Engineering Geology 189 (2015) 58–67

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Influence of mineralogy on granite decay induced by temperature increase: Experimental observations and stress simulation

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ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 31 January 2015
Accepted 31 January 2015
Available online 11 February 2015

Keywords:
High temperature
Granite
Stone decay
Finite-element modeling
Microcracking
Maximum principal stress

ABSTRACT

Rocks can be subjected to high temperatures in several instances as for example in geothermal processes or if affected by fires. Temperature variations lead to a complex stress distribution in crystalline rocks due to mineral thermal expansion. In polymineralic such as granites, these stresses depend on fabric parameters such as mineral proportion, grain size and their related thermal properties.

Eight granitic rocks were heated to less than 400 °C and their decay patterns were observed and quantified by means of scanning electron microscopy. Heating was also modeled by finite-element simulations (OOF software) with polymineralic microstructures. Quartz, feldspar and biotite contents were used as a variable in the model in order to elucidate the influence of mineralogy on the thermal-elastic response of granites.

Real and modeled heating showed similar trends of microcracking in microstructures and of thermal expansion coefficients. Microscopic observations of real samples revealed mainly intragranular microcracks in quartz, opening of cleavage plains and deformation in mica. Simulations confirmed that in spite of the high thermal and anisotropic expansion of quartz, the microstructure of rocks with large amounts of quartz does not necessarily experience large stresses. Biotite produces a concentration of stresses along their grain boundaries. As a result, OOF models with 10% biotite showed higher stresses than monomineral ones. Thermal expansion coefficients of real granites fitted within the limits of the simulated ones proving once more the success of using finite element modeling applied to polymineralic rocks.

1. Introduction

The study of thermal behavior of rocks at high temperatures is of great importance, as heating and cooling processes are relevant to their performance in geotechnical and engineering applications, such as radioactive waste storage (Liu et al., 2009; Yamamoto et al., 2013) and geothermal energy (Bartier et al., 2008; Marques et al., 2010). The effect of high temperatures is also essential when considering fire damage, both in forest fires or in the context of building stone. Fire is a prominent decay agent as it causes irreversible damage decay of rocks, with long-lasting effects, in a very short period of time (Gómez-Heras et al., 2009) leaving a stress legacy that may be exploited by other, less extreme decay processes for many years (McCabe et al., 2007, 2010; Ozguven and Ozcelik, 2013).

As opposed to matrix-rich granular rocks, which are usually more prone to chemical changes, low-porosity crystalline rocks present after being affected by high temperatures a noticeable mechanical decay consisting mainly of the generation or growth of cracks due to the thermal stresses (Gómez-Heras et al., 2006a; Homand-Etienne and Troalen, 1984; Menéndez et al., 1999) being the most compact rocks the ones showing the highest rates of porosity change (Gómez-Heras et al., 2006a).

In monomineralic rocks, intergranular thermal stresses during a uniform temperature change depend greatly on crystal anisotropy and heterogeneity. This is typically the case of marble, in which thermal decay is deeply dependent on the fabric and orientation of the very anisotropic calcite crystals (Ruedrich et al., 2002; Ruedrich, 2003; Siegesmund et al., 2000; Ozguven and Ozcelik, 2014).

However, in polymineral aggregates thermal cracking is a more complex problem, due to thermal expansion mismatch between very different mineral crystals (Homand-Etienne and Troalen, 1984). Some studies have revealed an increasing in microcracking with temperature (Inserra et al., 2013). In this case, rock's thermal behavior depends not only on mineralogy, but also on the proportion of each mineral in the rock, size, texture, orientation, and elastic properties as well as the anisotropy in thermal expansion of each mineral (Vázquez et al., 2011).

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http://dx.doi.org/10.1016/j.enggeo.2015.01.026
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Therefore, thermal deterioration and the way microcracks generate and grow are related to thermal diffusion, thermal expansion, mineralogy, maximum temperature attained and how quickly this is reached, as well as on, porosity, grain size and other textural factors (Calleja and Ruiz de Argandoña, 1985; Castro de Lima and Paraguassú, 2004; Shao et al., 1999; Vázquez et al., 2010).

The effects of high temperatures on granite have been described and the overall changes in porosity and mechanical properties have been quantified with several techniques, such as mechanical tests, acoustic emission, ultrasound velocity propagation and mercury intrusion porosimetry (Brotóns et al., 2013; Chaki et al., 2008; Dwivedi et al., 2008; Inserra et al., 2013; Kompaníková et al., 2014; Nasseri et al., 2007; Shao et al., 1999). Microcracking patterns and the distribution of intergranular and intragranular microcracks on granites have been studied before (Kudo et al., 1992; Nasseri et al., 2005; Takemura et al., 2003; Vázquez et al., 2010) and after they were affected by fires (Gómez-Heras et al., 2006b; Nasseri et al., 2007). Mineralogy is known to play an important role in granite thermal degradation. For instance, α to β quartz transition at 573 °C, β quartz to α cristobalite at 870 °C and the possible paramorphism of α quartz after cooling have been noticed as a factor generating crystalline deformation in rocks affected by fires (Gómez-Heras et al., 2010). This is coupled with micro-deformation of crystals. Quartz content will influence deterioration even at temperatures below α to β transition, due to its high and anisotropic thermal expansion.

In addition to studying experimentally the effects of temperature increase on rocks in the laboratory, computer models have been developed to understand cracking dynamics, mainly in building stone. This is the case of marble, whose thermoelastic behavior in marbles has been widely studied and modeled (Bellopede et al., 2006; Chau and Shao, 2006; Ferrero et al., 2009). Marble is one of the rocks used most extensively for modeling thermal cracking at high temperatures because it is a monomineralic compact rock. Specifically, finite-element modeling has been applied to verify the thermal stresses related to microcraking in different microstructures with various fabric parameters (Shushakova et al., 2011, 2012, 2013; Weiss et al., 2002, 2003, 2004). However, there are few references to the use of computer models of thermal cracking of granite with differences of temperature (Shao et al., 1999; Vázquez, 2010); one of the reasons is because of the difficulties associated to its variability and its polymineral character.

Under the light of these considerations, the present paper aims in the first place, to model a thermal elastic behavior upon temperature change for polymineralic rocks, particularly for granites. To perform such modeling, microstructure-based finite-element simulations have been used in order to simulate the thermal stresses of polymineralic rocks upon heating up to 400 °C, which is a temperature high enough to observe damage but not to produce quartz phase change. This model focuses on mineralogy as key-variable to assess the thermal elastic response of materials. The objective of the study is also to compare the results from computer simulations to real decay patterns observed in investigated granites with similar microstructure to the simulated one and validate them from thermal expansion measurements. The variations in the rock surface were probed by microscopical observations. Microcracking and the decay of each mineral at high temperatures were recognized with Environmental Scanning Electron Microscopy.

2. Methodology

2.1. Experimental

Eight granitoids used internationally as dimension stones were selected for this research. Their commercial names are Albero (“*A*”), Gris Alba (“*GA*”), Gris Mondariz (“*GM*”), Negro Galicia (“*NG*”), Rosa Porriño (“*RP*”), and Silvestre Moreno (“*SM*”) all from Spain; Golden Sky (“*GS*”) from Portugal, and Red Multicolor (“*RM*”) from India. Granites were oriented in the quarry, with (x) and (y) directions parallel to the foliation plane, and (z) normal to it. All granite types were selected to cover a wide range of mineralogical composition. Quartz and feldspar have equiaxed crystal shape and biotite exhibits the elongated one. Content of equiaxed and elongated crystals in microstructure used in simulations represents microstructure of investigated granites. Mineral proportion, grain size and microcracking were studied using optical polarization microscopy. Open porosity was obtained following the standard EN 1936. Linear thermal expansion coefficients (α) were determined using a dilatometer (Koch and Siegesmund, 2004; Strohmeyer, 2003) with $\Delta T = 70$ °C.

High temperature tests were carried out up to 400 °C. This temperature was chosen as it was the lowest one to show visible damage under the microscope. Temperatures lower than 400 °C hardly generate any visible damage in granites and temperatures higher than 400 °C generate obvious cracking (Homand-Etienne and Troalen, 1984). A maximum temperature of 400 °C was selected as a usual temperature for fires in buildings (Sanjurjo-Sanchez et al., 2013) and to avoid α to β quartz transitions. In addition, both in natural and built environments, being fed by coniferous wood combustible rarely exceeds temperatures of 500 °C (Gómez-Heras et al., 2009).

The specimens were dried at 60 °C to constant weight and left to cool down until reaching room temperature. After, the specimens were heated in a furnace with a heating ramp of 6 °C/min. This heating rate was chosen according to Ruiz de Argandoña et al. (1985, 1986) as enough to generate a thermal shock and irreversible damage in the rocks. The specimens were kept at the target temperature for 3 h to allow the core of the samples to reach the same temperature than the surface, as suggested by Ruiz de Argandoña et al. (1985, 1986). Afterwards, the samples were cooled unforcedly in the furnace to room temperature (approximately 24 h from the beginning of the test).

Open porosity of sound rocks and after heating to 200 °C and 400 °C was compared (EN 1936, 2006). Polarizing microscope was used to assess the variations in microcracks. Thin sections of the eight granitoids before and after heating were studied. Observations were focused on differences in mineral alterations and microcraking. In addition to this, thin sections of samples of a fine-grained leucogranite obtained from a historical building affected by fires were studied with a Scanning Electron Microscope (Jeol JSM 6400).

2.2. Modeling

Microstructure-based finite-element simulations have provided so far an excellent insight of the influences of rock fabric on the thermal degradation phenomena of marble (Shushakova, 2014), and the results from simulations were in good agreement with experimental findings. Therefore, this type of simulation was performed in the present study for modeling thermal-elastic response of crystalline polymineralic rocks such as granites. Shushakova et al. (2012) identified microcracks corresponded to regions with maximum principal stress in the microstructure induced by thermal expansion during temperature change. The temperature differential used here for granites was +400 °C (i.e., heating).

The two-dimensional, microstructure-based finite-element approach used here is based on the Object-Oriented Finite Element program OOF developed at the National Institute of Standards and Technology (Langer et al., 2001). The OOF software is in the public domain. Executables and manuals are available at the website: http://www.ctcms.nist.gov/oof/. The OOF1 software was used for present simulations.

There are four main rock-forming minerals in granitoids: quartz, alkali feldspar, plagioclase and mica. The influence of the mineralogy on the thermal elastic response of materials was assessed by the variation of quartz percentage and its combination with alkali feldspar/plagioclase and mica. These simulations have been validated by real experiments of thermal expansion of investigated granites. To assess the effect of mineral proportion on thermal degradation of granites it has been