Experimental assessment of high temperature-induced changes on frictional behavior of planar rock joints

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ABSTRACT: It is accepted that heat waves, whose occurrence have been increasing throughout the last decades in the Iberian Peninsula, associated with climate change, are one of the main hazards linked to the occurrence of wildfires and the increase of fire risk in the open-pit mining industry. To the best of our knowledge, studies that relate the effect of temperature (produced by a fire) on jointed rock masses are scarce. This paper considers the development of benchmark work for the determination of the basic friction angle on suitably prepared saw-cut planar granitic joints, some of them subjected to thermal ageing, and by means of an automatic tilt test apparatus for both reference (no thermal ageing) and thermally aged samples. The results show the influence of high temperatures on the frictional behavior of rock joints, particularly relevant for the stability assessment after a fire or wildfire occurrence near outcrops and excavations.

Keywords: Rock mass, joint, thermal ageing, friction angle, tilt test.

1 INTRODUCTION

It is widely accepted that climate change is leading, in the northern arc of the Mediterranean Sea, to temperature extremes that, in turn, causes the occurrence of fires and wildfires that affects many rock structures (Christensen et al., 2007; Meehl et al., 2007; Trenberth et al, 2007).

Rock thermal-induced decay has been the main focus of several studies already developed, most of them, in laboratory environment (e.g. Glover et al.,1995; Chopra, 1997; Zhang et al., 2001; McCabe et al., 2007; Tang et al, 2011; Heap et al., 2012; Ranjith et al., 2012; Zhao et al., 2012; Yang et al., 2014; Mao et al., 2015; Martinho & Dionísio, 2018; Paneiro et al., 2021). However, just a few works perform studies on what concerns the influence of high temperatures, like those induced by a wildfire in rock masses (Sarro et al., 2021).

Following the work of Alejano et al. (2017) and Pérez-Rey et al. (2020), the present paper presents the baseline results of the basic friction angles obtained from tilt tests on saw-cut planar joints on rock specimens subjected to different thermal ageing, namely 300ºC and 700ºC, and considering ambient moisture. These results correspond to a first incursion on assessing high temperature influence on rock mass stability.

2 MATERIALS AND METHODS

In the present section, the rock used in this experimental study, the tilt tests, and the thermal ageing processes to which the rock specimens were subjected are described.

2.1 The rock material and petrophysical characterization

A medium-to-coarse (1-6 mm) grained granite from NW Spain, commercially known as *Blanco Mera*, was selected (Figure 1). This rock presents an approximate UCS of 130 MPa, and is mainly composed of quartz (20%), alkaline feldspar (27%), plagioclase (35%), biotite (5%), muscovite (7%) and accessory minerals like sericite or chlorite (Pérez-Rey et al., 2020).

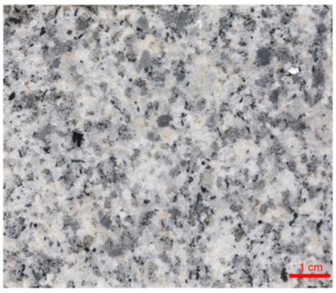

Figure 1. Image showing the rock texture.

Slab-like specimens measuring 8 mm × 7 mm × 2.5 mm in length, height, and width, respectively, were prepared according to Alejano et al. (2017). Four groups of seven specimens each (labelled B, B', C and C') were obtained making available, therefore, 28 slab-like rock specimens for testing. Each rock specimen was labelled with the corresponding letter and a number between 1 and 7 (i.e., for the 6th specimen in B': B'6).

The petrophysical characterization consider the determination of the density and the open porosity, the latter considering the EN 1936 standard.

This work also considers X-ray computerized tomography (CT) scanning. The tests were performed using a SkyScan 2214 over one cubic sample of each type (reference, subjected to 300 ºC and 700 ºC) with 26 x 26 x 26 mm dimensions, with a resolution of 13 µm per pixel.

2.2 Thermal ageing

Each group of rock specimens was divided into two subgroups of 3 and 4 elements. Within each group, three specimens were kept in laboratory environmental conditions for carrying out tilt-tests, and the remaining four were subjected to different thermal ageing processes before the petrophysical and tilt-tests. According to Figure 2, those specimens corresponding to groups B' and C' were subjected to 'Thermal ageing 1', and those corresponding to groups B and C, to 'Thermal ageing 2'.

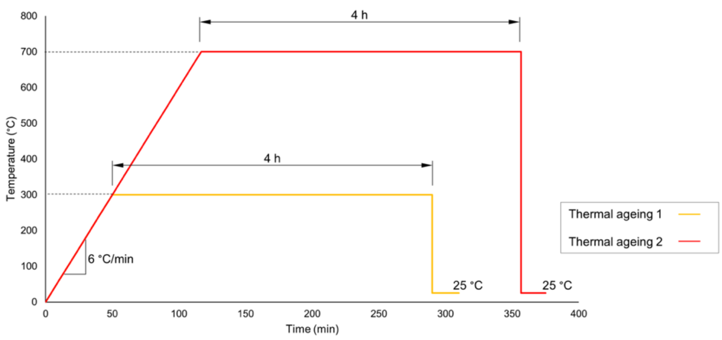

Figure 2. Chart summarizing the thermal ageing treatments designed for the present study.

The 'Thermal ageing 1' involved the heating of the group of specimens in a muffle furnace at a rate of 6 °/min until a temperature of 300 °C was reached. The specimens were kept at this temperature for 4 h, and then submerged into water at 25 °C for approximately 10 s. The 'Thermal ageing 2' was carried out similarly, except for the temperature attained (in this case, 700 °C). After the thermal ageing processes, the specimens were allowed to reach room temperature before being tested.

2.3 Tilt tests

After the completion of the thermal ageing processes, the basic friction angle of all the available contacts (each contact corresponding to a couple of surfaces) was determined through tilt tests. Since 28 specimens were used, the same number of contacts were available. Tilt-tests were carried out by following the recommendations contained in the ISRM Suggested Method (Alejano et al., 2018). A total of 140 tilt-tests were carried out for this study.

3 RESULTS AND DISCUSSION

The described physical and mechanical tests were performed over 28 specimens, where 12 are reference samples that weren't subjected to any thermal ageing, and 8 specimens were heated to 300ºC and another set of 8 specimens were aged at 700ºC.

In the following section the obtained results from the developed tests.

3.1 Temperature induced petrophysical changes

In what concerns to the petrophysical characterization tests, the results presented on Figure 3 show that with increasing temperature, in average, density decreases as porosity increases, as expected. In fact, from the reference samples to the ones heated to 300ºC the average density reduced from 2572.96 (± 25.09) kg/m^3 to 2567.60 (± 11.89) kg/m^3 which corresponds to a decrease of 0.21%. However, the samples heated to 700ºC, the obtained density is 2466,80 (± 113.72) kg/m^3, which corresponds to a decrease of 4,13% in average when compared to the reference samples density are presented.

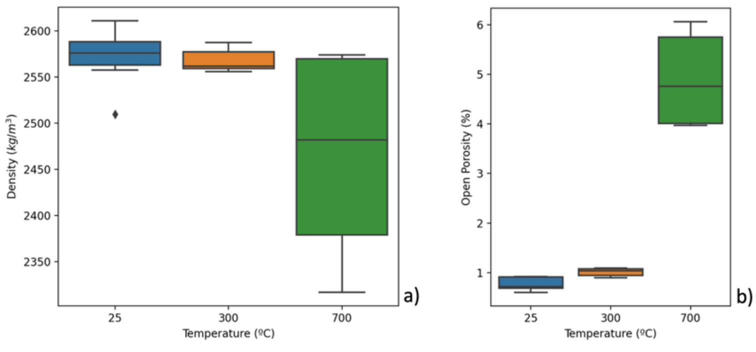

Figure 3. Graphical representations of the changes on (a) density and (b) open porosity with the thermal ageing.

In what concerns the open porosity, the opposite behavior is observed. From the reference to 300ºC heated samples, an increase of 25 %, from 0.8 (± 0.10) % open porosity of the reference samples to 1.00 (± 0.10) % for the 300ºC heated ones. This increase is much steeper for 700ºC as the obtained open porosity is 4.90 (± 0.10) %, which corresponds to an increase of 512,50%.

In fact, considering X-ray computerized tomography (CT) reconstructed models (Figure 4) of the reference and thermally aged samples, between the reference samples and the ones subjected to 300 ºC there are no big changes in the structure. However, for the scanned sample subjected to 700 ºC the presence of cracks is evident which is in accordance with the obtained results for open porosity and density. The different behaviour after thermal ageing at 700ºC is tentatively attributed to phase changes in the granite-forming minerals, namely quartz. Further studies will address this issue in more detail, however, similar results were obtained by Paneiro (2021) for other granites.

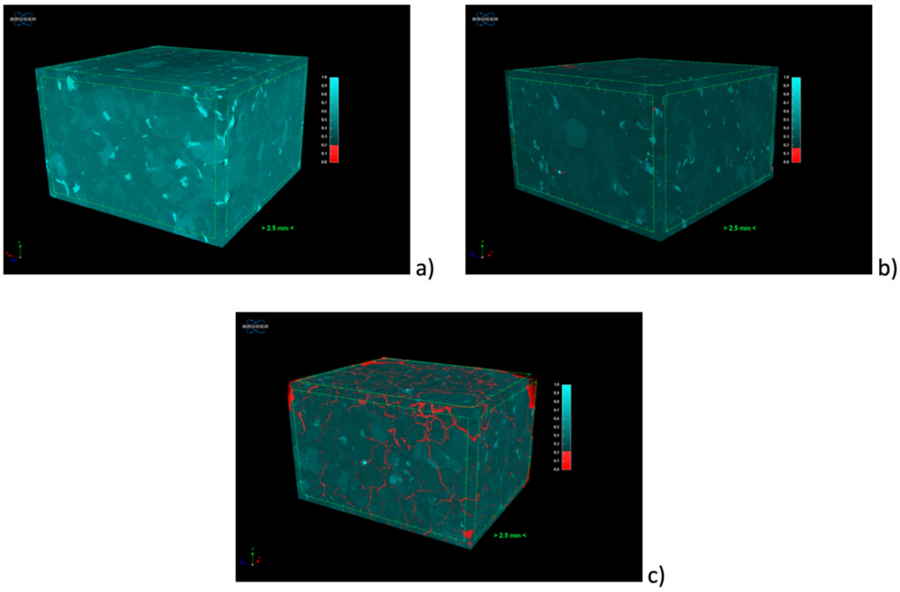

Figure 4. X-ray computerized tomography reconstructed models for a (a) reference sample, (b) sample subjected to thermal ageing of 300ºC, and (c) a sample subjected to 700ºC. The red shadings represent the presence of air (lower density).

3.2 Changes in the basic friction angle of tested joints

In what concerns the determination of the basic friction angle, Figure 5 presents the histograms and correspondent probability density functions, following Gaussian distribution, for the reference and thermally aged samples.

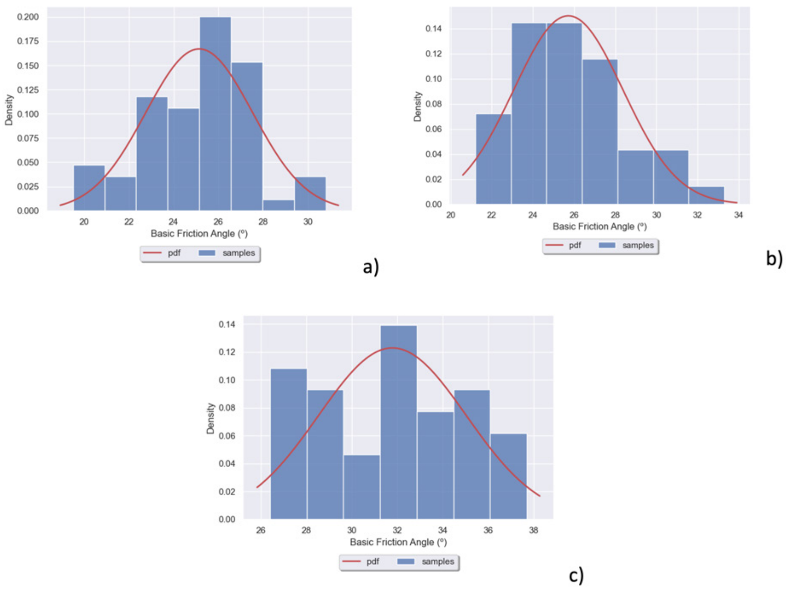

Figure 5. Histograms and corresponding Gaussian probability density functions of the obtained basic friction angles for the (a) reference samples, (b) for those heated to 300 ºC and (c) 700ºC.

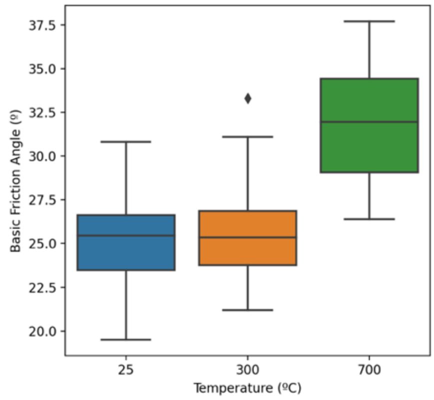

Figure 6. Boxplot representations of the basic friction angles obtained as a function of the thermal ageing.

According to the obtained results, summarized in Figure 6, the average basic friction angles for the reference samples surfaces is 25.14 (± 2.41) º and the angles of 25.72 (± 2.69) º and 31.79 (± 3.20) º were obtained for the samples subjected to 300 ºC and 700 ºC, respectively. This corresponds to an average increase on the basic friction of 2.31 % for 300 ºC and 26.45 % for 700 ºC, demonstrating a negligible effect of the thermal ageing of 300 ºC and being this effect more evident for 700 ºC. Moreover, there is an evident relation between the basic friction angle with the density and the open porosity.

4 CONCLUSIONS

The present paper presents the results of a benchmark experimental work to study the influence of high temperatures on the basic friction angle of discontinuities of rock masses. Despite the considered testing procedure, this work doesn't consider and in-depth approach, based on micromechanic issues that influence the observed changes.

Nevertheless, the obtained results show a clear influence of the thermal ageing on the basic friction angle determined from the tilt tests, particularly for those heated to 700 ºC. Also, these changes are in accordance with those observed in density and porosity, which are corroborated with the CT models.

Future works will consider not only an in-depth study of this behavior based on micromechanical analysis but also a joint effect with the presence of water.

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REFERENCES

Alejano, L.R., Muralha, J., Ulusay, R., Li, C.C., Pérez-Rey, I., Karakul, H., Chryssanthakis, P., Aydan, O., Martínez, J., Zhang, N., A Benchmark Experiment to Assess Factors Affecting Tilt Test Results for Sawcut Rock Surfaces, Rock Mechanics and Rock Engineering, 2017, 50: 2547-2562, https://doi.org/10.1007/s00603-017-1271-6

Alejano, L.R., Muralha, J., Ulusay, R., Li, C.C., Pérez-Rey, I., Karakul, H., Chryssanthakis, P., Aydan, O., ISRM suggested method for dertermining the basic friction angle of planar rock surfaces by means of tilt tests, Rock Mechanics and Rock Engineering, 2018, 51: 3853 – 3859, https://doi.org/10.1007/s00603-018-1627-6

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gau, X., Held, I., Jones, R., Kolli, R., Kwon, W., Laprise, R., Magaña Rueda, V., Mearns, L., Menndez, C., Raisanen, J., Rinke, A., Sarr, A. & Whetton, P., Regional climate projections, in: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H. L. Miller (Eds.), Climate Change 2007: the Physical Science Basis, Cambridge University Press, Cambridge, UK, 2007, pp. 847–940.

Chopra, P.N., High-temperature transient creep in olivine rocks, Tectonophysics, 279 (1997) 93–111, https://doi.org/10.1016/S0040-1951(97)00134-0.

EN, Natural Stone Test Methods - Determination of Real Density and Apparent Density, and of Total and Open Porosity, European Committee for Standardization, 1936, 2001.

Heap, M.J., Lavallée, Y., Laumann, A., Hess, K.U., Meredith, P.G., Dingwell, D.B., How tough is tuff in the event of fire? Geology 40 (2012) 311–314, https://doi.org/10.1130/G32940.1.

Mao, R.R., Mao, X.B., Zhang, L.Y., Liu, R.X., Effect of loading rates on the characteristics of thermal damage for mudstone under different temperatures, Int. J. Min. Sci. Technol. 25 (2015) 797–801, https://doi.org/10.1016/j.ijmst.2015.07.015.

McCabe, S., Smith, B.J., Warke, P.A., Sandstone response to salt weathering following simulated fire damage: a comparison of the effects of furnace heating and fire, Earth Surf. Process. Landforms 32 (2007) 1874–1883, https://doi.org/10.1002/esp.1503

Martinho, E., Dionísio, A., Assessment techniques for studying the effects of fire on stone materials: a literature review, Int. J. Architect. Herit. 14 (2018) 275–299, https://doi.org/10.1080/15583058.2018.1535008.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., Zhao, Z.C., Global climate projections, in: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Eds.), Climate Change 2007: the Physical Science Basis, Cambridge University Press, Cambridge, UK, 2007, pp. 747–845, 2007.

Paneiro, G., Dionísio, A., Luís, A., Felicity ratio as a fingerprint of the thermal-induced decay on a Portuguese granite, J. Build. Eng. 43 (2021) 103158, https://doi.org/10.1016/j.jobe.2021.103158

Perez-Rey, I., BAstante, F.G., Alejano, L.R. Ivars, D.M., Influence of microroughness on the frictional behavior and wear response of planar saw-cut rock surfaces, Int. J. Geomech., 2020, 20(8): 04020118, https://doi.org/10.1061/(ASCE)GM.1943-5622.0001742

Ranjith, P.G., Viete, D.R., Chen, B.J., Perera, M.S.A., Transformation plasticity and the effect of temperature on the mechanical behavior of Hawkesbury sandstone at atmospheric pressure, Eng. Geol. 151 (2012) 120–127, https://doi.org/10.1016/j.enggeo.2012.09.007.

Sarro, R., Pérez-Rey, I., Tomás, R., Alejano, L.R., Hernández-Gutiérrez, L.E., Mateos, R.M., Effects of Wildfire on Rockfall Occurrence: A Review through Actual Cases in Spain. Appl. Sci. 2021, 11, 2545. https://doi.org/10.3390/app11062545

Tang, F.R., Mao, X.B., Zhang, L.Y., Yin, H.G., Li, Y., Effects of strain rates on mechanical properties of limestone under high temperature, Min. Sci. Technol. 21 (2011) 857–861, https://doi.org/10.1016/j.mstc.2011.05.032.

Trenberth, K.E, Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Solden, B., Zhai, P.,Observations: surface and atmospheric climate change, in: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller (Eds.), Climate Change 2007: the Physical Science Basis, Cambridge University Press, Cambridge, UK, 2007, pp. 235–336.

Yang, S.Q., Jing, H.W., Huang, Y.H., Ranjith, P.G., Jiao, Y.Y., Fracture mechanical behavior of red sandstone containing a single fissure and two parallel fissures after exposure to different high temperature treatments, J. Struct. Geol. 69 (2014) 245–264, https://doi.org/10.1016/j.jsg.2014.10.014.

Zhao, Y.S., Wan, Z.J., Feng, Z.J., Yang, D., Zhang, Y., Qu, F., Triaxial compression system for rock testing under high temperature and high pressure, Int. J. Rock Mech. Min. Sci. 52 (2012) 132–138, https://doi.org/10.1016/j.ijrmms.2012.02.011.

Zhang, Z.X., Yu, J., Kou, S.Q., Lindqvist, P.A., Effects of high temperature on dynamic rock fracture, Int. J. Rock Mech. Min. Sci. 38 (2001) 211–225, https://doi.org/10.1016/S1365-1609(00)00071-X.