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Ultrasonic characterization of granites obtained from industrial quarries of Extremadura (Spain)

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Abstract

The industry of ornamental rocks, such as granites, represents one of the most important industrial activities in the region of Extremadura, SW Spain. A detailed knowledge of the intrinsic properties of this natural stone and its environmental evolution is a required goal in order to fully characterize its quality. In this work, two independent NDT acoustic techniques have been used to measure the acoustic velocity of longitudinal waves in different prismatic granitic-samples of industrial quarries. A low-frequency transceiver set-up, based on a high-voltage BPV Steinkamp instrument and two 50 kHz probes, has been used to measure pulse travel times by ultrasonic through-transmission testing. In complementary fashion, an Erudite MK3 test equipment with an electromagnetic vibrator and two piezoelectric sensors has also been employed to measure ultrasonic velocity by means of a resonance-based method, using the same types of granite varieties. In addition, a comprehensive set of physical/mechanical properties have also been analyzed, according to Spanish regulations in force, by means of alternative methods including destructive techniques such as strength, porosity, absorption, etc. A large number of samples, representing the most important varieties of granites from quarries of Extremadura, have been analyzed using the above-mentioned procedures. Some results obtained by destructive techniques have been correlated with those found using ultrasonic techniques. Our experimental setting allowed a complementary characterization of granite samples and a thorough validation of the different techniques employed, thus providing the industry of ornamental rocks with a non-destructive tool that will facilitate a more detailed insight on the properties of the rocks under study.

Keywords: Ultrasonic velocity; Ornamental rocks; NDT; Granite characterization

1. Introdution

The worldwide market of ornamental stone is characterized by its high degree of concentration, since only 10 countries account for more than 80% of production. Spain ranks first in slate production, second in marble, and is the top European producer of granite. Within the national panorama of the ornamental stone sector, more than 40 varieties are produced in the region of Extremadura which is second ranked nationally in the extraction of this type of stone [1]. The importance of this industrial sector in Extremadura is due to its geographical and therefore geological situation, since in it are located the westernmost outcrops of the European Hercynian chain, in which emerges the Pedroches batholith, an igneous intrusion of more than 200 km in length and 15 km in width consisting of various independent plutons [2].

There is ever more widespread use of the granites as construction materials. It is therefore indispensable to have the maximum of rigorous information about their physico-mechanical characteristics so that one can foresee their

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potential deterioration under the effects of external and internal agents. In this context, our team of researchers of the University of Extremadura, of the Technological Institute of Ornamental Stone and Construction Materials (INTROMAC), and of the Institute of Acoustics (CSIC) has been studying a broad range of specimens corresponding to 37 varieties of granite from industrial quarries of different locations in Extremadura. Of these, 34 have been subjected to some type of acoustic analysis. The fundamental goal has been to analyze these granites using both destructive and non-destructive (in particular, ultrasound) techniques for their petrological and physico-mechanical characterization.

The ultrasound trials were conducted on six $30 \times 10 \times 5$ (cm) prismatic specimens of each variety using two techniques. In the first, we determined the resonance frequency of the acoustic waves in the material [3], and, in the second, we measured the speed of propagation of ultrasound in the samples directly from the time of propagation of longitudinal waves [4]. For the latter measurements, we used a Steinkamp BP-V pulsed ultrasound device with 42.5 kHz transducers. For each specimen, we determined two values of the ultrasonic longitudinal wave velocity as averages of the measurements made longitudinally VL (30 cm) and transversally VT (10 cm). We also determine the longitudinal wave velocity by means of a resonance-based method using an Erudite MK3 test device, working in the range 1–100 kHz, which includes sonic and ultrasonic ranges. In our case, due to the length (30 cm) of the used granite specimens, we are working in sonic range. This equipment has an ultrasonic actuator and two piezoelectric sensors. The actuator is an electromagnetic acoustic vibrator driven by an amplifier. The sensors are of the piezoelectric type: one accelerometer and one low-mass surface mounting sensor. The MK3 detects the maximum amplitude indicating the resonance of the wave in the direction of the longest dimension of the specimen (30 cm). From this value of the frequency and knowing that the longitudinal wavelength in the fundamental resonance mode is twice the length of the specimen, we get a third value VFR of the longitudinal ultrasound wave velocity.

2. Results

Table 1 presents a summary of the results of the different characterization trials. For the non-acoustic cases, the results are comparable to those reported by other workers and to the systematic studies done by the INTROMAC for this type of stone [5]. The mean values of the longitudinal wave velocities are also comparable to those reported by other workers for granites. In particular, the value reported by Sheriff et al. is some 4500 m/s [6], and by the ASTM is 3470 m/s [7]. The velocities obtained by the three procedures described above were minimal for the variety Amarillo (Yellow) Jara (AJA) and maximal for Negro (Black) Villar (NVI). This could be because the former is a highly deteriorated variety extracted from the topmost zone of the batholith, whence its characteristic colouration (yellow) which is reflected in its commercial name, and the latter is in reality a diabase. Indeed, other physico-mechanical parameters also have extreme values for these varieties. Thus we found that the AJA granite has low comprehensive strength ($R = 143 \pm 12$ Mpa), flexural strength (Rtf $= 9.6 \pm 1.4$ Mpa), and apparent density ($\rho b = 2616 \pm 6$ kg/m^3), and the greatest open porosity (Po $= 1.93 \pm 0.09$%), while the NVI variety has the highest comprehensive strength ($R = 220 \pm 40$ Mpa), flexural strength (Rtf $= 38 \pm 3$ Mpa), apparent density (ρb $= 3030 \pm 9$ kg/m^3), and breaking load ($F = 3200 \pm 600$ N), and lowest open porosity (Po $= 0.10 \pm 0.01$ %).

Fig. 1 shows the box-and-whisker diagram for ultrasound velocities VL ordered by increasing mean value. This plots divides the data into four equal areas of frequency with the box enclosing the central 50%, the median is represented as a horizontal line inside the box and the mean is represented by a cross. Vertical lines – the whiskers –

Table 1
Statistical summary of the physico-mechanical variables measured in the tests carried out on the set of granite varieties studied

	Ultrasonic longitudinal wave velocity			Open porosity Po (%)	Water abs. capillarity C (g/m^2 s$^{0.5}$)	Water abs. atm. press. Ab (%)
	VL (m/s)	VT (m/s)	VFR (m/s)			
Mean	4492	4495	4285	0.66	0.48	0.21
Median	4449	4494	4329	0.60	0.45	0.20
SD	575	567	618	0.36	0.24	0.10
Range	2774–6272	2988–5999	2559–5919	0.10–1.93	0.11–1.19	0.1–0.5
N	34	34	32	36	36	36
	Apparent density ρb (kg/m^3)	Impact strength Is (cm)	Knoop hardness Dk (Mpa)	Comp. strength R (MPa)	Flexural strength Rtf (MPa)	Breaking load F (N)
Mean	2677	47	2277	154	14.2	2052
Median	2630	46	2131	151	13.5	2050
SD	114	11	739	22	5.4	499
Range	2570–3030	31–80	1086–4486	108–218	6.3–39.2	1000–3200
N	36	34	37	36	37	33

SD: standard deviation.

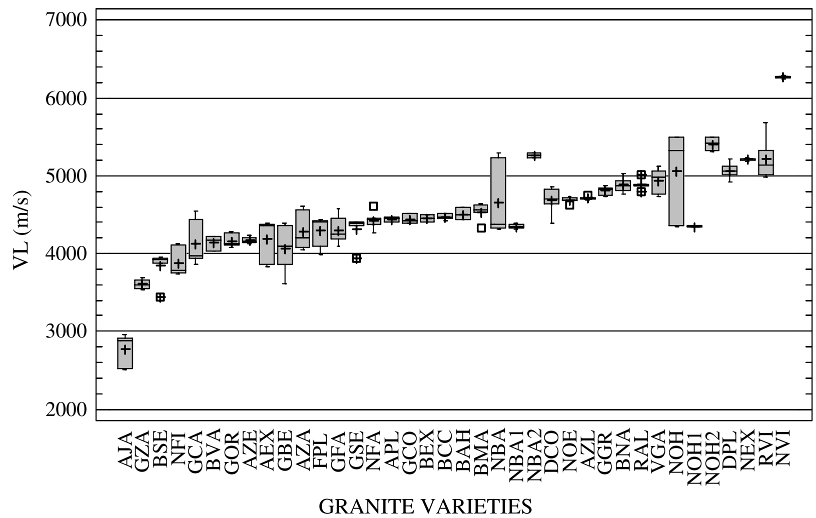

Fig. 1. Box-and-whisker diagram for the values of the longitudinal wave velocity VL of all the varieties of granite studied.

extend from each end of the box. Values that fall beyond the whiskers (outliers) are represented as individual points in the diagram. Only in four of the varieties, mean velocities below 4500 m/s have been measured, 15 were between 4000 and 4500 m/s, 10 between 4500 and 5000 m/s, and only five surpassed 5000 m/s. One observes that there is a good characterization of the values measured for each variety, since in almost all the cases the box represents less than 15% of the value, and indeed in most varieties less than 2%. In most cases, this allows the different varieties to be classified according to the velocity VL, with there being a clear distinction between them. This behaviour is similar for the VT and the VFR ultrasound speeds. There are two varieties, however, which did not follow this general behaviour: these were Negro (Black) Batalla (NBA) and Negro (Black) Ochavo (NOH), whose boxes ranged from 4300 m/s to 5300–5500 m/s, approximately. We found that the reason was the existence in each of these varieties of two groups of specimens which were clearly differentiated in their ultrasound speed VL, one at around 4300 m/s and the other at 5200–5400 m/s. We therefore divided these specimens into two groups labelled NBA and NOH 1 and 2, respectively, for each of the two varieties.

A study was made of the correlations between the values of the three longitudinal ultrasound wave velocities determined for each granite. They were all found to be strongly correlated with each other, with regression coefficients greater than 0.8. By way of example, Fig. 2 shows the straight line fit between VL and VFR. This indicates that the two techniques employed are valid, and interchangeable, for the analysis of granites. This is also reflected in the mean ratios between the different speeds: VL/VT = (0.99 ± 0.06), VL/VFR = (1.04 ± 0.08), and VT/VFR = (1.06 ± 0.09), where the associated error is the standard deviation of the distribution of the ratios for the different varieties.

Table 2 lists, for the varieties of granite studied, the linear regression coefficients (r) of other magnitudes. One observes that there were moderately strong correlations – with values of r around 0.8 – between the open porosity and the two parameters corresponding to water absorption (capillarity and atmospheric pressure). We also found correlations between the strength parameters (R, Rtf, Is, and F), with linear regression coefficients ranging between 0.713 and 0.527 (for R vs Is and R vs Rtf, respectively).

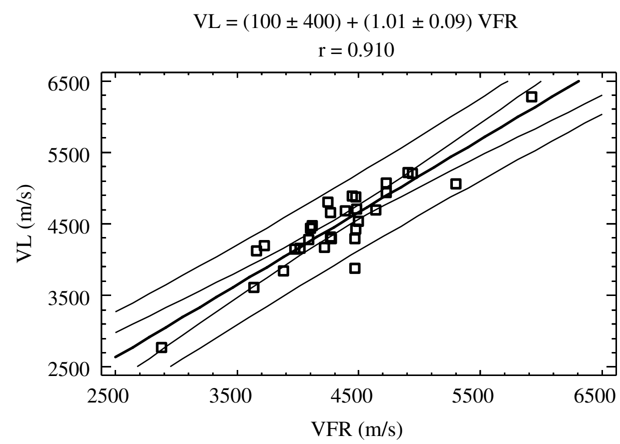

Fig. 2. Linear regression between the longitudinal wave velocities determined by through-transmission (VL) and by a resonance-based method (VFR) obtained for the set of granite varieties studied.

Table 2
Linear regression coefficients between some of the physico-mechanical variables that were determined

r	VL (m/s)	VT (m/s)	VFR (m/s)	Po (%)	C ($g/m^2 s^{0.5}$)	Ab (%)
VL (m/s)		**0.903**	**0.910**	**−0.675**	**−0.513**	**−0.610**
VT (m/s)	0.903		**−0.852**	**−0.655**	**−0.534**	**−0.689**
VFR (m/s)	0.910	0.852		**−0.554**	**−0.428**	**−0.492**
Po (%)	−0.675	−0.655	−0.554		**0.715**	**0.867**
C ($g/m^2 s^{0.5}$)	−0.513	−0.534	−0.428	0.715		**0.771**
Ab (%)	−0.610	−0.689	−0.492	0.867	0.771	

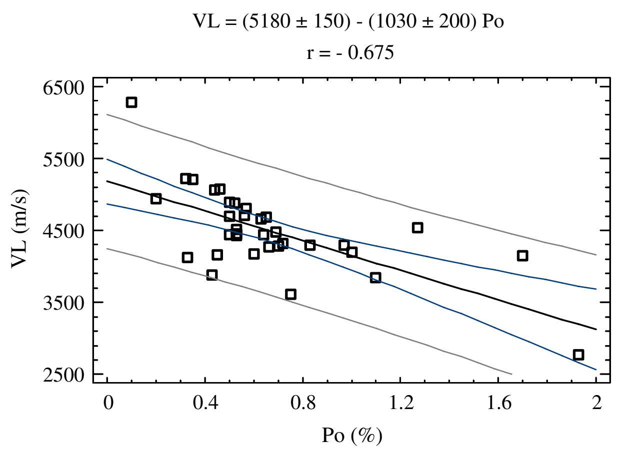

Fig. 3. Linear regression between the longitudinal wave velocity VL and the open porosity Po obtained for the set of granite varieties studied.

There were no significant correlations between the measured ultrasound velocities and the comprehensive and impact strengths, although VL and VFR did seem to be correlated with the flexural strength, the respective linear regression coefficients being 0.468 and 0.629.

Especially interesting were the moderate but significant negative correlations between the open porosity (or the water absorption) and the ultrasound speeds, with values of r around −0.6 (Table 2). As an example, Fig. 3 shows the regression between VL and the open porosity. This result is especially important given that the porosity of granite is extremely low. The values measured for our varieties were less than 1% in almost all cases, and the mean was 0.66% (Table 1). Negative correlations between these parameters have also been found for sandstones in a range of porosities from 2% to 30%, and sound wave speeds between 2500 and 6000 m/s approximately in acoustics well-logs [8], and for blocks of granite with measurements of six porosities (P) of between 0.6% and 1.1% and sound wave speeds (V) between 3200 and 5350 m/s. From the data provided by Carmichael [9], we obtained a regression equation of $V = 4450–558\ P$, $r = -0.742$. Microckracs, pores and the fluids contained within them have an important role in the acoustic properties of rocks. Several empirical relationships have been developed for acoustic wave velocity and porosity. In particular, the time average equation [10] has been widely used for sedimentary rocks, based on the observation of a strong linear correlation between wave slowness and porosity. This reduction in ultrasonic longitudinal wave velocity with increasing porosity could be related to a stiffness reduction.

3. Conclusions

In the present work, we studied the physico-mechanical properties of granites from industrial quarries using destructive tests and ultrasound techniques. Two independent NDT acoustic techniques were used to measure the acoustic velocity of longitudinal waves in different granite specimens: ultrasound through transmission testing and a resonance-based technique. We found the resulting values of the speed of propagation of the waves in the materials to be comparable and well correlated, with linear regression coefficients of 0.863, 0.871, and 0.917, for the relationships VL-VFR, VT-VFR, and VL-VT, respectively. We used these techniques to perform a preliminary characterization of the different varieties of granite studied, based on the mean values of the ultrasound speeds, since the box of the corresponding box-and-whisker diagrams represented in almost all the cases less than 15% of the mean value, and in most varieties less than 2%. We confirmed the existence of a negative correlation of the ultrasound speeds with the open porosity of the granites, and also with the water absorption (r around −0.6). There was also a moderate correlation between ultrasound longitudinal wave velocity and other individual magnitudes measured by destructive testing, in particular the strength coefficients (r between 0.468 and 0.629). Nevertheless, further work is needed in this sense for an accurate non-destructive characterization of granites, bearing in mind that the destructive trials were conducted with cube specimens of geometries different from those used for the ultrasound speed measurements, and that each destructive test also requires using a different cube specimen even though they belong to the same variety.

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