., 2008). The increase in open porosity, more pronounced than total porosity, indicates that thermal cycling enhances pore connectivity rather than generating new pore volume, consistent with previous observations (Yu et al., 2021).

The MIP results further support this interpretation, showing a redistribution of pore sizes and a shift toward larger pores, particularly at higher temperatures and after multiple cycles. This behaviour reflects the progressive coalescence of thermally induced microcracks, as also observed in studies on granite subjected to repeated thermal cycling (Junique et al., 2021). The more pronounced changes observed at 300 °C and especially 400 °C suggest the existence of a thermal threshold above which crack propagation becomes dominant. This threshold behaviour is consistent with previous findings indicating intensified damage beyond approximately 300–400 °C (Tomás et al., 2025).

Ultrasonic pulse velocity results provide additional evidence of damage evolution at the microstructural scale. The reduction in both P-wave and S-wave velocities with increasing number of cycles reflects the progressive degradation of the elastic properties of the granite, as widely documented in the literature (Junique et al., 2021; Rong et al., 2021). The greater sensitivity of S-wave velocity observed in this study is consistent with its stronger dependence on crack density and discontinuities, as reported in previous experimental works (Yin et al., 2021). Minor fluctuations at early cycles may be attributed to crack closure or stress redistribution, a phenomenon also observed in thermally treated rocks (Qin et al., 2020).

The XRD results further support the interpretation that thermal damage in the studied granite is predominantly governed by microstructural processes rather than mineralogical transformations. As observed in the diffractograms (Fig. 3), no significant changes in peak positions are detected between untreated samples and those subjected to thermal cycling at 200, 300 and 400 °C, even after five cycles. This confirms the absence of phase transformations within the investigated temperature range. However, slight variations in peak intensities are observed, particularly at higher temperatures and after five repeated cycles, indicating an increase in microstructural heterogeneity. These changes can be attributed to the development of microcracks, internal stress redistribution and preferred orientation effects, rather than to modifications in crystal structure.

Similar behaviour has been reported in previous studies on thermally treated granites, where physical damage induced by differential thermal expansion occurs without detectable mineralogical alteration (Gómez-Heras et al., 2008; Junique et al., 2021). Furthermore, the absence of differences between C1 and C5 samples in terms of peak position suggests that thermal cycling enhances the degree of damage without triggering new mineral phases, reinforcing the interpretation that the observed evolution in porosity, ultrasonic velocity and pore structure is controlled by progressive microcrack development (Gautam et al., 2020; Zhu et al., 2020).

The influence of temperature is clearly observed across all techniques, with more pronounced changes at 300 °C and 400 °C, indicating that thermal damage intensifies beyond moderate thresholds. At lower temperatures (200 °C), the observed variations are smaller and suggest that microstructural changes are still limited or partially reversible. This behaviour agrees with previous studies indicating that thermal damage at moderate temperatures is initially controlled by microcrack initiation and gradual propagation, without significant mineralogical transformations. Similar observations have been reported in experimental studies on granite, where early-stage thermal damage is dominated by physical processes related to differential thermal expansion (Tomás et al., 2025).

Although the observed mechanisms are consistent with previous studies on thermally treated granites, their magnitude is expected to depend on lithology, mineralogical composition and initial pore structure. Therefore, the present results should be regarded as representative of the investigated low-porosity granite and the tested thermal conditions. Further studies on rocks with contrasting petrophysical properties are required to assess the broader applicability of thermal cycling for geothermal reservoir stimulation.

Overall, the results indicate that thermal cycling at moderate temperatures induces progressive microcrack development, leading to improved pore connectivity and degradation of elastic properties without significant mineralogical alteration. The good agreement between porosity measurements, ultrasonic velocities and MIP data highlights the complementary nature of these techniques for characterizing thermal damage in low-porosity granites. This complementarity has also been emphasized in previous studies, where combined petrophysical and microstructural analyses provide a more comprehensive understanding of damage evolution (Junique et al., 2021; Yu et al., 2021).

5 Conclusion

Thermal cycling at moderate temperatures (200–400 °C) induces progressive microstructural damage in granite through microcrack development and coalescence. Although changes in bulk density and total porosity are limited, open porosity increases significantly, highlighting the dominant role of pore connectivity in the evolution of the pore network.

Ultrasonic velocity results confirm the progressive degradation of elastic properties, with S-wave velocity showing higher sensitivity to damage. MIP analyses indicate a shift toward larger pore sizes and improved connectivity after multiple cycles, particularly at 300 and 400 °C, indicating a thermal threshold beyond which damage becomes more pronounced.

Overall, the strong agreement between petrophysical and microstructural results demonstrates that thermal cycling is an effective method to enhance pore connectivity in low-porosity granites without significant mineralogical alteration, offering a practical and energy-efficient strategy for geothermal reservoir stimulation.

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