Cold Regions Science and Technology 113 (2015) 40–51

Contents lists available at ScienceDirect

Cold Regions Science and Technology

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

Freeze–thaw fracturing in building granites

D.M. Freire-Lista [a,b,*], R. Fort [a,b], M.J. Varas-Muriel [a,c]

[a] Instituto de Geociencias IGEO (CSIC, UCM) Spanish Research Council CSIC, Complutense University of Madrid UCM, Madrid, Spain
[b] CEI Campus Moncloa, UCM-UPM and CSIC, Madrid, Spain
[c] School of Geology, Complutense University of Madrid UCM, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 30 May 2014
Received in revised form 20 January 2015
Accepted 22 January 2015
Available online 30 January 2015

Keywords:
Granite
Durability
Weathering
Freeze–thaw test
Microcracks

ABSTRACT

Four types of granite widely exported and used in construction around the world were subjected to 280 accelerated freeze–thaw test cycles, conducted as stipulated in European standard UNE-EN, 12371, 2001 to ascertain their petrophysical response.

The techniques used to characterise the granite before and after freeze–thaw-induced microcracking included vacuum water absorption, ultrasonic P-wave pulse velocity and ultrasonic S-wave pulse velocity, mercury intrusion porosimetry and polarised optical and fluorescence microscopy to quantify the type of microcracks developing (inter-, intra- or transcrystalline) and identify the associated mineral phases: quartz, feldspar and biotite. The linear crack density (number of cracks per millimetre) was calculated based on the microscopic data collected. Young's modulus was likewise found before and after the freeze–thaw cycles.

The chief ice crystallisation mechanism was involved in microcracking and hence deterioration was ice segregation. In all four granites, ultrasonic propagation velocities and strength parameters declined with the development of freeze–thaw-induced microcracking. More intercrystalline microcracks were developed in the early cycles, while larger numbers of intracrystalline microcracks were found at the end of the test.

The results of this study can be applied to other granites with similar characteristics and whose microcracks are generated with same mechanisms of frost damage.

Upon conclusion of the cycles, Zarzalejo granite exhibited the largest number of microcracks, with a linear crack density of 3.9, as well as the highest rise in microcracking. Colmenar Viejo ended the freeze–thaw test with the fewest number of microcracks and a post-test linear crack density of 2.3, denoting greater freeze–thaw resistance. The smallest increase in the number of microcracks was found for Cadalso de los Vidrios granite.

The microscopic and microporosity findings reported in this paper revealed the existence of freeze–thaw test-induced microcracking which, while barely affecting mechanical stability (Young's modulus), did cause damage.

1. Introduction

Granite has been traditionally used as a building stone, in some countries because of quarry proximity to cities and in many others as a high quality import (Fort et al., 2013). Spain is the world's seventh largest producer of natural stone and the fourth largest exporter. Granite ships primarily to other European countries and North America for use in cities such as Vancouver, Paris, Cork, and Munich where temperatures dip below freezing over 30 times yearly, inducing freeze-thaw (FT) events (Ruedrich and Siegesmund, 2007; Ruedrich et al., 2011).

Thousands of tonnes of these granites are exported annually for use as construction materials in prominent buildings. Some examples are the Cork International Airport terminal in Ireland, Place Romagné in France, and retail parks at Dortmund, Germany and Guangzhou, China. Hence, there is the need to meet high quality standards to ensure the optimal performance in all manner of situations (Siegesmund and Török, 2011).

The aim of the present study is to determine the quality of four widely used building granites to FT weathering, determined on the grounds of (P- and S-wave) ultrasonic pulse velocity, Young's modulus, linear crack density and porosity in several FT weathering stages. Damage was established by comparing the findings obtained with destructive and non-destructive techniques.

The objective of FT testing is to simulate natural weathering caused by ice at a faster pace in the laboratory (Halsey et al., 1998). This may induce rapid change in the physical and mechanical properties of these materials in humid open systems with widely fluctuating temperatures (Ehlen, 2002; Gupta and Rao, 2001; Hall et al., 2012; Hudec, 1998; Iñigo et al., 2000; Jamshidi et al., 2013; Rivas-Brea et al., 2008; Sanjurjo and Alves, 2006).

FT has a direct impact on landforms and building stone durability (Kieslinger, 1931). It limits durability not only in very cold regions, but

---

* Corresponding author at: Instituto de Geociencias IGEO (CSIC, UCM), Calle José Antonio Novais, 12, 28040 Madrid, Spain. Tel.: +34 913944903; fax: +34 923219609.

E-mail addresses: d.freire@igeo.ucm-csic.es (D.M. Freire-Lista), rafael.fort@csic.es (R. Fort), mjvaras@geo.ucm.es (M.J. Varas-Muriel).

http://dx.doi.org/10.1016/j.coldregions.2015.01.008
0165-232X/© 2015 Elsevier B.V. All rights reserved.

also where freezing occurs during few days in temperate climates where temperatures occasionally drop to below freezing, particularly during the night (Takarli et al., 2008). Where these cycles are frequent (Halsey et al., 1998), they generate fatigue in granite and cracks through which water can ingress.

When ice crystallisation pressure equals the tensile strength of the rock, further microcracks develop and the existing cracks deepen and widen, damaging the rock. Ice crystallisation and growth mechanisms in geomaterials have been the object of research for several decades (Coussy and Fen-Chong, 2005; Hor and Morihiro, 1998; Scherer, 1999). Several mechanisms exist to explain ice crystallisation-induced stress in wall cracks (Chen et al., 2004; Ingham, 2005; Ruedrich and Siegesmund, 2007).

The volumetric expansion of water during freezing: when water congeals its volume increases about 9%, generating pressure on the walls of the cracks, which favours widening (Ozcelik et al., 2012). For cracking to be due only to the expansion associated with the water to ice phase change, the rock would have to be highly saturated. FT-induced natural damage occurs without such saturation. (Chen et al., 2004; Ruedrich and Siegesmund, 2007; Takarli et al., 2008).

Another mechanism is hydraulic pressure (Hor and Morihiro, 1998). The increase in volume attendant upon ice crystallisation confines the (liquid) water, which then places pressure on the walls of the cracks. This premise is based on the observation that ice crystallises as it moves deeper into the rock. Due to its increased volume, unfrozen water may ingress into the pore space. If insufficient expansion space is available near the ice front, stress is generated in the matrix. Other stress development models are based on osmotic pressure (Powers and Helmuth, 1953) and anomalous variations in ice density when it crystallises quickly.

Ice segregation (Akagawa and Fukuda, 1991; Arakawa, 1965; Hallet et al., 1991; Matsuoka and Murton, 2008; Tabor, 1929, 1930; Walder and Hallet, 1985) takes place in freezing or frozen microporous media. The unfrozen water held in microcracks and adsorbed onto the surfaces of mineral particles is forced by temperature gradient-induced suction through a porous medium such as micro-cracked granite toward freezing sites where ice lenses, ribbons, needles, layers or strands grow (Murton et al., 2006). In other words, water that starts off widely dispersed in the porous rock segregates into discrete pieces of ice. Since water but not ice can flow through pores of this size, ice segregation is a major cause of cracking in moist, porous rocks (Matsuoka, 2001).

Frost damage may entail a combination of several mechanisms, although one or another generally predominates, depending upon conditions (Ingham, 2005). Water and temperature are the main weathering agents in FT ageing. As a rule, crystallisation begins in large surface cracks, for in smaller cracks ice crystallisation calls for colder temperatures. FT-induced decay in natural stone therefore depends largely on the existence of open cracks, the natural channels for water penetration into rock, and their post freezing development (Martínez-Martínez et al., 2013).

Ice crystallisation cracking in granite is not fully understood, since it depends on a number of factors (Hudec, 1998): the temperature range, the frequency of FT, the stress applied, water composition and moisture content, as well as internal factors such as rock mineralogical composition, texture, rock strength, characteristics of the existing pore microstructure and thermal conductivity of the constituents.

Preceded by elastic deformation in granite (Lajtai, 1998), in addition to existing crack closure and internal crack sliding, changes in the microcrack network affect the physical and mechanical properties (Prikryl, 2001) of the rock and are responsible for the decay and anisotropy found in many granites (Fujii et al., 2007; Fort et al., 2011). Microcrack characteristics and the physical–mechanical properties of rocks are, then, essential considerations when assessing material durability (Matias and Alves, 2001; Sousa et al., 2005).

Mechanical strength in granites is related to a number of petrographic parameters, including: grain size (Akesson et al., 2001; Tuğrul and Zarif, 1999; Yilmaz Günes et al., 2011), microstructural characteristics (Alm et al., 1985; Carvalho et al., 1997; Feng and Yu, 2000; Lindqvist et al., 2007; Nasseri and Mohanty, 2008; Vasconcelos et al., 2008), mineral composition (Miskovsky et al., 2004), grain boundaries (Raisanen, 2004) and mineral shape and spatial arrangement (Akesson et al., 2003).

When destructive tests (such as static laboratory tests in heritage buildings) cannot be performed to determine the mechanical characteristics of the rock, the dynamic modulus (King, 1983; Vanheerden, 1987; Lam dos Santos et al., 2013) must be found with non-destructive techniques such as ultrasonic testing (Eissa and Kazi, 1988; Brotóns Torres et al., 2014). As mechanical moduli are required to calculate the strain on new buildings generated by the live loads applied, pre- and post-FT Young's modulus values were calculated in this study.

Like other agents of rock decay such as wet/dry cycles, thermal shock and salt crystallisation, FT is regarded as a physical weathering agent (Jamshidi et al., 2013; Shalkowshi et al., 2009), weathering granite at a rate of several millimetres per thousand years (Chen, 2000). An understanding of the long-term durability of construction granite exposed to FT cycles is therefore in order. While decay function models have been developed to predict FT-induced deterioration of the mechanical properties of building stone (Bayram, 2012; Jamshidi et al., 2013; Mutlutürk et al., 2004), the respective equations are only valid for specific rocks.

Although FT testing has been standardised (UNE-EN, 12371, 2011; TSE 699, 1987, ASTM D5312/D5312M-12, 2013; DIN 52104, 1982), the number of FT cycles applied and the physical property used to quantify FT action differ among standards. The effect of FT has therefore been studied from different perspectives for different types of rocks.

A sizeable number of studies have been conducted on freezing in building stones in recent decades. The number and duration of FT cycles and the temperature sequence and range applied in those studies varied widely. The concomitant inconsistencies in the findings (Cárdenes et al., 2014) must be borne in mind when comparing the results.

Ingham (2005) ran 50 cycles, for instance, compared to the 1400 run by authors such as Ruedrich et al. (2011), Iñigo et al. (2000), García-del-Cura et al. (2008), Karaca et al. (2010), Jamshidi et al. (2013) applied 24-hour cycles, while in the Del Río et al. (2005) study cycle duration was 4 h and in the Tan et al. (2011) survey, 8. The temperature ranges also varied: Ozcelik et al. (2012) established a low of −40 °C and a high of 180 °C, while in Wang et al. (2007) the interval ran from −7 to 14 °C.

Some authors measured FT-induced decay on the grounds of sample weight loss (Erguler and Shakoor, 2009; Iñigo et al., 2000) or variations in ultrasonic pulse velocity (Iñigo et al., 2013; Liu et al., 2012; Matsuoka, 1990; Ruedrich, et al., 2011; Takarli et al., 2008). Others developed equations from which to infer microcrack distribution in granites (Nara et al., 2011; Sano et al., 1992; Takemura and Oda, 2006). Moreover, the intrinsic characteristics of the granite (mineralogy and texture) also impact the type of microcracking generated by FT (inter-, intra- or transcrystalline) and hence rock petrophysical properties and ultimately durability.

The matrix (Yavuz, 2011), pore size and pore size distribution are especially important factors in granite resistance to ice crystallisation. Many authors (Haynes and Sneck, 1972; Wolfenden and Winslow, 1991; Mallidi, 1996; Benavente et al., 2007; Martínez-Martínez et al., 2013,) contend, based on mercury intrusion porosimetry findings, that intra-pore crystallisation is favoured by slow capillary kinetics, while others (Oguchi and Yuasa, 2010) claim that these developments are driven by fast capillary kinetics.

The present study explored the physical and mechanical effects of FT testing on the quality of granite exported for use in construction. Microcracking favours soiling, lichen colonisation and in some cases, crystal detachment. An understanding of the performance of granite used in construction in climates prone to FT cycles will help