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Spatial attenuation: The most sensitive ultrasonic parameter for detecting petrographic features and decay processes in carbonate rocks

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The evaluation of stone quality by means of non-destructive tests is of vital importance, especially when rock is used as a building material. Usually, however, only vp (P-wave velocity) is considered when rock properties such as strength, durability or decay level are assessed. In this paper, we propose a novel ultrasonic estimator based on wave energy: spatial attenuation (α_s). The benefits of this estimator were evaluated by comparison with five other ultrasonic parameters: compressional (v_P) and shear (v_S) wave velocities, velocity ratio (v_P/v_S), waveform energy and temporal attenuation.

The sensitivity of each ultrasonic parameter was compared by measuring 300 samples from ten different types of rock. Each type was selected according to its mineralogy (calcite and/or dolomite rock) and structural complexity (homogeneous, fractured, brecciated, foliated or laminated). Samples were subjected to weathering tests (thermal shock and salt crystallisation tests) in order to study the sensitivity of both ultrasonic parameters during fracture initiation, fracture growth and rock fabric disintegration.

Results show that although vp is the most widely used parameter, the information it yields is extremely imprecise. However, the new parameter α_s is highly sensitive to the petrographic characteristics of rocks as well as to the presence of individual defects (fractures, vugs or disintegrated areas). Moreover, the most significant aspect of α_s is that its values fall between two fixed limits: 0 dB/cm and 20 dB/cm. A rock with a α_s value close to 0 dB/cm is an unweathered, homogeneous and good-quality rock whilst a α_s value higher than 12 dB/cm indicates extreme decay, i.e. open fractures, developed vugs and/or disintegrated areas.

1. Introduction

Ultrasound is one of the most important non-destructive tests that can be applied to rocks (Winkler, 1997) as it is a fast and economical technique that is easy to apply in both field and laboratory studies, and, most importantly, the ultrasonic data obtained depend on rock features such as crystal size, porosity and the presence of fractures (Winkler, 1997; Montoto, 2003). However, the influence of petrographic aspects on ultrasonic propagation is unfortunately difficult to gauge (Schön, 1996).

Several authors have studied the influence of different petrographic characteristics on ultrasonic wave propagation (for instance: Goueygou et al., 1999; Hernández et al., 2000; Assefa et al., 2003; Punurai et al., 2006). Their results show interesting relationships between petrographic parameters (such as crystal size and/or porosity) and ultrasonic wave propagation velocity. Moreover, the relationship between ultrasonic wave velocity and the degree of weathering in rocks is analysed in numerous papers (for example: Ould Naffa et al., 2002; Malaga-Starzec et al., 2006; Veniale et al., 2008).

However, most of these studies present some limitations. Firstly, the influence of crystal size on wave velocity is not clear. For instance, whilst Eberhardt et al. (1999) obtain an inverse relationship between both parameters (the greater the crystal size, the lower the propagation velocity), Sarpün et al. (2005) indicate a contradictory direct relationship. Secondly, the influence of fractures in rock samples on ultrasonic propagation has not been tackled in depth and most studies of this type tend to adopt a theoretical approach (Boadu, 1997; Ju et al., 2007; Zhao et al., 2008). Thirdly, results concerning the influence of crystal size, porosity and the degree of weathering in rocks on ultrasonic propagation are usually unsatisfactory as they tend to refer exclusively to the materials studied and thus cannot be extrapolated to different materials. Furthermore, certain studies only express qualitative results (Vergara et al., 2001; Benson et al., 2005; Malaga-Starzec et al., 2006; Machek et al., 2007; Veniale et al., 2008). Finally, in the vast majority of papers, wave propagation is only quantified by vp (ultrasonic wave velocity) (Darot and Reuschlé, 2000; Weiss et al., 2002; Sarpün et al., 2005; Rodríguez-

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Gordillo and Sáez-Pérez, 2006; Ersoy and Atici, 2007; Machek et al., 2007). However, according to previous studies by the authors of this paper (Benavente et al., 2006; García-del-Cura et al., 2011), the energy of the transmitted waveform also provides important information.

In view of the above, the aims of this research were threefold. The first aim was to obtain a full quantification of the ultrasonic behaviour of rocks. As mentioned above, previous studies have shown that vp (ultrasonic wave velocity) does not offer a complete evaluation of the wave transmission process (Benavente et al., 2006) as vp only quantifies aspects related to time domains. Amplitude and wave energy must also be evaluated in order to obtain an accurate quantification of ultrasonic waveform.

With this ultrasonic quantification, the minimum number of ultrasonic parameters must be identified in order to obtain the maximum amount of information concerning waveform. Definitive parameters must also be calculated quickly and effectively so that they may be used in future ultrasonic applications.

The second aim was to attain a thorough understanding of the influence of rock fabric on wave propagation. This was an extremely important goal as it represents a means of contributing to a definitive clarification of /ultrasonic dependence on crystal size, porosity and fractures. This is a highly complex task since ultrasonic results are relatively easy to interpret in homogeneous rocks but are almost impossible to obtain in stones with complex and heterogeneous fabrics (Winkler, 1997). In order to guarantee rigorous results, the study of the influence of rock fabric on ultrasonic wave propagation was carried out not only by considering the influence of rock fabric on vp, but also by analysing the entire range of ultrasonic parameters obtained from the aforementioned quantification. A wide range of rock fabric types were also selected, namely ten different types of carbonate rocks: limestones, travertines, dolostones, calcite marbles and dolomite marbles. These lithologies comprise some of the most important and common types of stone in the ornamental stone industry. Rocks were selected carefully in order to obtain materials with varying porosities (from <0.5% to higher than 10%), structural complexity (from homogeneous limestones to brecciated dolostones or foliated marbles) and/or crystal size (from <5 μm to several millimetres).

The final aim of this paper concerned obtaining data on how ultrasounds are affected by rock weathering processes. Results obtained from the study of ultrasonic propagation in decayed rocks were extremely interesting in two aspects. On the one hand, the ultrasonic technique is one of the most widely used non-destructive tests in the area of Cultural Heritage and is used in order to evaluate the degree of weathering in stones and their durability. On the other hand, the stone decay process involves progressive changes in the porous system, in material loss and/or in the appearance of fractures. All these petrographic transformations entail changes in ultrasonic wave propagation, and consequently, in the calculated parameters.

A comparison between rock fabric changes (before and after weathering processes) and ultrasonic variations should enable the relationships established in the second aim to be confirmed, and new correlations to be establish if new results are observed.

2. Materials

Ten commercial varieties of carbonate rocks were selected (Figures 1 and 2A, B, Tables 1 and 2). Each of the rocks chosen had a constant mineralogy (carbonate) as well as differing crystal sizes, porosities and structural complexities. This selection produced a wide range of petrological characteristics and facilitated the study of how each petrographic variable affects ultrasonic propagation.

2.1. Ambarino (A)

This rock is classified as a brecciated dolostone. It is highly complex and presents numerous discontinuities. It is constituted by clasts (mm-size) surrounded by a porous fine-grained matrix. Clast mineralogy is basically dolomite, while the fine-grained matrix presents a variable proportion of calcite and dolomite content, between 50% and 80% of calcite (according to XRD data).

2.2. Amarillo Triana (AT)

This corresponds to a yellow dolomite marble with abundant fissures partially filled with both calcite and iron/manganese oxides/hydroxides. This marble shows signs of metamorphic foliation, although not necessarily highly developed in some samples.

2.3. Blanco Alconera (BA)

White crystalline limestone formed basically of calcite, although some samples can show a significant dolomite content (up to 75% in some areas). This rock variety is highly homogeneous and does not present significant fissures or veins.

2.4. Blanco Tranco (BT)

White homogeneous calcite marble with low development of metamorphic foliation. The main mineralogy of this marble is calcite (99%), although other minor minerals can be found such as pyrite, chalcopyrite, apatite, dolomite and micas.

2.5. Beige Serpiente (BS)

This rock variety is very similar to *Ambarino (A)*. BS is also a brecciated dolostone, but with slightly larger clasts (cm-size). Clasts in this stone are surrounded by a porous fine-grained matrix constituted mainly by calcite and some dolomite crystals.

2.6. Crema Valencia (CV)

Cream micritic limestone (99% calcite) with abundant stylolites filled with quartz (80%) and kaolinite (11%).

2.7. Gris Macael (GM)

This rock variety corresponds to a grey calcite marble with clear metamorphic foliation. This marble is constituted mainly by calcite (99%) with minor minerals such as quartz, micas, pyrite and ilmenite.

2.8. Marrón Emperador (ME)

Brown brecciated dolostone with high structural complexity. Clasts are defined within a dense network of fractures. Clasts are constituted basically by dolomite (99%) and the frequent veins which run through the rock are filled with calcite.

2.9. Rojo Cehegín (RC)

Two different rock fabrics are present in this rock: i) micritic limestone with abundant clay minerals filling the space between the calcite crystals and ii) biomicritic limestone, with many bivalve fossils. RC has a large number of white calcite veins. Stylolites can be also frequent, filled with quartz (24%), siderite (21%), kaolinite (14%), smectite (16%), muscovite (15%) and hematite (10%). The abundant discontinuities provide the rock with a brecciated appearance.

2.10. Travertino Amarillo (TrA)

This yellow travertine is a layered limestone with: 1) porous layers composed by micrite and/or microcrystalline calcite; and ii) other layers of low porosity with mesocrystalline or crystalline fibroradiate