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Thermal stress-induced microcracking in building granite

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ABSTRACT

Microcracking induced by wide fluctuations in temperature affects granite quality and durability, making the stone more vulnerable to decay. Determining the extent of that effect is not always straightforward, however, given the excellent durability of these materials.

Four types of construction granite quarried in the region of Madrid, Spain, and frequently used in both the built heritage and in de novo construction (Alpedrete, Cadalso de los Vidrios, Colmenar Viejo and Zarzalejo) were exposed to 42 thermal cycles (105–20 °C; UNE-EN, 14066, 2003). Petrographic and petrophysical properties were analysed using both destructive and non-destructive techniques. Microcracking generated in the granite stones by 42 thermal cycles had barely any impact on their petrophysical properties, which are the parameters normally assessed to establish material quality and durability. Their petrographic properties, which are not generally assessed in this type of studies, were affected, however. This study contends that petrographic analysis is needed to objectively quantify the actual quality and durability of the most highly resistant materials when petrophysical studies are inconclusive. Petrographic and fluorescence microscopy, along with fractography, are among the most prominent techniques for petrographic exploration. Thanks to the deployment of these techniques, mineral microcracking could be monitored throughout the present tests conducted.

The microscopic findings revealed substantial micro-textural and microstructural change in and around the granite minerals, which play a prominent role in decay. The findings showed that pre-existing microcracks coalesced and generated further microcracking as decay progressed. Microcracking was most intense in Zarzalejo granite due to its textural characteristics determined by its high feldspar content. Microscopic observation revealed that the microstructure of feldspar minerals, with their crystallographic anisotropies and secondary mineral phases, favoured microcrack development. Zarzalejo granite exhibited lower quality and durability than Colmenar Viejo and Cadalso de los Vidrios granites, which were more resistant to heat treatment.

1. Introduction

The granite in historic and contemporary buildings is exposed to thermal changes that may induce stone decay. When thermal stress is high and the material is unable to adapt quickly enough to accommodate the strain generated during cooling, microcracks appear due to differences in the expansion coefficients between constituent minerals or even within the same mineral (Hall, 1999; Hale and Shakoor, 2003; Yavuz, 2011; Demirdag, 2013; Hall and Thorn, 2014). The effects of thermal changes on granite have been studied by a number of authors (Simmons and Cooper, 1978; Heuze, 1983; Homand-Etienne and Troalen, 1984; Homand-Etienne and Houpert, 1989; Iñigo et al., 2000, 2013; Sousa et al., 2005; Nasseri et al., 2007; Takarli, et al., 2008) in experiments in which temperatures and number of heating cycles differed. The temperatures generating stone decay range widely: granite exposed to heating–cooling cycles over a range of 30 °C to 80 °C exhibited significant decay (Gräf et al., 2013). Lin (2002) established a threshold temperature of 100 °C to 125 °C for microcracking in Inada granite.

The procedure described in Spanish and European standard UNE-EN 14066, 2003 for accelerated ageing in natural stone calls for heating the material to 105 °C in air followed by cooling in water to 20 °C.

Exposing the stone to such temperatures at short (24 h) cycles simulates the effects of fire extinction (Pires et al., 2014; Mambou et al., 2015), indoor heating, abrupt cooling by frequent rain after intense solar radiation (tropics) or the significant differences in day and night time temperatures in desert climates, such as found in the Middle East and certain continental regions of Asia, Australia, Europe and the United States (Halsey et al., 1998; Erguler and Shakoor, 2009).

To ensure high performance under any circumstances, building stone must meet high quality standards (Siegesmund and Török, 2011). Such performance is normally determined on the grounds of petrophysical properties and mechanical strength (UNE-EN 771-6, 2012).

This study determined the thermal effect of accelerated ageing as specified in Spanish and European standard UNE-EN 14066, 2003 on four types of granite widely used in heritage construction on the Iberian

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Peninsula and more recently in other areas of the world (Freire-Lista et al., 2015a–d; Freire-Lista and Fort, 2015). This study aimed primarily to establish a new analytical method for ascertaining the quality and durability of building stones exposed to variations in temperature when their petrophysical properties remain largely unaffected. That method is based on assessing variations in their petrographic properties.

The assessment of the physical and mechanical properties of building stone has been amply addressed in the literature (Dearman et al., 1978; Raisanen, 2004; Fort et al., 2010, 2011; Siegesmund and Dürrast, 2011). These studies examine fundamental properties such as apparent density and porosity (Benavente et al., 2006). Other trials that furnish information on ultrasonic wave velocity, Young's modulus, colour and surface hardness are imperative to predicting stone performance under environmental conditions that may drastically reduce its service life (Přikryl et al., 2003; Smith et al., 2011). Such trials are also essential in restoration studies prior to or conducting stability analyses on, conserving or cleaning granite structures.

Despite the significant role of petrographic properties such as particle size and shape and microstructural features such as microcracks (Tuğrul and Zarif, 1999; Tuğrul, 2004; Seo et al., 2002; Upadhyay, 2012; Sousa, 2014; Sajid et al., 2016), in the long-term behaviour of granite, very little research has been conducted on these parameters under varying construction and environmental conditions.

As thermally induced propagation of microcracks (Alm et al., 1985; Taboada and García, 1999; Iñigo et al., 2000, Akesson et al., 2003, Nasseri et al., 2007; Anders et al., 2014) affects the constituent minerals in granite differently (Miskovsky et al., 2004), it may cause physical and chemical changes in the internal texture of the stone, associated on occasion with changes in its physical and mechanical properties (Kern et al., 1997; Tuğrul, 2004; Schubnel et al., 2006). Microcrack propagation and stone colour change (Ozcelik et al., 2012) are the most common symptoms of thermally induced decay.

Since granite massifs are regarded, worldwide, as a reservoir of suitable building stone, granite durability and its determination are a major concern when choosing a construction material (Sousa et al., 2005; Chaki et al., 2008; Dwivedi et al., 2008; Takarli et al., 2008; Wanne and Young, 2008; Franzoni et al., 2013; Shao et al., 2014). Microcrack coalescence and the thermally induced generation of further cracking induces decay in building granite that may be intensified by the action of other agents of decay, such as lichen colonies (De la Torre et al., 2010, Scarciglia et al., 2012), pollution-related grime (Schiavon et al., 1995) and graffiti (Rivas et al., 2012).

2. Materials and methods

The decay caused by the thermal treatment test was monitored in four types of granite building stones with nine analytical techniques: effective porosity (*Pe*), bulk density (ρb) ultrasonic pulse velocity P (V_p) and S (V_s), dynamic Young's modulus (E_{dyn}), mercury intrusion porosimetry (MIP), surface hardness (*L*), spectrophotometry and microcracking calculating linear crack density (LCD).

2.1. Rock samples

The Spanish Central System comprises primarily Variscan granitoids (344 Ma to 285 Ma; Villaseca et al., 2012). The stone forming the Sierra de Guadarrama, located on the northeastern edge of the system, includes four major types of monzogranite: biotitic monzogranites containing some cordierite, biotitic monzogranites containing some amphibole, biotitic monzogranites with no cordierite or amphibole, and leucogranites (see Fig. 1).

The four monzo- and leucogranite stones selected for this study, Alpedrete (AL), Cadalso de los Vídrios (CA), Colmenar Viejo (CO) and Zarzalejo (ZA) (Fig. 2), were quarried in the Sierra de Guadarrama (Spanish Central System). These stones, popularly called 'Piedra Berroqueña', have been traditionally used in construction in Madrid and surrounds (Gómez-Moreno et al., 1995; Fort et al., 2013; Freire-Lista et al., 2015b, c; Freire-Lista and Fort, 2015), where they are still used today, while some are also exported for construction.

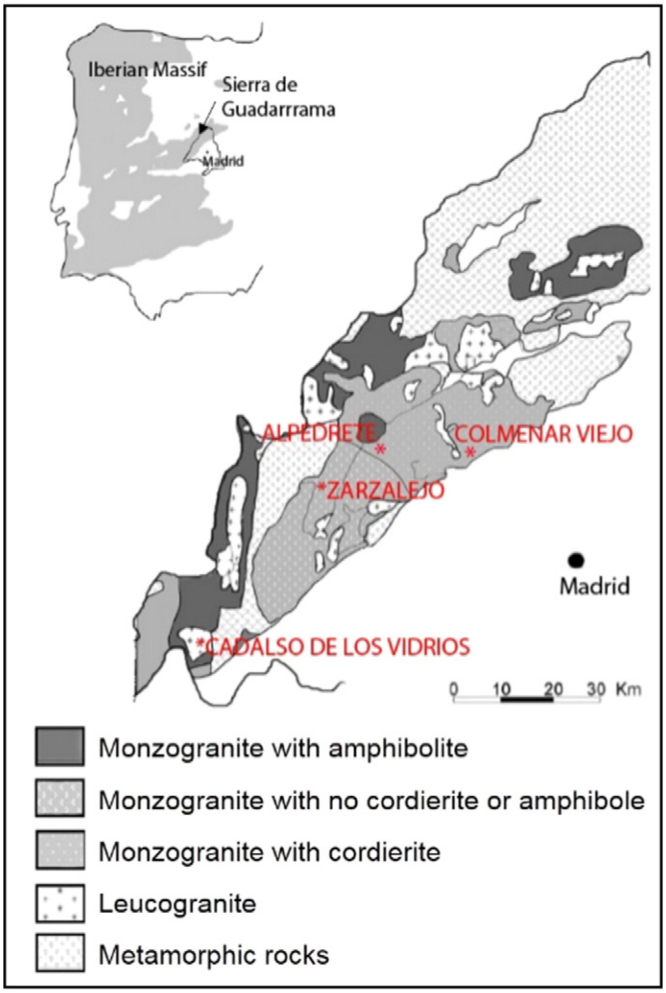

Fig. 1. Site map for Alpedrete, Cadalso de los Vidrios, Colmenar Viejo and Zarzalejo granites.

Fresh, poorly fractured blocks located far from fault systems were selected from four outcrops close to the old quarries and extracted along the quarry orientation. Quarry locations are shown in Fig. 1. Following extraction, seven cubic (5 × 5 × 5 ± 0.5 cm) specimens of each of the four types of granite were cut at low speed (120 rpm) and low strain. Surface areas were rejected to minimise the effect of possible extraction-induced cracking. No fissures were visible in any of the samples tested.

AL, a medium-grained, hypidiomorphic, equigranular monzogranite with cordierite, has been used in the construction of prominent heritage buildings, including the Royal Palace (1738–1764) and the Puerta de Alcala (1770–1778) in Madrid. This granite has been nominated as a 'Global Heritage Stone Resource' (Freire-Lista et al., 2015b) for its significance in the built heritage.

CA, a fine-to-medium-grained hypidiomorphic, equigranular leucogranite, can be seen on heritage buildings such as the Palacio de Villena (15th century). Much more recently, under the trade name Blanco Cristal, it has been used in places such as Cork Airport in Ireland, and shopping centres in China (Guangzhou, Shanghai).

CO is a medium-to coarse-grained, heterogranular monzogranite with no cordierite or amphibolite. It has been found in archaeological sites dating from the 6th to the 7th century and forms part of much more recent structures, including prominent government buildings such as the Nuevos Ministerios complex in Madrid (1933–1942).