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PREDICTION OF THE MECHANICAL PROPERTIES OF GRANITES BY ULTRASONIC PULSE VELOCITY AND SCHMIDT HAMMER HARDNESS

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Abstract: The present work deals with the use of simple and economical non destructive techniques, ultrasonic pulse velocity and Schmidt hammer to predict the strength and elastic properties of granitic stones that are characteristic in ancient masonry constructions. Good correlations between NDTs and strength and modulus of elasticity were found, which indicate them as appropriate techniques for estimating the mechanical properties.

Introduction

One of the major challenges in the scope of rehabilitation and repair of existing structures is the inspection, which includes the detection of the damaged zones, cracking and defects, and mechanical characterization of materials. This preliminary work is generally carried out not only based on experimental investigation on the laboratory but also by means of in situ nondestructive methods. Sophisticated non destructive techniques have been developed and improved throughout the years and are applied to various types of structures in distinct fields, namely masonry structures. Examples of such techniques are the ground probe radar and the sonic tests, which appears to be powerful tools in the detection of structural irregularities such as inclusions, moisture content and in the identification of the cross section of ancient multiple leaf masonry walls (Binda et al., 1998; Schuller et al., 1997). These tests are mainly used in structural identification, whereas other, easy, simple, flexible and economical tests such as the ultrasonic pulse velocity and Schmidt hammer tests are essentially suitable in the characterization of elastic and strength properties of structural materials. The ultrasonic pulse velocity test has been pointed out by several authors as an useful and reliable non destructive tool of assessing the mechanical characteristics of concrete from existing

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structures, such as, the modulus of elasticity and the compressive strength (Hassan et al., 1995). In the field of rock structures, the ultrasonic pulse velocity has also been suggested as an useful method for a preliminary estimation of elastic and strength properties. This aim has been accomplished by means of empirical correlations between the ultrasonic pulse velocity and the compressive strength and elastic modulus. However, its applicability can be much more enlarged. When associated to tomography, it can give good qualitative information on the changes of material properties as well as on its microcracking state (Popovics, 2003). Ultrasonic pulse velocity was found, recently, to provide quite good indication about the damage in concrete. The Schmidt hammer was initially developed for concrete, but extensive application of it has been performed as a preliminary estimation of the stone strength (Katz et al., 2000).

The main goal of the present study consists of the attainment of empirical correlations between the ultrasonic pulse velocity (UPV) and the Schmidt hammer rebound number (N) and the mechanical properties that describe the tensile and compressive behavior. Besides, a discussion of the factors that induce variations on the velocity measurements and on the rebound number is also carried out (moisture content, weathering state and material anisotropy are highlighted). The weathering state of granites of the same facies is identified by visual inspection. Weathered granites present a yellow aspect, whereas fresh granites exhibit predominantly blue color. The major significance of the proposed statistical correlations using simple nondestructive techniques consists of the possibility of estimating the mechanical properties of similar granitic lithotypes existing in masonry structures of ancient buildings, especially in the northern region of Portugal. This can be of great value in a preliminary phase of the diagnosis and inspection of the structural and material condition, particularly in cases in which the possibility of sampling material cores is reduced.

Brief description of the material

Granite is the most used stone in the construction of ancient buildings located in the North of Portugal, either in monumental or vernacular architecture. A wide range of granitic rocks is present in masonry constructions, depending on their petrographic features, such as grain size and internal texture. Therefore, the mechanical characterization of only one type of granite would be rather limitative. The granites used for mechanical characterization were mostly collected from the Northern region of Portugal. The selection of the granitic types was based on the mineralogical composition and grain size, aiming at providing a comprehensive sample of the Portuguese granites. In addition to these criteria, the presence of preferential orientation planes and weathering condition were also taken into account. The natural orientation planes of granitic rocks or preferred orientation of minerals (foliation) can be relevant for further analysis of the variation of the mechanical properties. Three orthogonal planes can be identified with rock splitting planes (quarry planes) defined as planes of preferred rupture. The rift plane is the plane corresponding to the easiest splitting in the quarry being easily recognized by the quarryman, being associated to the plane of easiest finishing. In Table 1, the more weathered types of the same granite facies are distinguished with an asterisk (*). The loading directions considered in the experimental program are also indicated. When the granite was assumed isotropic (random orientation of minerals), only the direction parallel to the rift plane was considered (granites BA, GA, GA*, RM, MC). If the granite presented visible foliation, the perpendicular and parallel directions to the foliation plane were considered (AF, MDB, MDB*, PTA). In granites PLA and PLA*, the preferred orientation of feldspar phenocrystals (flow structure) is subparallel to the rift plane and, consequently, two loading directions (parallel and perpendicular to the rift plane) were adopted.

Table 1. Brief description of the selected granites and directions considered in the tests

Granite designation	Petrologic description	Loading directions
BA	Fine to medium-grained porphyritic biotite granite	Parallel to the rift plane
GA, GA*	Fine to medium-grained, with porphyritic trend, two mica granite	Parallel to the rift plane
RM	Medium-grained biotite granite	Parallel to the rift plane
MC	Coarse-grained porphyritic biotite granite	Parallel to the rift plane
AF	Fine to medium-grained two mica granite	Parallel and perpendicular to the foliation plane
MDB, MDB*	Fine to medium-grained two mica granite	Parallel and perpendicular to the foliation plane
PTA, PTA*	Fine to medium-grained two mica granite	Parallel and perpendicular to the foliation/rift plane
PLA, PLA*	Medium to coarse-grained porphyritic biotite granite	Parallel and perpendicular to the rift plane

Mechanical properties of granites

The mechanical properties of granites, tensile and compressive strength as well as the modulus of elasticity, were obtained by means of an enlarged experimental program, including direct tensile tests and uniaxial compressive tests aiming at obtaining the fracture properties of granites under tensile and compressive loading (Vasconcelos, 2005). Prismatic specimens of 80mm height, 50mm length and 40mm width were used in the direct tensile tests carried out on a CS7400S servo-controlled universal testing machine. Cylindrical specimens (75mm diameter and 150mm height) were used in the uniaxial compressive tests from which the compressive strength and modulus of elasticity were derived. The modulus of elasticity was calculated by averaging the vertical strains measured by two strain gauges attached to the specimen.

The average values of the tensile and compressive strength and the modulus of elasticity for the different types of granites are indicated in Table 2. It can be seen that there is a wide range of variation for the mechanical properties among the granites, with low to moderate levels of scatter. According to what was largely discussed by Vasconcelos (2005), the weathering state, planar anisotropy and even the grain size influence considerably the strength and elastic properties of granites. It is observed that the granites under study exhibit from low to high anisotropy under tensile loading. Under compression, the anisotropic behavior is more moderate, which can be attributed to the fact that the localized macrocrack is not perfectly aligned with the plane of anisotropy (foliation or rift plane) as in case of the direct tension. It should be noticed that the macrocracking in tension is caused by tensile stresses according to the loading, whereas in compression the tensile stresses occurs almost in the perpendicular direction to the loading. It is observed that the weathering of the granites reflect the decrease on the strength and elastic properties.

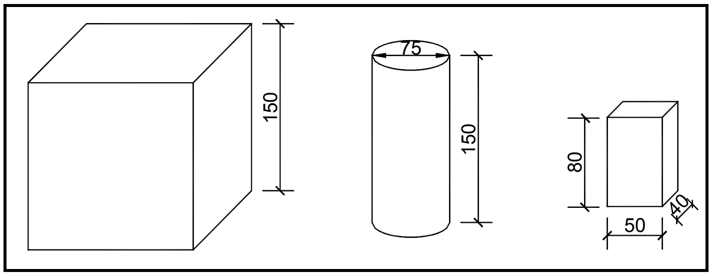
Table 2. Mechanical properties of granites. Coefficient of variation inside brackets (%).

Granite	f_t (N/mm^2)	f_c (N/mm^2)	E (N/mm^2)
BA	8.08 (11.4)	148.5 (4.8)	59939 (5.2)
GA	6.01 (11.1)	135.7 (5.0)	52244 (2.3)
GA*	3.52 (12.3)	89.5 (2.5)	35088 (3.3)
RM	4.51 (9.3)	159.8 (2.5)	58926 (1.8)
MC	5.23 (6.3)	146.7 (2.8)	63794 (5.6)
AF ⊥ foliation	2.34 (11.5)	66.7 (7.8)	15748 (7.2)
AF // foliation	3.04 (3.0)	68.9 (5.6)	18954 (6.9)
MDB ⊥ foliation	2.36 (5.4)	49.7 (5.2)	15886 (13.5)
MDB // foliation	2.20 (4.9)	44.8 (2.8)	11600 (4.2)
MDB* ⊥ foliation	1.83 (4.3)	35.2 (3.4)	11028 (12.0)
MDB* // foliation	1.97 (5.3)	26.0 (7.1)	12243 (13.6)
PTA ⊥ foliation	4.15 (14.1)	119.1 (3.1)	40526 (3.1)
PTA // foliation	4.90 (15.6)	109.1 (7.3)	41504 (1.6)
PTA* ⊥ rift plan	1.56 (11.3)	60.4 (4.8)	15008 (7.1)
PTA* // rift plan	2.12 (4.1)	50.2 (11.1)	18168 (3.3)
PLA ⊥ rift plan	2.79 (10.5)	147.0 (2.6)	53737 (2.8)
PLA // rift plan	6.31 (13.2)	125.2 (6.1)	58180 (2.6)
PLA* ⊥ rift plan	1.91 (11.1)	88.5 (4.2)	28981 (1.6)
PLA* // rift plan	3.86 (5.1)	76.9 (3.2)	41607 (7.6)

Measurements of the ultrasonic pulse velocity and Schmidt rebound number

Geometry, shape of specimens, testing equipment and testing procedure

As mentioned above, the main goal of using the ultrasonic pulse velocity (UPV) and the hardness number (N) as a non destructive techniques, in the scope of the present work, is the evaluation of the elastic and strength properties of the granites under study. This implies that measurements of these mechanical properties and the NDTs should be made on the same specimens. Thus, before tensile and compressive tests have been undertaken, the ultrasonic pulse velocity was measured in the tensile and compressive specimens, despite their reduced size imposed by technical limitations. According to ASTM D2845 (1995), the ultrasonic pulse velocity is influenced by the shape and size of the specimens. Also due to the limited dimension of the tensile and compression specimens, the Schmidt hammer testing was performed only on the cubic dry specimens, where ultrasonic pulse velocity was also measured, see Figure 1. Since moisture content of the tests specimen is expected to affect the ultrasonic pulse velocity measurements, two extreme moisture conditions were considered: dry and saturated. The ultrasonic pulse measurements were carried out by using the TICO equipment, see Figure 2a.



(a) (b) (c)

Figure 1. Geometry of the distinct specimens (dimensions in mm); (a) cubic specimens; (b) cylindrical specimens; (c) prismatic specimens

Piezoelectric transducers of natural resonance frequency of 54kHz and 150kHz were used in the measurements. The main reason for using distinct frequencies was the small lateral dimension of the tensile specimens, in which only the transducers of natural resonance frequency of 150kHz could be used. The ultrasonic pulse velocity was obtained by direct transmission, where the transmitter and the receiver transducers are located directly opposite each other on parallel surfaces, see Figure 2a. The connection of the transducers to the specimen was improved through the application of an appropriate coupling paste so that the influence of voids between the material and the transducers was reduced. The transit time was recorded for each specimen as the average of three independent readings. The mean values of the ultrasonic pulse velocity were obtained by dividing the path length, *L*, by the average transit time, *t*, of the three measurements.

(a) (b)

Figure 2. Testing equipment; (a) ultrasonic pulse velocity; (b) Schmidt hammer

The determination of the hardness of the granites was carried out according to ASTM D5873 standard recommendations. A mesh of five points was marked in each cubic specimen at both opposite surfaces, so that its location was sufficiently far from the edges and spaced by at least the diameter of the plunger, see Figure 2b. A total of 10 readings was recorded resulting from a single impact at each point by using a e Schmidt hammer type NR, to which an impact energy of 2.207N.m is associated. From the ten single measures that were recorded at each point, the average value was calculated and the readings differing from the average by more than seven units were excluded. For each granite, the Schmidt hammer rebound mean value is obtained by averaging the four specimens that were considered in the testing program. The specimens were clamped in a three-dimensional frame by means of a vertical pre-load so that movements or vibrations could be prevented. The influence of the roughness of the surface in the testing was minimal since the specimens were cut by means of a saw machine. All measurements were carried out in the direction perpendicular to the vertical surface.

Results

The mean values of the ultrasonic pulse velocity (UPV) and the rebound number (N) measured in the cubic specimens and the corresponding coefficients of variation are shown in Table 3. As concerns the results of UPV, the values obtained for different moisture contents, dry and saturated conditions, and for two distinct frequencies of the transducers are included. Notice that the results obtained in the cubic specimens are considered as the reference, given the reduced dimensions of the compressive and tensile specimens.

Table 3. Average values of the ultrasonic pulse velocity and Rebound number. Coefficient of variation is inside brackets (%).

Granite	Dry specimens		Saturated specimens		Dry specimens
	UPV_{54} (m/s)	UPV_{150} (m/s)	UPV_{150} (m/s)	UPV_{54} (m/s)	N (rebound value)
BA	4804 (1.5)	4776 (1.7)	5457 (1.1)	5527 (1.0)	71.4 (0.5)
GA	4593 (1.0)	4556 (1.2)	5359 (1.5)	5423 (1.4)	71.4 (0.7)
GA*	3244 (2.1)	3203 (2.4)	4505 (1.4)	4598 (0.97)	66.3 (0.7)
RM	4104 (4.0)	4037 (4.1)	5266 (1.9)	5369 (1.3)	70.8 (1.3)
MC	4083 (1.1)	3986 (0.85)	5361 (1.1)	5489 (0.89)	71.6 (0.9)
AF ⊥ foliation plan	2256 (4.4)	2186 (6.0)	4163 (1.8)	4276 (2.0)	67.5 (0.9)
AF // foliation	2572 (3.7)	2523 (4.0)	4310 (4.8)	4410 (4.7)	68.6 (0.8)
MDB ⊥ foliation	2488 (1.5)	2426 (1.8)	3888 (2.1)	4041 (1.5)	65.5 (2.4)
MDB // foliation	2241 (2.7)	2181 (2.8)	3805 (5.7)	3994 (4.2)	65.6 (0.6)
MDB* ⊥ foliation	2340 (1.6)	2273 (2.1)	3933 (3.1)	4025 (1.5)	62.6 (2.2)
MDB* // foliation	2341 (0.76)	2301 (0.80)	3894 (2.5)	4029 (2.4)	62.5 (1.8)
PTA ⊥ foliation	3278 (0.53)	3210 (0.26)	4576 (2.8)	4723 (2.4)	68.9 (1.6)
PTA // foliation	3585 (0.35)	3567 (0.5)	4779 (2.4)	4873 (2.0)	69.9 (1.7)
PTA* ⊥ rift plan	1956 (17.8)	1899 (18.5)	3874 (9.0)	4024 (7.2)	64.3 (1.4)
PTA* // rift plan	2545 (12.5)	2495 (12.2)	3907 (7.0)	4032 (5.4)	63.2 (0.8)
PLA ⊥ rift plan	2743 (1.8)	2626 (2.2)	4602 (5.0)	4706 (5.1)	71.4 (1.7)
PLA // rift plan	4162 (2.1)	4037 (1.9)	5268 (2.3)	5421 (2.9)	71.6 (0.8)
PLA* ⊥ rift plan	2650 (2.6)	2543 (3.1)	4294 (6.2)	4522 (5.5)	69.6 (1.1)
PLA* // rift plan	3720 (2.3)	3595 (2.2)	4851 (2.9)	4981 (2.7)	68.3 (1.3)

It can be observed that the values of the ultrasonic pulse velocity obtained for frequencies of 54 and 150kHz differs slightly. If a linear correlation is fitted to the experimental data, the velocity obtained with 150kHz transducers could be obtained from the velocity attained with the transducers of natural frequency of 54kHz by the expression $v_{150} = 0.98v_{54}$ ($r^2 = 1.00$). This means that, for practical purposes, both transducers yield the same results. As regards the ultrasonic pulse velocity obtained when frequencies of 54kHz are considered, the values range from 1956m/s for the granite PTA* to 4805m/s for granite BA. The latter value is close to the typical values pointed out for fresh granites (Kahraman, 2002). In case of saturated specimens, the values are between 3994m/s and 5527m/s, which means that a narrower range of values is observed for this moisture condition. By comparing the average values of ultrasonic pulse velocity obtained in the specimens with distinct shape and size, all granites exhibit higher values in the cubic specimens with respect to the tensile specimens (Vasconcelos, 2005). As far as the rebound number is concerned, the range of variation is relatively narrow and it is between 62.5 for granite MDM and 71.6 for granite MC and PLA. These values are close to the values reported in literature for granites. The Schmidt hammer rebound obtained for granite MDM is close to the value of 62.3 pointed out by Kahraman et al. (2002), also for granite. Concerning the rebound number, it is observed that the values approach the value of 73.4 indicated by Katz et al. (2000). The scattering found reflects the heterogeneity of the material that belongs to the same block. Its low value confirms the reliability of the ultrasonic pulse velocity testing.

Evaluation of the factors that influence the NDT's results

Aiming at obtaining a better insight into the main factors that contribute to the range of variation of the ultrasonic pulse velocity among the granites under study, internal microstructural aspects related to the planar anisotropy, weathering state and moisture content were analyzed.

Weathering state and planar anisotropy

The comparison between the values of the ultrasonic pulse velocity measured in fresh and weathered granites is shown in Figure 3. It is observed that the weathering state influences the velocity of propagation of the ultrasonic waves through the elastic matrix of the material, both for dry and saturated conditions. Apart from the granite MDB and MDB* in the direction parallel to the foliation, higher values of the ultrasonic velocity were obtained in less weathered granites considering dry conditions. Among these, more remarkable differences were recorded in case of granites PLA and PTA. This behavior can be related to the degree of alteration that can be evaluated through the increase on the porosity (indicated inside brackets in Figure 3a due to degradation of the rock forming minerals strength and of the grain boundaries stiffness. The higher amount of voids, pores and unavoidable microfissures reflects the slower propagation of the elastic waves. This difference is less significant in case of saturated specimens since pores, voids and microfissures are filled with water (Vasconcelos, 2005). Assuming that the ultrasonic pulse velocity is highly affected by the microfissuring of the material, it can be a simple and economic tool to evaluate the degree of weathering of granites. In particular, Goodman (1989) refers it as an index of the degree of fissuring. The Schmidt hammer rebound appears also to be a simple nondestructive method able to evaluate the weathering of the granites. By comparing the values between less weathered and weathered granites, it is possible to observe that a lower Schmidt hammer rebound was recorded in weathered granites. The decrease is about 7.1% in granite GA, 4.8% in granite MDB, 8.9% in granite PTA and 3.7% in case of granite PLA. As concerns the detection of planar anisotropy, the Schmidt hammer rebound is not effective since only minor differences were found between the direction parallel and perpendicular to the planar anisotropy in granites AF, PTA, PTA* and PLA*. Under free stress conditions, the velocity anisotropy reflects the internal structure of the material related to the preferential alignment of minerals or cracks (Han et al., 2004). The effect of the structural arrangement of the grains on the velocity of propagation of the ultrasonic waves concerning the planar anisotropy (foliation and quarry planes), can be observed in Figure 3b. The analysis of the results stresses the role of the foliation and rift planes in the velocity of propagation of the ultrasonic waves, mainly in the following granites: AF, PTA, PTA*, PLA and PLA*. The velocity of propagation of the ultrasonic pulse velocity is always higher in the direction parallel to the foliation or rift planes. No significant differences were found in granites MDB and MDB*, as expected.

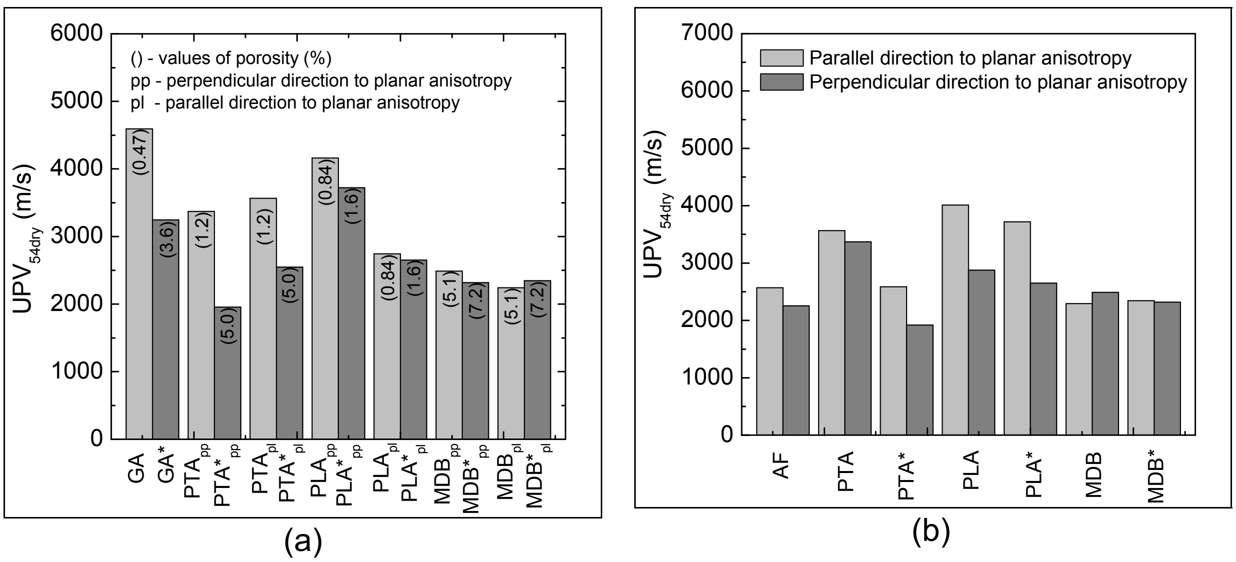


Figure 3. Comparison of the ultrasonic pulse velocity between fresh and weathered granites using 54kHz transducers; (a) dry cubic specimens; (b) saturated cubic specimens

Influence of the moisture content on UPV

In this work, the effect of the water saturation is investigated by comparing the values of the UPV found in dry and saturated specimens. This analysis shows that moisture content has a remarkable influence on the velocity of propagation of the ultrasonic waves. The results indicate a clear tendency for dry specimens to exhibit considerable lower values of the ultrasonic pulse velocity (UPV_{dry}) regarding the ones obtained in saturated specimens (UPV_{sat}). Similar tendency was found by Gupta and Rao (1998) also for granites, as well as for basalts. Figure 4 shows the increase of the ultrasonic pulse velocity measured on saturated specimens with respect to dry specimens defined by the following expression:

$$\Delta UPV_{sat} = \frac{UPV_{sat} - UPV_{dry}}{UPV_{dry}} \qquad \textbf{[1]}$$

In low porosity granites like BA and GA, the difference on the ultrasonic pulse velocity measured in dry and saturated specimens is of 14.1 and 17.4%, whereas in granites RM and MC, the saturated specimens exhibit 30.5 and 35.0% larger values than dry specimens.

Reduction of approximately 30% of the dry velocity was recorded in granite PTA. A lowering of the ultrasonic pulse velocity in dry specimens relatively to saturated specimens of about 20-30% was also reported by Todd and Simmons (1972) in low porosity rocks. Nevertheless, higher deviations were found in high porosity granites such as granites AF, PTA*, MDB and MDB*, where an increase of the ultrasonic pulse velocity in saturated specimens attains a maximum of 105% in granite PTA* in the direction perpendicular to the rift plane. With the exception of granite MDB, the remaining granites exhibit an increase of the ultrasonic pulse velocity in saturated specimens more noticeable in the direction perpendicular to the foliation or rift planes (PTA*, PLA, PLA*, and AF). The direct consequence of this behavior is the reduction of the anisotropy of granites under saturated conditions, which seems to be related to the loss of sensitivity for the ultrasonic pulse velocity test to detect the major discontinuity in continuum medium associated to pre-existing microfissures aligned in the direction parallel to the rift plane (PLA, PLA*, PTA*) or to foliation plane (AF).

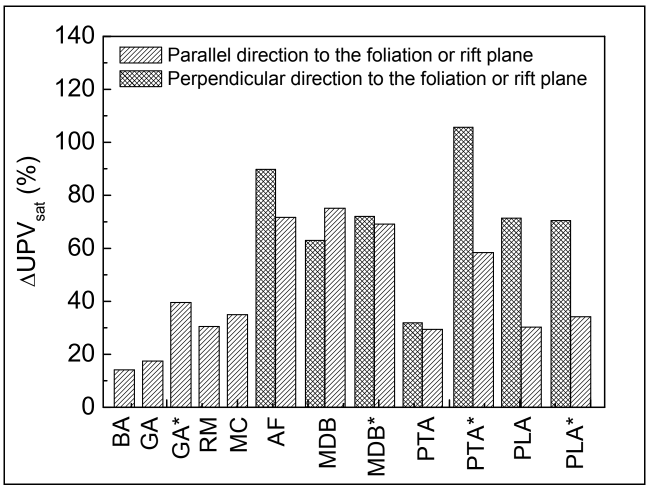


Figure 4. Increase of the UPV in saturated specimens with respect to the dry specimens

Correlations between NDT and mechanical properties

Even if limitations are present in the ultrasonic pulse velocity testing, it can effectively be used as a non destructive technique that allows the definition of the elastic properties like the modulus of elasticity through the ultrasonic velocities measured across isotropic or slightly anisotropic rocks. Such elastic properties can be used further in the evaluation of the performance of built structures. Concerning the assessment of the rock properties by means of simple non destructive techniques, various results revealed the dependence of the mechanical properties, namely the modulus of elasticity and compressive strength, on the ultrasonic pulse velocity (Tuğrul and Zarif, 1999). The present section aims at the attainment of statistical correlations enabling a first estimation of the mechanical properties from the described non destructive techniques. The experimental data collected in the present testing program includes the ultrasonic pulse velocity measured in the cubic, tensile and compressive specimens and the values of the Schmidt hammer rebound obtained in the cubic specimens. The relationships between the velocity of the longitudinal ultrasonic waves and the tensile and compressive strength are displayed in **Figure 5**. A reasonable nonlinear correlation was found between the tensile strength and ultrasonic velocity (r^2 = 0.89), meaning that ultrasonic velocity can provide a reliable preliminary prediction of the tensile strength. High strength granites exhibit high values of velocity. On the other hand, the compressive strength can only be roughly estimated by the linear function shown in **Figure 5**b, whose coefficient of correlation is lowered by the remarkable scattering (r^2 = 0.72). This statistical correlation is, to great extent, affected by the anisotropy of the granites, particularly, of granites PLA and PLA*.

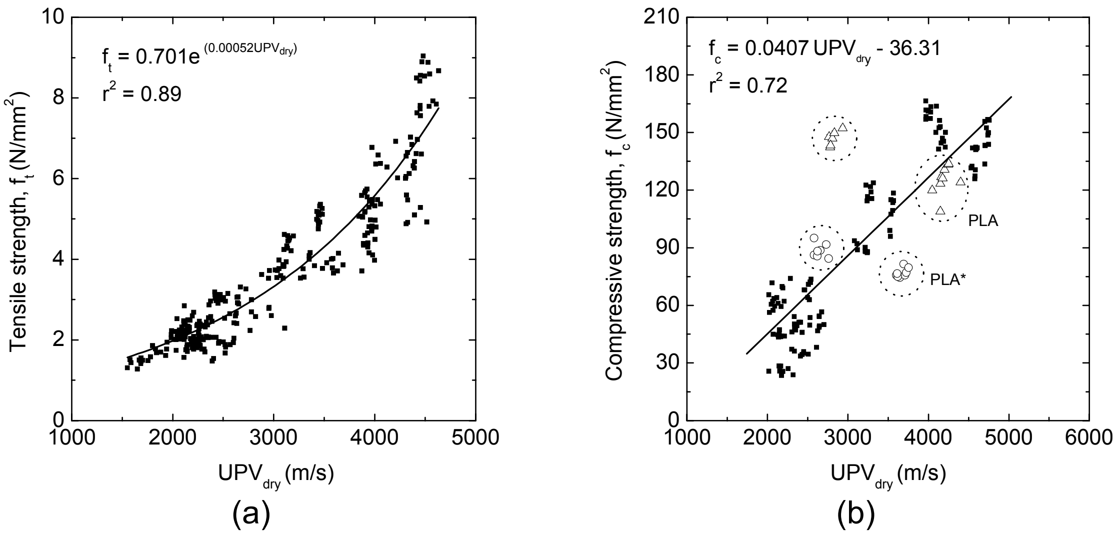
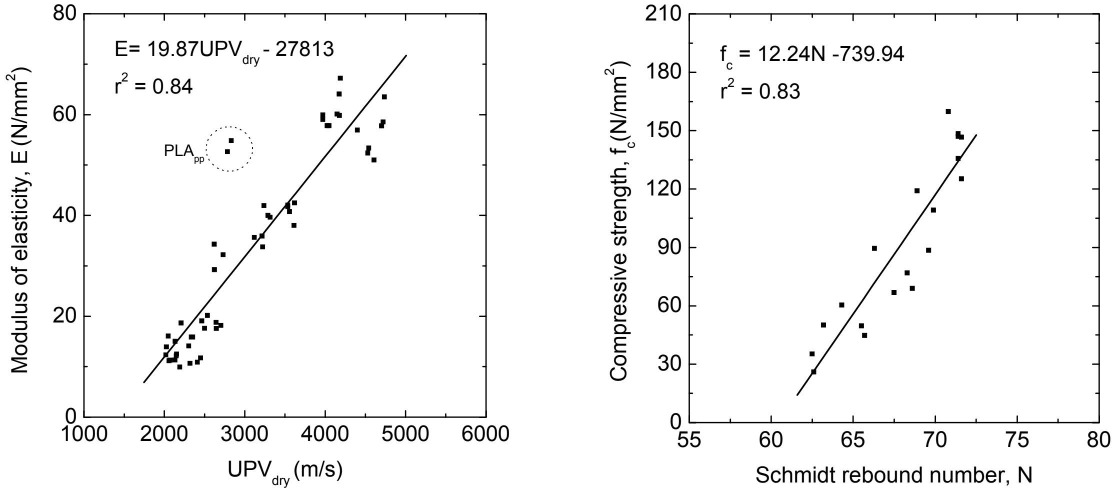


Figure 5. Relation between UPV and granite strength: (a) UPV vs. tensile strength; (b) UPV vs. compressive strength

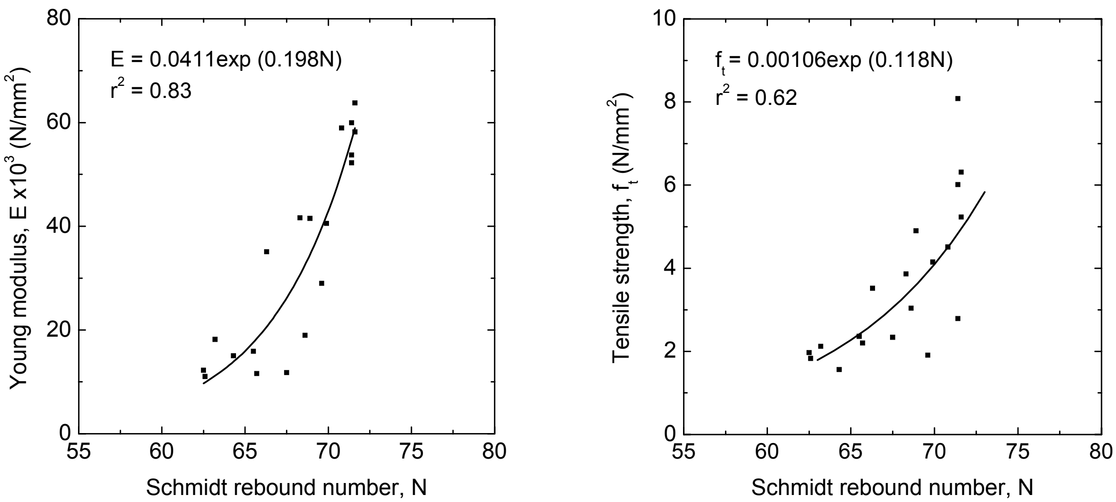
If the values concerning the granites PLA and PLA* were excluded from the experimental data, a linear function $f_c = 0.0446UPV_{dry} - 46.70$ would be found for the relationship between the compressive strength and the ultrasonic pulse velocity with a remarkable higher coefficient of determination (r^2 = 0.85). This indicates that improved correlations shall be attained in case of more isotropic granites. Linear correlations between the compressive strength and the UPV were also pointed out by Tuğrul and Zarif (1999) for granites. The relation between the ultrasonic pulse velocity and the modulus of elasticity is displayed in Figure 6a. The significant linear correlation achieved between the modulus of elasticity and the UPV (r^2= 0.84) confirms the expected relation between both properties. It should be noticed that, theoretically, the propagation velocity depends on the dynamic modulus of elasticity of the continuum medium. The statistical correlations that were achieved between Schmidt hammer rebound number and the strength and elastic properties can be seen in Figure 6b and Figure 7. It is stressed the significant relations that were found between the rebound number and the compressive strength and Young modulus, from which a coefficient of correlation of r^2 = 0.83 was obtained. The compressive strength increases linearly with Schmidt hammer rebound number and the Young modulus can be obtained from the exponential function displayed in Figure 7a. Several other studies have pointed out reliable correlations between the mechanical properties and the Schmidt hammer rebound number for different types of rocks (Dinçer et al., 2004). It should be underlined that ultrasonic testing and the Schmidt hammer rebound have been used as nondestructive techniques of preliminary evaluation of the rock strength in stone building structures (Uchida et al., 1999).

The tensile strength can only be obtained in a roughly way from the Schmidt hammer rebound, as shown by the weak nonlinear correlation between both properties. This can be attributed to the fact that Schmidt hammer rebound is not sensitive to the planar anisotropy.



(a) (b)

Figure 6. Relationship between ultrasonic pulse velocity and the elastic parameters; (a) UPV_{dry} vs. modulus of elasticity; (b) UPV_{dry} vs. Poisson's ratio



(a) (b)

Figure 7. Relationship between Schmidt hammer rebound number and: (a) compressive strength; (b) Young's modulus

Conclusions

In order to obtain a better insight about the adequacy of using simple and economical nondestructive techniques to predict the elastic and strength properties of granite, a set of ultrasonic pulse velocity and Schmidt hammer tests was carried out. Factors like weathering state and moisture content were found to affect remarkably the values of ultrasonic pulse velocity and the Schmidt hammer rebound number. The weathered granites exhibit lower values either for UPV or Schmidt hammer rebound number. Besides, the internal microstructure related to the planar foliation or rift plane leads to remarkable anisotropy of the ultrasonic pulse velocity. However, the anisotropy can be to great extent hidden by water saturation of the specimens. The significant statistical correlations that were established between the ultrasonic pulse velocity and the mechanical properties, like compressive strength and modulus of elasticity, indicate that these parameters can be reasonably estimated by means of this nondestructive method. Similarly, Schmidt hammer rebound number can also be used as an early prediction of the elastic and strength properties as well in the easy and fast evaluation of the weathering state of the granites. It should be underlined that the statistical correlations obtained between UPV and compressive and tensile fracture parameters can be used also for a preliminary evaluation of the fracture behavior of granites.

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