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Application of ultrasonics to brecciated dolostones for assessing their mechanical properties

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Abstract: Brecciated dolostones are widely used as construction and building materials, mainly for cladding, flooring and paving. Consequently, the mechanical properties of these rocks are an important characteristic to be taken into account for ensuring that these stones are used correctly in building processes.

There are many varieties of brecciated dolostones marketed as commercial marble. These stones belong to Group C of the commercial marble in accordance with the MIA classification. In this study, three of these Spanish varieties have been chosen due to the varying degrees of breccification and their different mechanical properties: Marrón Emperador, Beige Serpiente and Amarillo Triana. These varieties correspond to dolostones with varying crystal sizes and a differing number of calcite and dolomite veins.

In order to assess the mechanical properties of these varieties of brecciated dolostones, the ultrasonic technique has been used. Four ultrasonic parameters have been obtained from the digital analysis of the transmitted waveform, namely compressive and shear wave velocities, velocity ratio and waveform energy.

The mechanical properties determined on core samples of the analysed varieties include uniaxial compressive strength, unitary strain and the Young static elasticity modulus. In order to evaluate the best ultrasonic parameter for estimating mechanical properties, statistical tools of multivariate analysis have been applied (scatter diagrams, principal components and cluster analysis).

The results reveal a strong logarithmic relationship between wave velocities and compressive strength in the studied brecciated dolostones. Moreover, a relatively new relationship has been defined between waveform energy and uniaxial compressive strength logarithms. Effective porosity has a clear influence on most of the calculated parameters. This study confirms the suitability of the ultrasonic test as an effective non-destructive technique to assess the mechanical properties of these kinds of materials.

Résumé: Des dolostones avec bréchification textures sont largement utilisés comme matériaux de construction, principalement pour le revêtement, le plancher et le dallage. À cette fin, les propriétés mécaniques des roches sont une caractéristique importante à prendre en considération pour s'assurer que ces pierres sont employées correctement dans les processus de construction.

De nombreuses variétés de dolostones avec bréchification textures sont lancées sur le marché en tant que marbre commercial. Ces pierres appartiennent au groupe C du marbre commercial selon la classification de MIA. Dans cette étude, trois de ces variétés espagnoles ont été choisies pour leurs différents degrés de bréchification et leurs propriétés mécaniques: Marrón Emperador, Beige Serpiente et Amarillo Triana. Ce sont tous des dolostones avec différentes tailles de cristaux et des quantités variables de veines de calcite et de dolomite.

Afin d'évaluer les propriétés mécaniques de ces variétés de dolostones avec bréchification textures, la technique ultrasonique a été employée. Quatre paramètres ultrasoniques ont été obtenus à partir de l'analyse numérique de la forme d'onde transmise. Ces paramètres sont: compression et coupe des vitesses d'onde, rapport de vitesse et énergie de l'onde.

Les propriétés mécaniques déterminées sur des échantillons des carottes des variétés analysées comprennent la résistance à la compression uni-axiale, la tension unitaire et l'élasticité statique du module. Les méthodes statistiques de différentes analyses ont été utilisées (diagrammes de dispersion, analyses des principaux composants et analyses Cluster) en vue de choisir le meilleur paramètre de signal pour estimer les propriétés mécaniques.

Les résultats indiquent une relation logarithmique entre les vitesses d'onde et la résistance à la compression des dolostones bréchiformes étudiés. De plus, une relation a été définie entre l'énergie de l'onde et la résistance à la compression uni-axiale. La porosité effective a une influence sur plusieurs paramètres calculés. Cette étude confirme l'aptitude du test ultrason comme technique non-destructive pour évaluer les propriétés mécaniques de ce type de matériaux.

Keywords: Mechanical properties, Compressive strength, Laboratory studies, Discontinuities, Sedimentary rock, Metamorphic rock.

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INTRODUCTION

The ultrasonic method is a non-destructive test based on the propagation of high frequency elastic waves through materials. This propagation depends on the elastic properties of the minerals that form the rock, porosity, degree of fracturing, etc. In this sense, if we carry out a correct analysis of the ultrasonic signal, we can obtain precise information about the petrophysical and mechanical properties of rocks.

In contrast with traditional destructive tests, the analysis of the propagation of ultrasonic waves through materials allows an estimate of the mechanical properties of rocks to be obtained without destroying the sample used. This is an important breakthrough as it may be applied in different tests and to repeat measurements of the same sample.

The most widely-used ultrasonic parameter in material strength determination is compressional wave velocity (v_p). However, the analysis of the elastic wave propagation can be substantially enhanced when digital anlysis of the transmitted signal is used to obtain information from the waveform. There are two domains which can be used to analize the recorded signal: the time domain, where the amplitude of the signal is studied depending on the time; and the frequency domain, where the different frequencies which constitute the signal are analyzed. In this study, several ultrasonic parameters have been calculated in order to obtain a detailed study of the materials. However, four of them have been selected as the most interesting: compressional and shear wave velocities (v_p and v_s, respectively), velocity ratio (v_p/v_s) and waveform energy.

A number of microstructural factors induce the reduction in waveform energy and wave velocity, such as boundaries between grains, size and shape of grains and the presence of heterogeneities such as pores and cracks. Thus, reflections, scattering, absorption and frictional dissipation of energy in these microstructural factors take place in different proportions to produce an overall attenuation of waveform energy. Therefore, in rocks with a high degree of fracturing and breccification waveform energy is substantially reduced.

In this study, an ultrasonic test has been carried out on three different commercial varieties of brecciated dolostones: Amarillo Triana, Marrón Emperador and Beige Serpiente. Brecciated dolostones are highly fractured materials with a great petrographic heterogeneity. The size of their crystals and the number of calcite and dolomite veins varies and in the case of the Amarillo Triana, iron oxides are abundant. Some petrologic parameters have been established in order to measure the porosity and density of these dolostones.

These rocks are widely used as a construction and building material, mainly for cladding, flooring and paving. The mechanical behavior of these brecciated dolostones is an important characteristic to be taken into account for ensuring its correct use and high durability. The measurements taken in this study in order to obtain the mechanical properties of the core samples include uniaxial compressive strength, unitary strain and the static elasticity modulus. These mechanical parameters are highly important since they provide information on the behaviour of rocks under mechanical forces and their capacity for supporting stresses. This capacity depends on the elastic characteristic of the constituent minerals of the rock, as well as porosity, density, crystal size and type of grain contact, degree of fracturing and characteristics of said fractures.

Both the modulus of elasticity (*E* or Young's modulus) and the Poisson's ratio are the most commonly-used moduli to obtain the elastic response of intact rock to compression. The modulus of elasticity, which is derived from Hooke's law, is calculated by means of the applied axial compressive stresses and the resulting axial strain. The modulus of elasticity *E*, and Poisson's ratio may be obtained by dynamic methods (ultrasounds), as well as by static compression tests. The dynamic modulus of elasticity is generally greater than the static modulus. This is due to the fact that the response of the specimen to the very short duration strain and low stress level is essentially purely elastic (Goodman 1989; Christaras, Auger & Mosse 1994; Gueguen & Palciauskas 1994; Schön 1996). When both the duration strain and the stress level are high, the presence of cracks, microcracks and porosity produces a remarkable initial and final inelastic yielding in the materials (Walsh 1965b; Prikryl, Pros & Lokajícek 1998).

The interrelationship between measured ultrasonic, mechanical and petrographical parameters has been analysed using different multivariate analysis statistical tools: scatter diagrams, principal components and cluster anlalysis.

The aim of this paper is to assess the mechanical properties (rock strength and unitary strain) of three varieties of brecciated dolostones by means of a non-destructive test (ultrasonic technique). The following four ultrasonic parameters are used, as they are easy and practical to obtain: compressional and shear wave velocities, velocity ratio and waveform energy. Thus, the interrelationship between these ultrasonic parameters and the mechanical and petrographic characteristics of the rocks has been analysed, by applying multivariate analysis statistic tools: scatter diagrams, principal components and cluster analysis.

MATERIALS

In this study, three different types of sedimentary rocks from the Betic Cordillera (SE of Spain) have been tested. These rocks are quarried and commonly used as building materials, with three varieties of brecciated dolostones marketed as Marrón Emperador (ME), Beige Serpiente (BS) and Amarillo Triana (AT).

Marrón Emperador

ME is defined as a strongly fractured dolostone (Figure 1A). In this variety, abundant fractures with strong dissolution processes are observed, although no preferred orientation has been noted. This fractured system defines clasts that vary greatly in size. In general, clasts correspond to microcrystalline and/or mesocrystalline dolostones (according to Friedman's terminology, Friedman 1965). The cement, which surrounds the clasts and fills the veins, is over 90 % calcite mineral. The calcite and dolomite mineral ratio varies greatly and depends on the sample in question.

Beige Serpiente

BS corresponds to a breccia where clasts are not clearly defined by fractures (Figure 1B). In this case, as in the ME variety, clasts correspond to microcrystalline and/or mesocrystalline dolostones, although calcitic fragments are not often present. Clast size distribution is more homogeneous than in the previous case, even though small clasts are more abundant. Many clasts show thin white calcitic veins that do not appear over the whole rock. The finer-grained matrix, which surrounds the clasts, is formed by a mixture of calcite (20%) and dolomite (80%) crystals. The porosity associated to the finer-grained matrix is relatively high, and millimetric-size geodes can sometimes develop.

Amarillo Triana

AT is a marble formed by over 97% dolomite and a low percentage of other minerals, such as calcite, iron and/or manganese oxides, micas, etc. Two different types of rocks are recognised, namely dark and light stone types (Figures 1C and 1D). Samples of both types are classified as mesocrystalline dolostones, according to their texture, although some differences have been observed between them. On the one hand, the texture of the light stone shows a banded structure defined by different size crystaloblasts and a remarkable preferred orientation. On the other hand, the average crystal size in the dark types is slightly higher than the light one, and no preferred orientation is observed. AT samples are affected by numerous fracture planes and as a result calcite and iron oxide mineralizations have developed. Moreover, in the dark stone type it is possible to identify zones with an intense karstification. In these areas, large voids can be seen, and these vugs are totally or partially filled with dolomite and calcite cements.

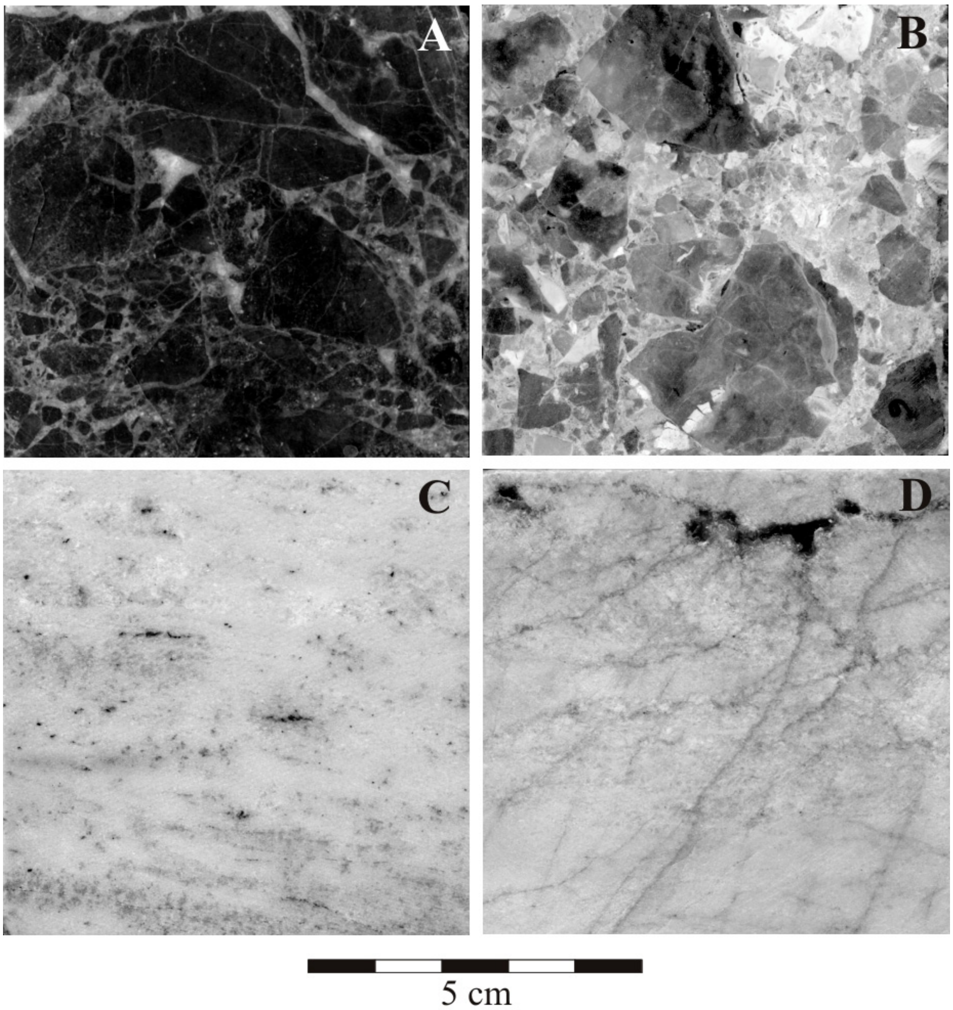

Figure 1. Three tested varieties of brecciated dolostone: (A) Marrón Emperador; (B) Beige Serpiente; (C) Amarillo Triana (light stone type); and (D) Amarillo Triana (dark stone type).

METHODOLOGY

Six cubic samples (7x7x7 cm) of each variety were used in this study. This geometry allows three orthogonal axis systems to be defined and, since ultrasonic tests are non-destructive, measurements in the three perpendicular directions of the samples have been taken. Consequently 54 different ultrasonic signals have been recorded.

Petrophysical characterization

The most important petrophysical parameters calculated are effective porosity and bulk density, which were tested in accordance with UNE-EN 1936. The specimens were placed under vacuum for 24 hours and water was then slowly introduced into the vacuum vessel until the specimens were covered, and the vacuum was maintained for another 24 hours. In order to weigh the water-saturated samples, these were dried at 60 ºC for 48 hours and subsequently cooled in a desiccator. From the weight of the dried cores, effective porosity and bulk density were measured. The bulk density (ρ_{bulk}) is measured as a ratio of mass to sample volume (including the volume of voids), and the effective porosity (n_o) is calculated as the ratio of the difference between water-saturated and dried sample weight and the volume of the sample.

On the other hand, several petrographic aspects were studied by means of a transmitted light microscope and scanning electron microscopy in backscattering secondary electron mode (SEM - BSE). Some of the petrographic characteristics analysed are composition, crystal size and its distribution throughout the sample, preferred orientation in crystals or microfracturing, etc.

Ultrasonic measurements

In order to obtain reproducible conditions in the ultrasonic measurement, the samples were dried at 60 ºC for 48 hours and tested immediately after they had cooled in a desiccator.

The ultrasonic transmission method was used. This involves two piezoelectric sensors coupled to the object at constant pressure by means of the hand procedure. One of the transducers is stimulated using an ultrasonic pulser and the other is used as a receptor sensor. Therefore, this method measures the propagation wave characteristics induced by microstructural factors. Compressional (P) and shear (S) waves were measured using polarised Panametric transducers (500 kHz) and a Sonic Viewer-170, which acquired and digitalised waveforms to be displayed, manipulated and stored the data. A visco-elastic couplant was used to achieve good coupling between the transducer and the sample.

Compressional (v_p) and shear (v_s) wave velocities, velocity ratio (v_p/v_s) and waveform energy are obtained in order to estimate rock strength. Due to the fact that the P-wave signal is more stable and reproducible than the S-wave signal, the energy is only obtained for the P-waves. All of these ultrasonic parameters were determined from the mean of a minimum of three measurements for each direction considered.

Propagation velocity (both compression v_p and shear v_s) was determined from the ratio of the length of the specimen to the transit time of the pulse.

Transducers measure particle displacement through time. Consequently, the signal amplitude quantifies particle displacement. Thus, in order to quantify the energy waveform, particle displacements are converted to velocities since energy waveform is proportional to square velocity. Waveform energy ( ) is presented in a dimensionless form and is defined as the integral of the area under the square rectified amplitude (Benavente *et al*. 2005).

Young's dynamic modulus of elasticity (E_d) and Poisson's ratio ( ) were calculated from P-waves and S-waves velocities (Eq. 1 and Eq. 2).

$$E = \rho_{bulk} v_P{}^2 \frac{(1-2\nu)(1+\nu)}{(1-\nu)} \qquad (1)$$

$$\nu = \frac{(v_P/v_S)^2 - 2}{2\left[(v_P/v_S)^2 - 1\right]} \qquad (2)$$

These equations are valid for isotropic media. In anisotropic rocks, such as the brecciated dolostones, they could be valid only for the direction of the measurement, instead of the whole sample. As for the cubic samples used in this study, wave velocities were measured in the three main axes of the core samples, and specific value was compared with the direction in which the static modulus of elasticity was measured.

Mechanical characterisation

Uniaxial compressive strength (σ_c) is used to determine the maximum value of stress attained before failure. The test was carried out with the same samples used in the ultrasonic measurement. Six specimens were sampled for each rock type, carrying out two measurements for each axial direction. Linear variable differential transformers (LVDTs) were assembled in order to measure axial strains in the samples. The test was carried out at a constant stress rate until failure of the specimens was achieved. Young's secant static modulus (E_{st}) (after ASTM D3148-93) and the uniaxial compressive strength were calculated.

Multivariate analysis

Three different multivariate analysis statistical tools were applied for stabilising the structure of the variable dependence and the interrelationship. The strategy employed in the statistical analysis is summarised in the following steps:

- A scattering diagram analysis, which allows a general study of the data to be carried out.

- A principal components analysis, which was applied to the database in order to obtain correlations between the different parameters calculated.
- A cluster analysis, to analyse the overall similar behavior patterns of the three previously described materials.

Scattering diagrams and Pearson's correlation coefficients

Scattering diagrams are a kind of illustration, which enable a different distribution of the variables' data (normal or log-normal) to be recognized and the correlation level between two parameters to be analysed. This correlation level is quantified by Pearson's correlation coefficient which expresses numerically (from 0 to 1) the approach of the points to a linear relationship.

Principal component analysis

Principal component analysis is a multivariate method mainly used for data reduction. It aims at finding a number of components that explain major variations within the data. Each component is a weighted, linear combination of the original variables. Usually, only components with an eigenvalue greater than 1 are of any interest. In order to make the components more interpretable, while still being orthogonal, a varimax rotation is used.

Cluster analysis

Cluster analysis is a popular technique used to find groups of data. In clustering, the objects are grouped so that "similar" objects fall into the same class. Objects in one cluster should be homogeneous, with respect to certain characteristics describing properties, and well separated from elements in other clusters. This separation of clusters is based on multivariate distance. Generally speaking, the most interesting feature of this tool is when unexpected groups are found, as they can reveal some hitherto unknown information about the data.

RESULTS AND DISCUSSION

Ultrasonic parameters (compressional and shear wave velocities, velocity ratio and the energy of signal), the effective porosity, density, compressive strength and elasticity constants (dynamics and statics) are shown in Table 1.

Table 1. Compressional (v_p) and shear (v_s) wave velocities; velocity ratio (v_p/v_s); waveform energy (ε); dynamic Young's modulus (E_d); dynamic Poisson's ratio (υ_d); uniaxial compressive strength (σ_c); static Young's modulus (Est); effective porosity (n_o) and bulk density (ρ_{bulk}), of the three studied varieties of brecciated dolostones: Amarillo Triana (AT), Marrón Emperador (ME) and Beige Serpiente (BS).

	v_p [km/s]	v_s [km/s]	v_p/v_s	$\varepsilon \cdot 10^{10}$	$E_d \cdot 10^{10}$ [Pa]	υ_d	σ_c [MPa]	Est $\cdot 10^9$ [Pa]	n_o %	ρ_{bulk} [g/cm^3]
AT	6.07	3.44	1.67	7.25	4.07	0.22	123.06	15.49	7.80	2.80
	6.14	3.17	1.93	159.33	5.26	0.31	151.20	3.69	9.81	2.81
	5.63	2.97	1.90	142.19	6.44	0.30	71.46	5.98	6.79	2.79
	5.68	3.35	1.56	1.13	3.48	0.15	83.65	9.84	13.25	2.72
	4.51	2.51	1.80	52.91	4.14	0.27	24.95	0.53	26.72	2.57
	4.08	1.72	2.36	3.50	2.23	0.39	25.79	0.58	12.81	2.68
ME	5.54	3.05	1.81	411.12	6.53	0.28	81.57	29.70	1.93	2.73
	6.11	3.30	1.85	451.34	7.79	0.29	119.05	4.86	1.06	2.76
	6.12	3.25	1.88	255.72	7.37	0.30	76.16	1.11	3.04	2.68
	5.95	3.09	1.92	161.68	6.72	0.31	60.58	3.46	2.17	2.67
	6.38	3.33	1.91	99.85	8.06	0.31	102.58	5.43	0.88	2.76
	5.74	3.00	1.90	488.00	6.41	0.31	65.14	8.23	1.51	2.71
BS	5.72	3.11	1.83	2469.93	6.72	0.29	45.53	0.88	4.07	2.69
	5.95	3.26	1.82	1103.35	7.39	0.28	156.86	3.52	3.48	2.71
	5.50	3.07	1.78	792.68	6.46	0.27	81.47	5.43	3.99	2.68
	5.54	3.10	1.78	332.70	6.51	0.27	95.89	24.26	4.10	2.66
	5.62	3.04	1.84	148.82	6.23	0.29	100.14	5.10	4.09	2.60
	5.44	3.14	1.73	1600.40	6.83	0.25	99.76	15.68	4.02	2.76

The high level of anisotropy observed in some parameters (v_p, v_s, σ_c, etc) is a consequence of the complexity and heterogeneity present in brecciated dolostones. In particular, the Amarillo Triana variety is the most anisotropic material due in part to the existence of fractures. Moreover, this anisotropy is associated to a well-developed preferred orientation of major rock-forming minerals.

Principal component analysis, scattering diagrams and Pearson's correlation coefficients

Principal component analysis has been carried out with the code SPSS® v.11.5.1. Two principal components were extracted which accounted for 72 % of the total variance (Figure 2).

Figure 2 shows the significant relationship existing between the ultrasonic parameters (v_p, v_s, log(ε)) and compressive strength (log(σ_c)). Moreover, a positive correlation between these parameters and density can be observed, whereas effective porosity reveals a negative correlation with all of these. These connections prove that the ultrasonic test is an effective non-destructive technique for assessing the mechanical properties of these kinds of materials.

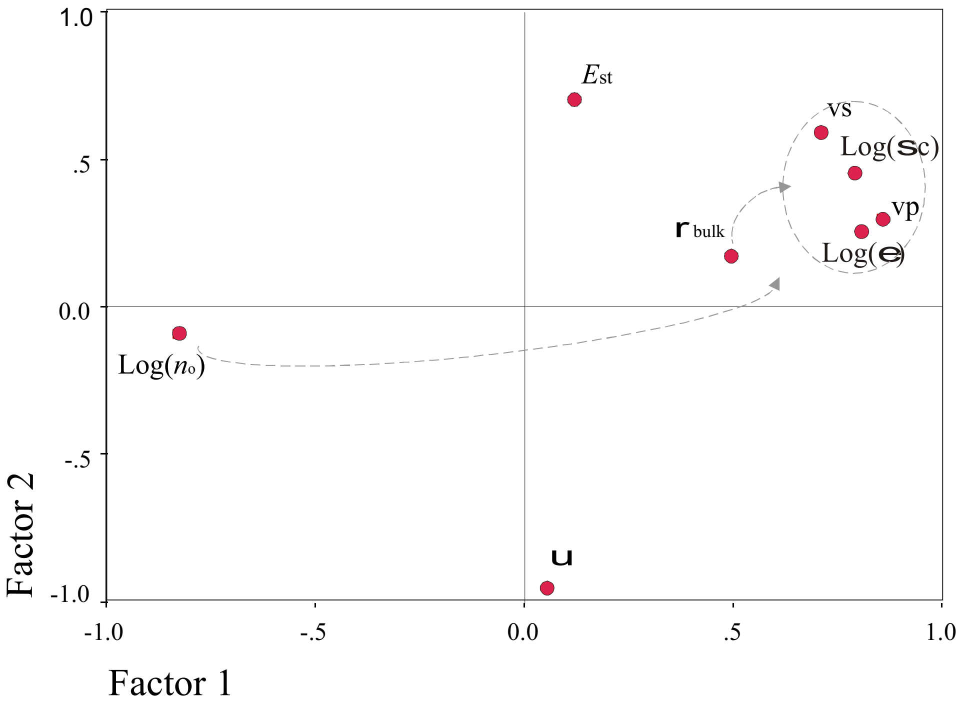

Figure 2. Principal component analysis with the most representative variables: P-wave velocity (vp), S-wave velocity (vs), waveform energy logarithm (Log(ε)), density (ρ_{bulk}), effective porosity logarithm (Log(n_o)), compressive strength logarithm (log(σc)), Young static elasticity modulus (E_{st}) and Poisson's ratio (υ).

These results have been analysed further using scattering diagrams and Pearson's correlation coefficients.

The aptitude of the three ultrasonic parameters (v_p, v_s and ε) to assess the ultimate compressive strength of brecciated dolostones has been analysed. The relationship between uniaxial compressive strength and both compressional and shear wave velocity appears in Figures 3 and 4, respectively. The uniaxial compressive strength increases as v_p and v_s increase. The presence of pores and cracks produce discontinuities in the rock, thereby decreasing ultrasonic velocity and increasing breakability under compression. The value of P-wave velocity as an index of rock strength is well documented by Christaras *et al.* 1994; Gueguen & Palciauskas 1994; Walsh 1965a; Schön 1996; Tugrul & Zarif 1999; Nicholson 2002; Sousa et al. 2005; etc. In all of these works, different equations have been presented correlating σ_c and wave velocities. Many of these equations represent a linear relationship between both variables, although other authors propose a logarithmic relation (Schön 1996). In this study, a good correlation has been found between the compressive strength logarithm and both v_p (Eq. 3, $R^2 = 0.633$) and v_s (Eq. 4, $R^2 = 0.630$).

$$\log(\sigma_c) = 0.313 \cdot v_p + 0.121 \quad (3)$$

$$\log(\sigma_c) = 0.457 \cdot v_s + 0.497 \quad (4)$$

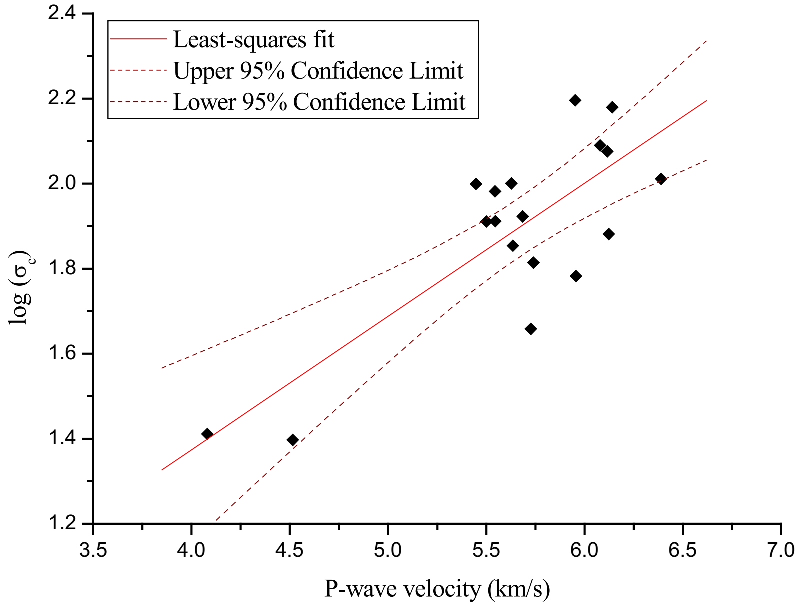

Figure 3. Relationship between logarithm of uniaxial compressive strength (log(σ_c)) and P-wave velocity.

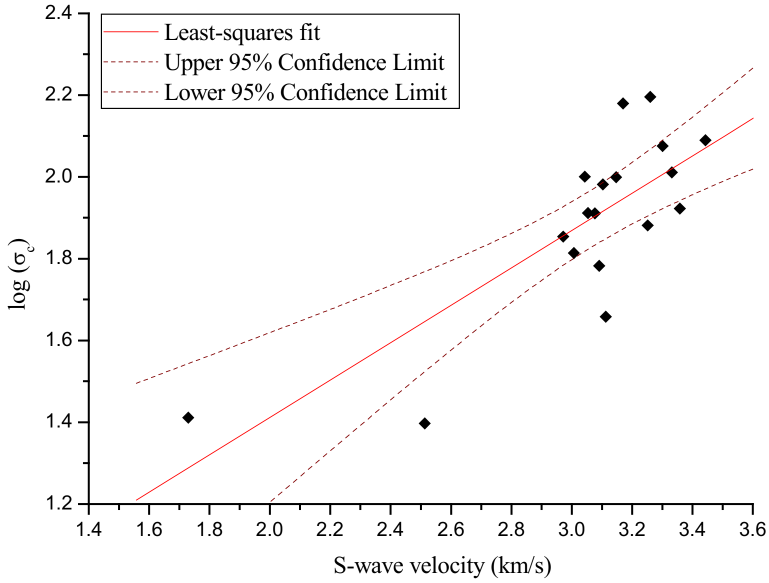

Figure 4. Relationship between logarithm of uniaxial compressive strength (log(σ_c)) and S-wave velocity.

Moreover, there is a statistically significant correlation between the uniaxial compressive strength logarithm (log (σ_c)) and the waveform energy logarithm (log(ε)) (Eq. 5, $R^2 = 0.608$) (Figure 5).

$$\log(\sigma_c) = 0.185 \cdot \log(\varepsilon) - 0.349 \quad (5)$$

This relationship is a new discovery and is based on the fact that, in these kind of rocks, the main microstructural factors, which influence energy of the waveform, are fractures, vein and intercrystalline porosity and calcite veins. These factors are responsible for causing a reduction in waveform energy, and also in wave velocity. Moreover, they influence the ultimate strength of the rock and control the direction in which failure occurs since they may act as surface weaknesses. Therefore, the energy parameter (ε) can be applied to assess the mechanical properties of brecciated dolostones (Benavente *et al.* 2005).

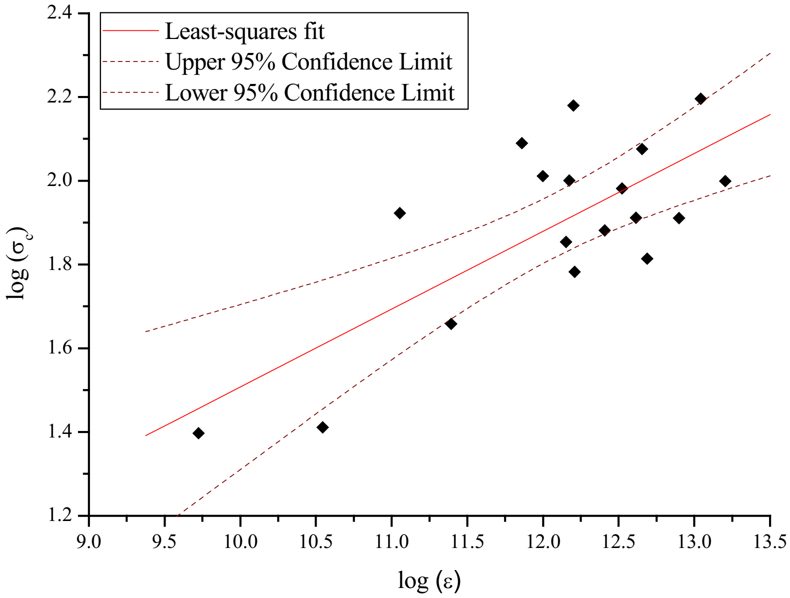

Figure 5. Relationship between logarithm of both uniaxial compressive ($\log(\sigma_c)$) strength and waveform energy ($\log(\varepsilon)$).

On the other hand, a high correlation between wave velocities and effective porosity has been observed. This relationship is in keeping with the results provided by several authors (Gueguen & Palciauskas 1994; Schön 1996; Valdeón *et al*, 1996; Tugrul & Zarif 1999; Boadu 2000; Nicholson 2001; Sousa et al. 2005), who underline several linear equations connecting wave velocity and n_o. However, in this paper, a linear-relationship has been denoted between v_p, v_s and the n_o logarithm. Equations 6 ($R^2 = 0.755$) and 7 ($R^2 = 0.684$) quantify this relationship.

$$v_p = -0.724 \cdot (\log n_o) + 4.641 \quad (6)$$

$$v_s = -1.398 \cdot (\log n_o) + 4.822 \quad (7)$$

In spite of the relationships presented in the bibliography between density and wave velocity, in these kinds of materials a low Pearson's correlation coefficient has been recorded ($R^2 = 0.07$). This could be explained due to the short range of density values (2.6 – 2.8 g/cm^3) and the high anisotropy of these types of materials which produces a high scattering of v_p and v_s values.

As expected, inverse relationships exist between uniaxial compressive strength (σ_c) and effective porosity (n_o). Porosity is an important factor in rock strength in that voids reduce the integrity of the material. A small change in pore volume can produce an noticeable mechanical effect (Tugrul & Zarif 1999). In this study, a considerable relationship ($R^2 = 0.61$) has been obtained between the logarithms of both variables.

The influence of effective porosity is clear in the values of the dynamic elasticity modulus. The measurements taken from brecciated dolostones confirm a definite decrease in Young's dynamic modulus with increasing effective porosity ($R^2 = 0.741$). However, this influence is not so clear when the static elasticity modulus is considered ($R^2 = 0.224$). This could be due to the fact that the porosity and the presence of microcracks cause a variable inelastic yielding in rocks and, as a consequence, produces a major scattering when Young's secant modulus is calculated. This reason is also valid for explaining the insignificant relationship between elastic and static elasticity moduli in these materials, even though the E_d values are always larger than the E_{st}, according to the relationship presented in the bibliography (Goodman 1989; Christaras *et al.* 1994; Schön 1996).

Cluster analysis

In this study, cluster analysis is an efficient tool for comparing the characteristics of the three different varieties of brecciated dolostones described. This analysis has been carried out in two different steps, whereby the samples have been grouped accordingly in terms of ultrasonic (Figure 6) and mechanical (Figure 7) properties.

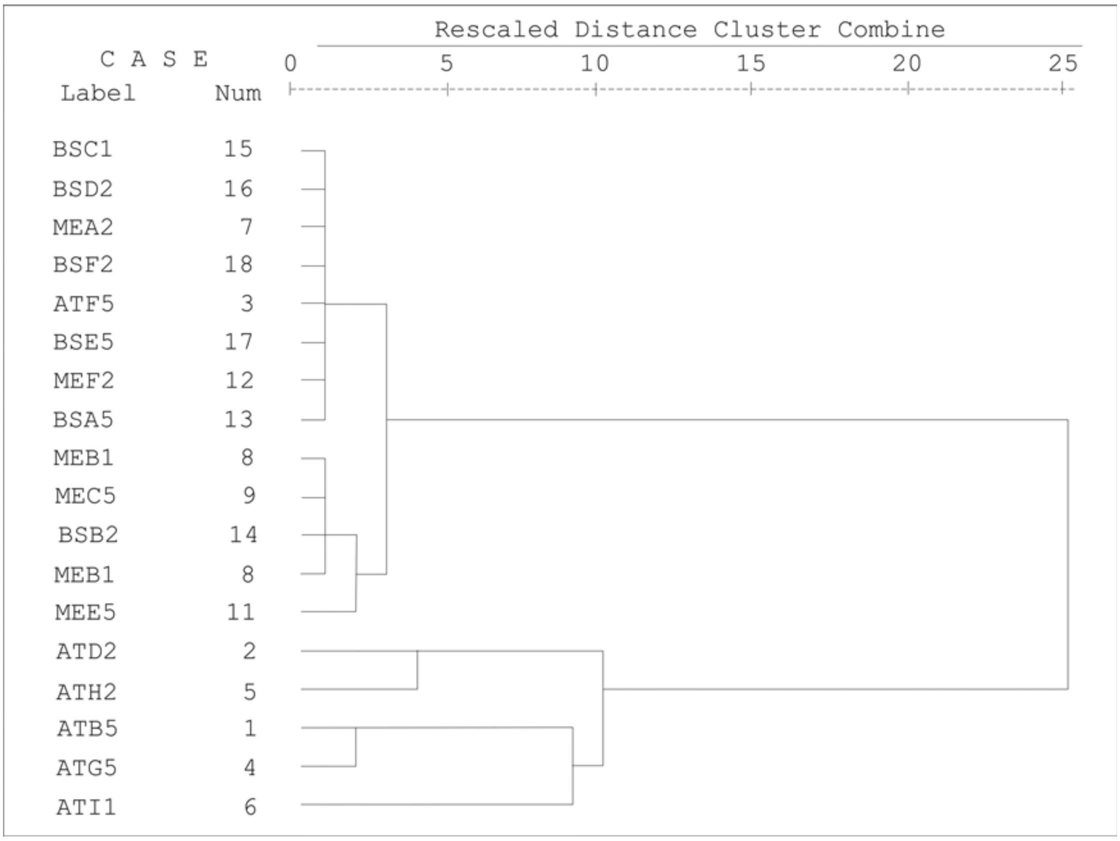

Figure 6. Cluster Analysis of the samples as a function of its ultrasonic properties (AT: Amarillo Triana; BS: Beige Serpiente; ME: Marrón Emperador).

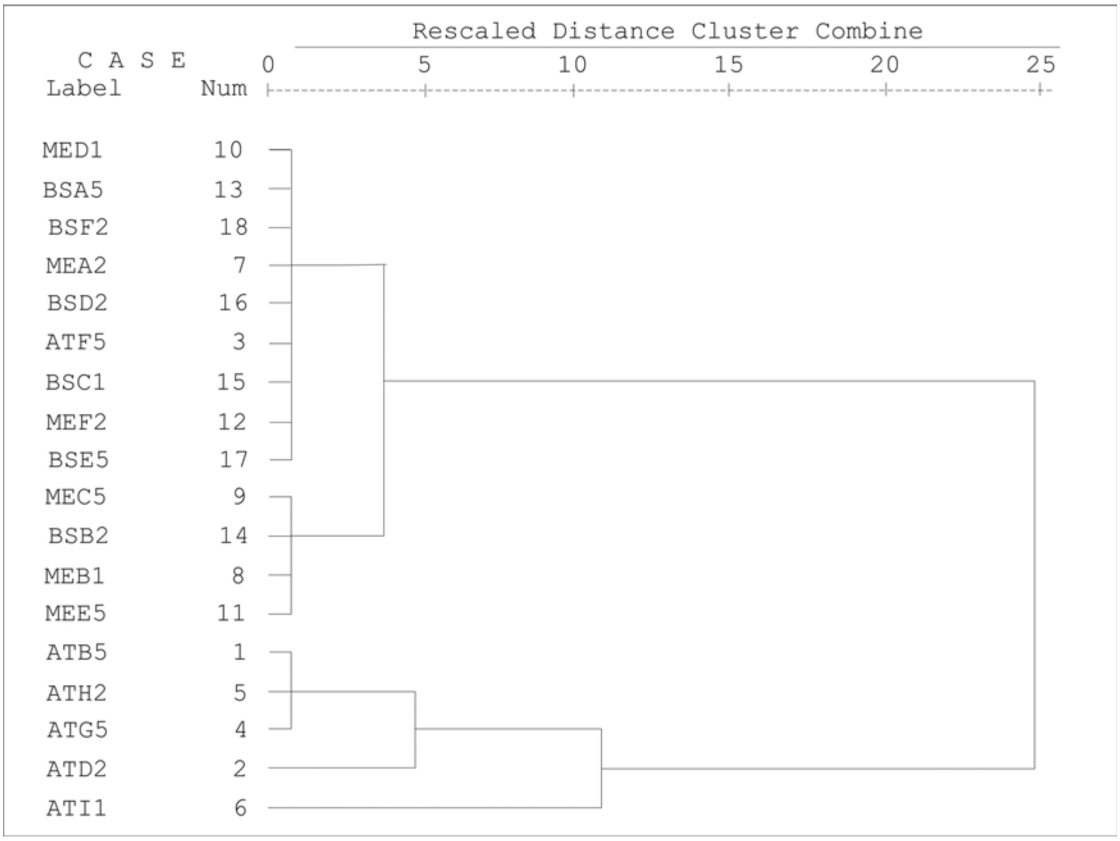

Figure 7. Cluster Analysis of the samples as a function of its mechanic properties (AT: Amarillo Triana; BS: Beige Serpiente; ME: Marrón Emperador).

Two groups have been established in both classifications (Figures 6 and 7). One of these groups is formed by Marrón Emperador and Beige Serpiente samples. This fact indicates that both varieties have the same mechanical and ultrasonic properties. On the other hand, the Amarillo Triana variety has different characteristics from the other two materials, and therefore constitutes an individual cluster.

According to these results, two materials are recognized taking into account petrophysical and petrographical criteria, despite the fact that three varieties of commercial marble are distinguished (Amarillo Triana, Marrón Emperador and Beige Serpiente).

CONCLUSION

The ultrasound test has been applied to three different commercial varieties of brecciated dolostones in order to assess its mechanical properties. For this propose, four ultrasonic parameters have been calculated from the digital analysis of the transmitted waveform (v_p, v_s, v_p/v_s and waveform energy). Mechanical properties have been estimated by means of the measurement of compressive strength and both static and dynamic elastic constants. Moreover, the effective porosity and bulk density of each sample were measured. The interrelationships between all these parameters were studied and the conclusions are as follows:

- Effective porosity has a clear logarithmic influence on most of the calculated parameters (v_p, v_s, v_p/v_s, σ_c, E_d). This can be explained due to the fact that an increase in effective porosity involves an increase in the number of discontinuities, and consequently, worsens conditions for ultrasonic wave propagation (more scattering, etc). On the other hand, porosity is an important factor in rock strength in that voids reduce the integrity of the material.
- A high correlation between both wave velocities (v_p, v_s) and compressive rock strength has been obtained. Furthermore, a new relationship between waveform energy and compressive strength has been defined. These relationships are based on the fact that in this kind of rock, the main structural factors which influence waveform are fractures, veins and porosity. These factors are responsible for causing a reduction in ultrasonic parameters as well as in the ultimate strength of the rock.
- On the contrary to what was expected, a low correlation has been measured between density and wave velocity in these kinds of materials. This could be explained by the short range of density values, and the high anisotropy of this type of materials which produces a high scattering of v_p and v_s values.
- According to the results obtained in the cluster analysis, two materials are recognized taking into account petrophysical and petrographical criteria, despite the fact that three varieties of commercial marble had been distinguished in agreement with their aesthetic characteristics (Amarillo Triana, Marrón Emperador and Beige Serpiente).

The associations and relationships found in this study confirm the suitability of the ultrasonic test as an effective non-destructive technique for assessing the mechanical properties of these kinds of materials.

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