Ultrasonics 54 (2014) 156–167

Contents lists available at SciVerse ScienceDirect

Ultrasonics

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

New contributions to granite characterization by ultrasonic testing

C. Cerrillo [a], A. Jiménez [b,*], M. Rufo [b], J. Paniagua [b], F.T. Pachón [b]

[a] Tribology Unit, IK4-TEKNIKER, C/Iñaki Goenaga 5, 20600 Eibar, Gipuzkoa, Spain
[b] GRnI Research Group, Department of Applied Physics, Polytechnic School, University of Extremadura, Av. Universidad, s/n, 10071 Cáceres, Spain

ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form 5 June 2013
Accepted 10 June 2013
Available online 20 June 2013

Keywords:
Granite characterization
Nondestructive testing
Ultrasonic testing
Mechanical properties
Fast Fourier Transform

ABSTRACT

Ultrasound evaluation permits the state of rocks to be determined quickly and cheaply, satisfying the demands faced by today's producers of ornamental stone, such as environmental sustainability, durability and safety of use. The basic objective of the present work is to analyse and develop the usefulness of ultrasound testing in estimating the physico-mechanical properties of granite. Various parameters related to Fast Fourier Transform (FFTs) and attenuation have been extracted from some of the studies conducted (parameters which have not previously been considered in work on this topic, unlike the ultrasonic pulse velocity). The experimental study was carried out on cubic specimens of 30 cm edges using longitudinal and shear wave transducers and equipment which extended the normally used natural resonance frequency range up to 500 kHz. Additionally, a validation study of the laboratory data has been conducted and some methodological improvements have been implemented.

The main contribution of the work is the analysis of linear statistical correlations between the aforementioned new ultrasound parameters and physico-mechanical properties of the granites that had not previously been studied, i.e., resistance to salt crystallization and breaking load for anchors. Being properties that directly affect the durability and safety of use of granites, these correlations consolidate ultrasonics as a nondestructive method well suited to this type of material.

1. Introduction

The fundamental purpose behind national and international standards regulating rock building materials is to ensure sustainability, durability, and safety in their use. These characteristics are given primarily by a rock's physico-mechanical properties. Ultrasonic testing allows these properties to be determined unaggressively, unlike other, traditional, destructive methods such as those set out in standardized testing procedures.

Several authors have analysed the characteristics of ultrasound propagation as a means of studying the physico-mechanical properties of rocks. In particular, one of the commonly used techniques is the determination of the ultrasonic pulse velocity (UPV) [1–4]. There are also several studies conducted on the subject that focus on the study of different varieties of granite [5–9]. The procedure used in all these works consists basically of establishing statistical correlations between the rocks' ultrasound parameters (velocity, amplitude, quality factor Q, frequency components, etc.) and those physico-mechanical properties obtained from destructive testing [10–12].

The main objective of the present study is to use ultrasound inspection techniques to characterize cubic specimens of ten varieties of Spanish granites, and, in doing so, to make a series of new contributions to the current state of knowledge on the subject. The principal novel contributions are: the determination and analysis of parameters other than the UPV deriving from ultrasonic testing; extending the frequency range typically used in these studies; the consideration of physico-mechanical properties of granites which had not previously been included in similar studies (the Knoop microhardness, resistance to salt crystallization and breaking load for anchors); and the implementation of certain methodological improvements to the procedures used.

The parameters obtained from the ultrasonic evaluation were the longitudinal and shear ultrasonic pulse velocities (UPV_L) and (UPV_S), the anisotropy percentages, the 25th, 50th, 75th and 99th percentiles of the received signal in the cumulative frequency periodograms of the Fast Fourier Transform (FFT) and the ultrasonic pulse attenuation quantified in terms of the time taken to receive the energy. Furthermore, taking into account the different nominal frequencies of the equipment and transducers used and the considerable number of specimens studied, a complementary study to validate the UPV data obtained is also carried out. Finally, a linear statistical correlation analysis is performed among the different ultrasonic parameters, and between them and the physico-mechanical properties of the ten granite varieties.

The interest of this work lies in the possibility of making use of ultrasonic methods to estimate the physico-mechanical properties

* Corresponding author. Tel.: +34 927 257 195; fax: +34 927 257 203.
E-mail address: ajimenez@unex.es (A. Jiménez).

0041-624X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2013.06.006

Table 1
Brief petrographic description of the granites.

Granite designation	Petrographic description
Blanco Valle (BV)	Muscovite leucogranite
Blanco Cáceres (BC)	Biotite-muscovite leucogranite
Blanco Extremadura (BE)	Cordierite-bearing biotite-muscovite granite
Gris Conquistador (Gco)	Two-mica monzogranite
Gris Campanario (Gca)	Two-mica granite with megacrystals
Gris Quintana (GQ)	Biotite monzogranite
Azul Extremadura (AzE)	Biotite quartz diorite
Azul Platino (AP)	Two-mica porphyritic granite
Amarillo Extremadura (AmE)	Cordierite-bearing biotite-muscovite granite
Rosa Alba (RA)	Biotite granite

of granite varieties without their being subjected to destructive testing. The implementation of this type of inspection technique makes more efficient use of resources compared with traditional destructive characterization testing.

2. Description of the material

Granite varieties are classified into categories based on the predominant hue they present: grey, white, blue, black, yellow and pink. For the present study, a representative set of these categories produced in Spanish quarries has been selected – a total of ten varieties from different locations. The specimens tested were 30-cm cubes with a polished finish, which reduces their surface porosity and facilitates the penetration of ultrasound. The essential petrographic features of these ten varieties, obtained in accordance with the UNE-EN 12407:2001 standard [13], are presented in Table 1. The data are extracted from a comprehensive study of granite varieties [14].

Regarding the choice of geometry and size of the specimens, cubes of 30-cm edges help reduce some of the experimental errors associated on the one hand with measurements made on different inspection geometries in the three spatial directions [5,8], and on the other with near-field effects. The specimens' characteristics also meet the requirements of the ASTM D2845-08 standard [15], which establishes minimum dimensions as a function of grain size and the nominal frequencies of the transducers to ensure that the results for the pulse propagation velocities are accurate and reliable.

Given the considerable number of varieties of granite studied and the use of various ultrasonic natural resonance frequencies, there were sufficient data to ensure the statistical significance of the correlations found between the measured ultrasonic parameters and the physico-mechanical properties of the granites. These latter were taken from the aforementioned comprehensive study of granite varieties [14] (see Table 2).

3. Methods

As mentioned above, the present study includes a number of novel aspects with respect to previous work on the topic, aspects which also affect the working procedures.

Firstly, the granites were inspected ultrasonically using contact techniques in through-transmission (T-T) mode. Fig. 1a shows schematically the set-up used for the measurements. The transducers were mounted on a custom-designed metal structure that ensured their perfect face-to-face alignment (Fig. 1b), also reducing the risk of other errors being introduced by the operator, primarily those due to variations in the pressure exerted on the specimens with the transducers and to involuntary movements by the operator [16].

Secondly, the normally used range of frequencies (50–150 kHz) for the study of granite specimens has been extended by using a total of six different transducers (three longitudinal wave and three shear wave transducers) of 100, 250, and 500 kHz frequencies. This allows determining whether the inspection device frequency affects in some way the values determined for the different ultrasonic parameters.

And thirdly, as was mentioned above, parameters deriving from the ultrasonic analysis and physico-mechanical properties of the granites that had not previously been considered in this field have been taken into account.

3.1. Ultrasonic parameters

As already described, the ultrasonic parameters determined are UPV, the anisotropy percentages, various percentiles of the received signal in the cumulative frequency periodograms of the FFT and the attenuation quantified in terms of the time taken to receive the energy. These parameters were determined along the three axes of the ten specimens for each of the selected inspection

Table 2
Physico-mechanical properties of the granite varieties studied.

Variety	Grain size	Apparent density (g/cm)^3	Open porosity (%)	Compressive strength (kg/cm^2)	Flexural strength (kg/cm^2)	Impact strength (cm)	Frost resistance (%)	Knoop microhardness (MPa)	Resistance to salt crystallization (%)	Breaking load for anchors (N)
BV	Fine	2.580	1.7	1440	95	54	8	2131	0.06	1000
BC	Medium	2.620	0.6	1500	128	42	0	2563	0.04	1550
BE	Medium (porphyritic)	2.630	0.5	1550	119	–	5	2226	–	–
GCo	Medium (porphyritic)	2.570	0.5	1420	102	36	8	2110	0.09	2050
GCa	Fine to medium (porphyritic)	2.630	0.4	1640	107	41	10	2757	0.03	1950
GQ	Fine	2.650	0.4	1700	181	55	8	2348	0.00	2600
AzE	Fine	2.730	0.6	1560	178	55	3	1600	0.10	2900
AP	Medium	2.650	0.8	1600	144	50	0	2081	0.07	3150
AmE	Medium (porphyritic)	2.623	1.0	1260	80	32.5	7	2085	0.05	2050
RA	Medium (porphyritic)	2.600	0.5	1060	81	37	0	1331	0.10	1800