Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014
Porto, Portugal, 30 June - 2 July 2014
A. Cunha, E. Caetano, P. Ribeiro, G. Müller (eds.)
ISSN: 2311-9020; ISBN: 978-972-752-165-4

The influence of joints and stone properties on sonic tests

Luis Miranda[1], Lorenzo Cantini[2], Joao Guedes[3], Luigia Binda[4], Anibal Costa[5]
[1]Faculdade de Engenharia e Tecnologias, Universidade Lusíada, Portugal
[2]Department Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Italy
[3]Department of Civil Engineering, University of Porto, Portugal.
[4]Department of Civil and Environmental Engineering, Politecnico di Milano, Italy
[5]Department of Civil Engineering, University of Aveiro, Portugal
email: barbosamiranda@gmail.com, lorenzo.cantini@polimi.it, joao.guedes@fe.up.pt, luigia.binda@polimi.it, agc@ua.pt

ABSTRACT: sonic testing is a Non-Destructive Technique (NDT) that is used for studying the characteristics of single fairly homogeneous materials and composite structures. If properly applied to, and with the right configurations, this technique allows detecting material variations, cracks and other discontinuities. Since many years, this technology is used on masonry structures, mostly to quantify the compactness of the material through its thickness using direct configurations. The joints, either dry or filled in with mortar, have an important effect on the propagation of the sonic waves, changing the velocities and detecting, indirectly, the influence of these discontinuities on the mechanical characteristics of the masonry. This work presents the results of sonic direct and sonic echo tests conducted on individual stones and triplets with dry and lime mortar joints to assess the reliability of the technique to detect the influence of the joints on the propagation of sonic waves.

KEY WORDS: sonic direct test; sonic echo test; joint effect; stone masonry, P waves.

1 INTRODUCTION

Since the diffusion of diagnostic techniques applied to the assessment of the mechanical and physical characteristics of construction elements that the potentialities of sonic technology have been explored for this effect. The application of acoustic tests to fairly homogeneous materials is nowadays a quite normal procedure, and standards are available for some materials (e.g. concrete [1]).

According to existing standards and studies, the measurements consider mainly the P-wave velocities, i.e., the fastest waves crossing a material that are commonly obtained through direct type tests (emitter and receiver placed on opposite sides of the crossed material). In fact, most of the information that concerns sonic propagation applied to masonry refers to P-wave velocities and to direct testing configurations [2-6].

Notice that stone masonry is a very complex and heterogeneous composite material that follows “artisan” construction procedures. To assess its properties it is necessary to take into account the mechanical and geometrical characteristics of the stone blocks (a natural material) and of the joints between blocks. Moreover, the properties of stone masonry can be quite sensitive to the manner the blocks are positioned one above the other: with or without wedges and (or) mortar, filling completely, or partially the joints surfaces.

In this work, the authors characterize masonry samples made of large granite blocks using sonic echo tests. In particular, it is evaluated the effect of the joints on the propagation of sonic waves through the masonry samples. The results of sonic direct and echo tests are compared for each specimen condition.

2 SONIC WAVES PROPAGATION

Sonic tests consist on the analysis of the propagation of a pack of waves between two points through a vehicle of propagation: a simple or complex material. The first point corresponds to the place where the pack of waves is produced and the second where the waves are received, i.e. to the position of an emitter and a receiver, respectively. Sonic and ultrasonic tests are very similar, but, due to their wave content (lower frequencies than ultrasonic) sonic tests are more efficient for long propagation paths and (or) less homogeneous materials.

Sonic tests have three typical configurations, depending on the relative position of the emitter and the receiver, which usually correspond to an instrumented hammer and an accelerometer, respectively: direct, if emitter and receiver are placed in opposite sides; indirect or surface, if emitter and receiver are on the same side; and semi-direct when emitter and receiver are placed in adjacent sides (see Figure 1).

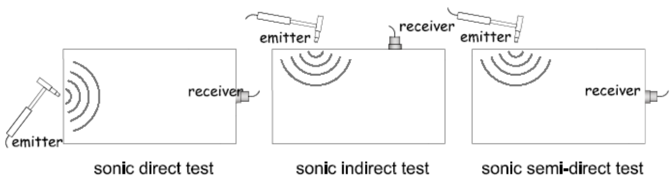

Figure 1, Sonic tests layouts

The choice of a particular configuration is related to the site conditions (users do not have always access to both sides of an onsite wall, for instance) and to the investigation purposes (e.g. detect discontinuities, estimate the material modulus of elasticity, or the deepness of a joint in a multiple leaf wall…). Moreover, depending on the configuration, there are wave types that are more easily assessed than others, namely:

a) Longitudinal or P-waves - mostly detected through direct tests, but also through indirect tests;
b) Shear or S-waves - mostly detected through semi-direct tests and more rarely through direct tests;
c) Surface or R-waves – mostly detected through indirect tests.

Sonic echo test is a technique based on the impact echo test [7], being considered a variation of the indirect test: both the emitter and the receiver are placed one close to the other on the same surface. The results of the experimental campaign here presented show that sonic echo tests give interesting results when applied to masonry specimens with fairly solid sections. However, when using this technique, the results must be analysed in frequency domain and not in time domain, as it happens when applying the sonic "traditional" testing configurations expressed in Figure 1; the reflections caused by the presence of discontinuities, such as joints or material changes, are recognized in the frequency domain. Knowing the waves propagation path length, i.e. the distance between the impact and the reflection surface, *e* (m), and the frequency, *f* (Hz), that corresponds to the successive reflections, it is possible to determine the velocity of the waves on that sample, using Equation 1:

$$V = 2 \times e \times f \tag{1}$$

3 EXPERIMENTATION ON STONE MATERIALS

3.1 *Experimental campaign*

A set of sonic direct and sonic echo tests were performed on individual stones and triplets with both dry and lime mortar joints to assess the reliability of the technique in detecting the influence of the joints on the propagation of sonic waves. The tests were conducted at the Laboratory for Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of Porto University (FEUP).

3.2 *Equipment and data elaboration*

The sonic tests were performed by using a 0.32-kg instrumented hammer with a range of frequencies between 0–1 kHz (flat response). In its upper limit, the hammer can send a pack of frequencies up to 6 kHz, a value much lower than its own resonant frequency, which is greater than 22 kHz. The receivers consist of unidirectional miniature accelerometers with a flat response up to 10 kHz. The accelerometers were coupled to the stone surfaces with grease to promote a good wave transmission [8]. The data acquisition system is a NI-9233 compact module with a resolution of 24 bits and a maximum sampling rate of 50 kHz.

3.3 *Granite specimens*

The tests were performed on four large granite stones referred to as A, B, C and D, with similar characteristics (taken from the same quarry). The specimens consisted of prismatic stones, with dimensions of around $0.85 \times 0.85 \times 0.24$ m^3 each, and having rough surfaces, (see Figure 2). Afterwards, each stone was sawed into three samples (A1, A2, A3; B1, B2, B3; C1, C2, C3; D1, D2, D3) with dimensions of approximately 0.85 x 0.275 x 0.24 m^3, which were superposed to construct four triplets, each one being made of the three samples of the same original stone (see Figure 3).

3.4 *Tests layouts*

The experimental campaign consisted on performing sonic tests on the granite samples by using the acoustic technique applied with two different configurations: direct and echo.

The tests were performed in two steps. First, each specimen A, B, C and D was tested separately using sonic direct tests performed between pairs of opposite lateral faces. Four directions (from L–E, from E–L, from M–H, and from H–M) were considered (see Figure 2). The tests were carried out using three points per face and repeating the measurements once per path, summing a total of 24 tests per specimen, i.e. 96 tests in total. The results allowed assessing the first wave arrival propagating along the stones in its original state.

Afterwards, each specimen was sawed into three samples (see Figure 3) that were individually tested, using direct configurations, to ensure that the same results were obtained before and after de blocks being sawed.

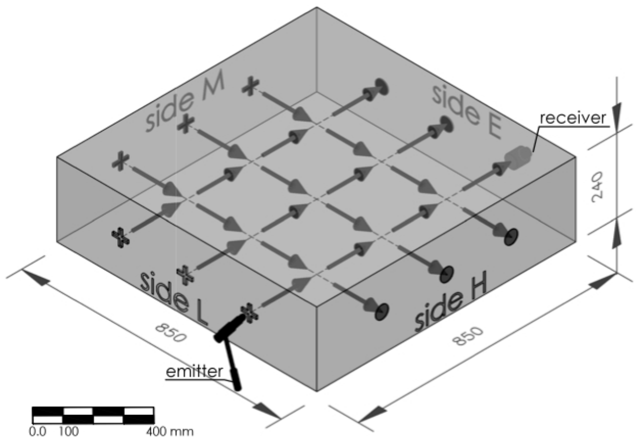

Figure 2, Layout of the granite block and paths of the tests.

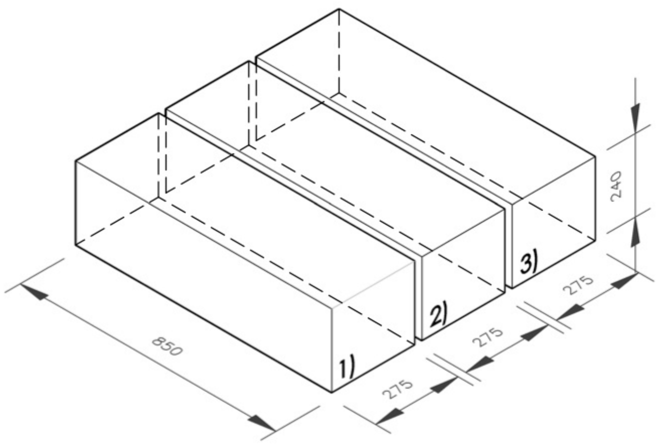

Figure 3, Layout of the sawn samples obtained from blocks A, B, C and D.

After this step, where the stones were tested and analysed alone, the pre-cut original specimens A, B, C and D were reconstituted by assembling the sawn specimens to create four triplets made of regular stones that were placed in the upright position (horizontal bed joint surfaces).

The second step consisted on applying a campaign of sonic direct and sonic echo tests to these triplets, a first time with dry joints, i.e. with the stones superposed without any mortar, and afterwards with the joints filled in with lime mortar, being repeated during the mortar curing process. In particular, it consisted of:

a) sonic direct tests, with the emitter placed at the top and the receiver at the bottom of the triplets, in opposite positions, so that the waves propagation path becomes perpendicular to the bed joints. In this configuration it is supposed that P-waves are the first ones to arrive and those that are detected with higher energy content;
b) sonic echo tests, with the emitter and the receiver placed at the top of the triplets, to study the reflections of the emitted signal.

Erro! A origem da referência não foi encontrada. illustrates the testing layouts applied to the triplets obtained from specimen A. The same procedure was applied to the triplets B, C and D.

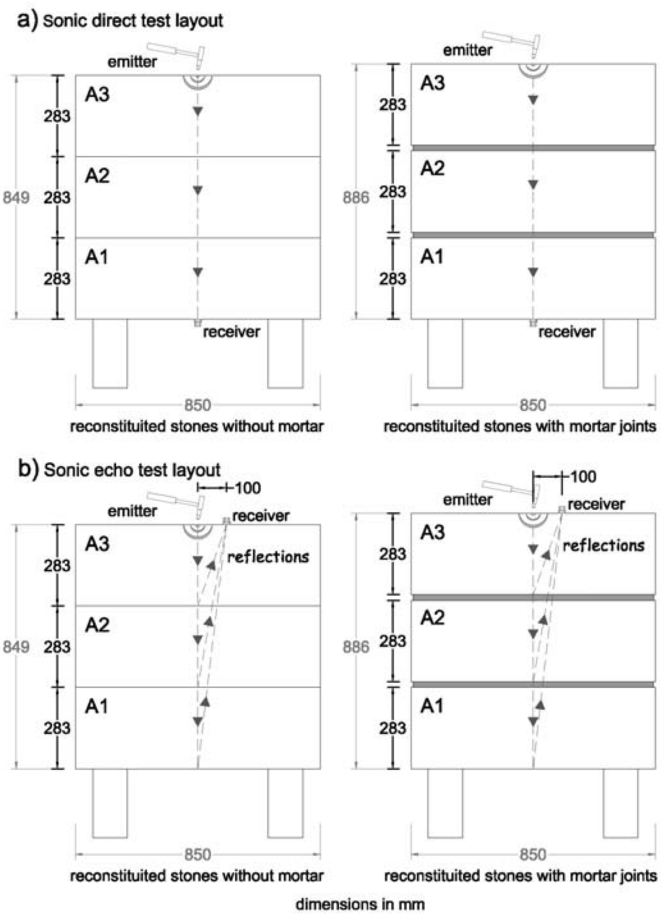

Figure 4, Layouts of the sonic direct and echo tests applied to the (a) dry joints triplets and the (b) mortar joint triplets.

4 RESULTS

4.1 Specimens and sawn samples

The tests carried out in the first step allowed measuring the velocity of propagation of P-waves on the single stones. The analysis of the results of the sonic direct tests gave the following average velocities for each of the four stones (see Table 1).

Table 1. P-waves average velocities measured by sonic direct tests on the specimens A, B, C and D.

Stone Specimens	Velocity (m/s)
A	1890
B	2123
C	1336
D	1996

These results show that, apart from specimen C that seems to be less compact, or stiff, the three other stones are expected to have similar mechanical properties. In fact stone C appeared to be in worst conditions than the other stones and, certainly, having internal defects, which induce lower wave propagation velocities. Notice that stone is a natural material, and the fact that the four specimens come from the same quarry doesn't imply they have equal properties.

The sonic direct and sonic echo tests on the samples obtained from sawing the specimens have shown results that are identical to those of the initial specimens, as it is shown by Table 2. However, the average velocity obtained on stone C samples through the sonic echo tests was around 30% lower than the velocity obtained through the sonic direct tests.

Table 2. P-waves average velocities measured by sonic direct and sonic echo tests on the sawn samples

Swan stone samples	Sonic Direct Velocity (m/s)	Sonic Echo Velocity (m/s)
A (1, 2, 3)	1813	1851
B (1, 2, 3)	2167	2163
C (1, 2, 3)	1321	1048
D (1, 2, 3)	1885	1817

4.2 Triplets with dry joints

The tests carried out on the triplets that represent the reconstituted specimens A, B, C and D with dry joints, provided the following results (see also table 3):

a) sonic direct tests: average velocity around 1000 m/s;
b) sonic echo tests: the presence of dry joints made quite difficult the acquisition of data through this technique. The Fast Fourier Transform (FFT) of the registered accelerations presented several dominant peak frequencies, denoting the existence of a large number of reflections inside the triplets. The adopted criterion to obtain the sonic

echo velocity was to use the frequency associated to the highest FFT peak. The correspondent velocity was achieved through Equation 1 and using the longest vertical path for each triplet, i.e. the total high.

Table 3. P-waves average velocities obtain by sonic direct (with % decrease compared to the stones alone in parenthesis) and sonic echo tests on the triplets with dry joints.

Triplets with dry joints	Sonic Direct Velocity (m/s)	Sonic Echo Velocity (m/s)
A_{1-2-3}	1171 (-35%)	435
B_{1-2-3}	908 (-58%)	1005
C_{1-2-3}	862 (-34%)	-
D_{1-2-3}	1020 (-46%)	932

As it was expected, the FFT of the accelerations obtained from the echo tests on the triplets with dry joints contains lots of important peaks, which indicate lots of intermediate reflections. Figure 5 represents an example of an FFT, obtained on a reconstituted stone (stone A). Nevertheless, in few cases the frequency that corresponds to the first reflection point was accessed. However, it wasn´t found any objective criterion which enables to relate a peak with a certain reflection surface and, consequently, with a certain wave velocity.

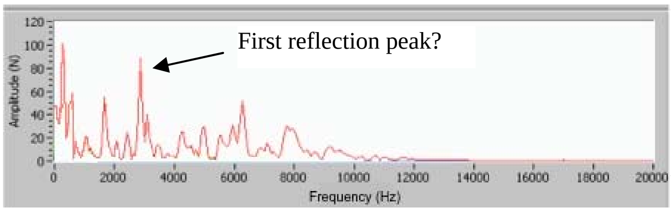

Figure 5, FFT of the received signal on a sonic echo test applied to the triplet A with dry joints.

When compared to the individual results on stones, the results on the triplets show that the existence of dry joints between stones made the velocity decrease, in average, around **40%**. Notice that the stone with the higher average P-wave propagation velocity, stone B, was the one that corresponded to the higher decrease percentage, 58%. On the contrary, the stone with the lower average of the very first arrival (supposed to be the P-wave) stone C, was the one that corresponded to the lower percentage decrease, 34%. In reality, the velocities of the four specimens after being sawed and reassembled were much closer than before, around 1000m/s. This indicates that, apparently, the mechanical properties of stone masonry may be dominated more by the joints than by the stones quality.

4.3 *Triplets with lime mortar joints*

The testing campaign with the previous four triplets was repeated, but now with the reconstituted specimens A, B, C and D with lime mortar joints, allowing going further in the investigation on the propagation of sonic waves. The same set of tests was then applied to the triplets, providing the following results, in particular after 28 days mortar curing:

a) sonic direct tests: average velocity around 1600 m/s;
b) sonic echo tests: 1360 m/s.

In this case, the triplets presented a good contact and continuity between stones, which caused an increase of about 60%, on average, on the velocity obtained by sonic direct tests (see Table 4) when compared to the dry joints triplets.

Table 4. Average velocities obtain from direct tests on the four specimens (with % decrease compared to the stones alone in parenthesis) in different conditions: individual stones, triplets with dry joints and with mortar joints.

Triplets	Sonic Direct Velocity (m/s) (before cutting)	Sonic Direct Velocity (m/s) (Triplets with dry joints)	Sonic Direct Velocity (m/s) (Triplets with mortar joints after 28 days curing)
A_{1-2-3}	1890	1171 (-35%)	1788 (-5%)
B_{1-2-3}	2123	908 (-58%)	1795 (-15%)
C_{1-2-3}	1336	862 (-34%)	1259 (-6%)
D_{1-2-3}	1996	1020 (-46%)	1801 (10%)

Moreover the sonic echo test identified the main reflection surface of each triplet as the bottom surface of the lower stone. In opposition to what happened in the case of dry joints, when the joints were filled in with mortar, just one dominant frequency peak is obtained in the FFT of the received signal when using the sonic echo configuration. For instance, Figure 6, presents the FFT of the accelerations obtained in this configuration for stone A, again. The main frequency peak (718Hz) is the one that corresponds to the multiple reflections on the bottom and top surface of the triplet, i.e. that corresponds to the wave propagation along the total high of the triplet.

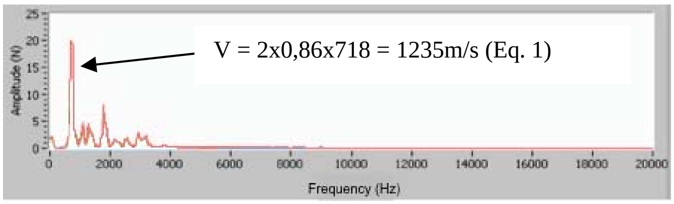

Figure 5, FFT of the received signal of a sonic echo test applied to the triplet A with joints filled in with mortar.

Figure 5 presents the velocities obtained with the specimens before being sawed, after assembling with dry joints and during the hardening process of the mortar joints until the age of 28 days, using sonic direct tests.

The comparison between the dry and mortar joints shows that the mortar was able to restore most of the compactness of the original stones, i.e. before being sawed. Moreover, the wave's propagation velocities determined by the application of the direct sonic tests to the triplets considering different mortar curing times show, with some exceptions, a tendency for the velocity to increase with curing time.

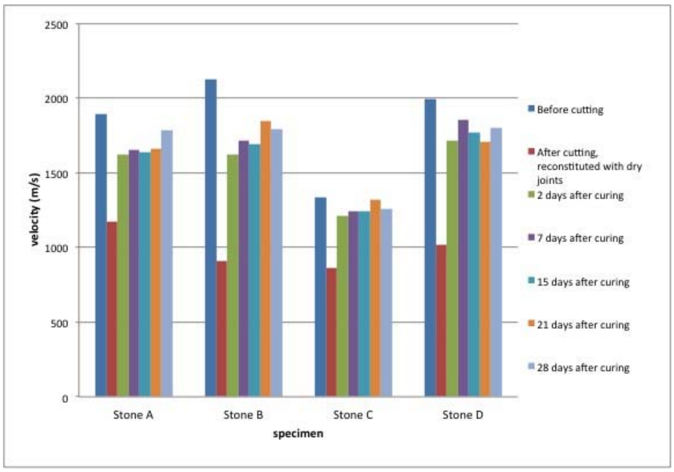

Figure 6, Average wave propagation velocities obtained on the different samples using sonic direct tests.

Although the results of sonic echo tests show the same tendency for the velocity to increase with the mortar curing, as it can be seen in Figure 7, these results indicate a higher velocity decrease from the values of the single stones to the triplets with mortar joints when compared to the results obtained with sonic direct tests. In the case of stone C, the triplets with mortar joints showed an even higher propagation velocity when compared to the single stones, suggesting that the mortar improve the compactness, or the stiffness of the stone.

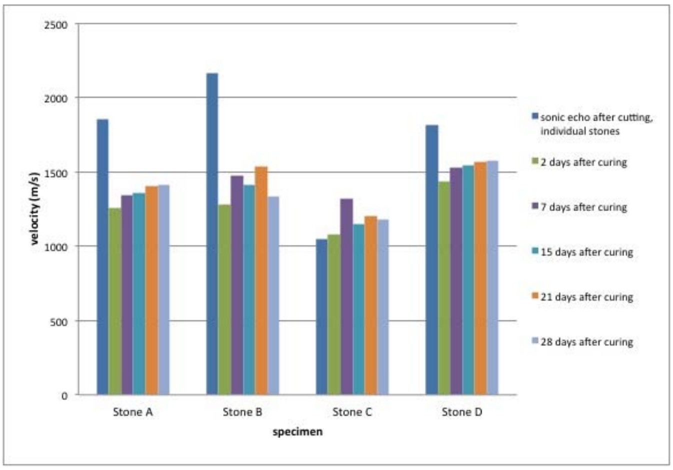

Figure 7, Average wave propagation velocities obtained on the different samples using sonic echo tests.

5 CONCLUSIONS

This paper presents a study on granite samples following a sequence that goes from stones without joints, triplets with dry joints and, finally, triplets with mortar joints, using sonic direct and sonic echo tests. It was verified that sonic echo tests don´t give clear results when performed on samples with dry joints in opposition to what happens with sonic direct tests.

It was noticed a great decrease (about one half) on the sonic propagation velocities (very first arrival) on the triplets with dry joints when compared to the single stones. Notice that also the modulus of elasticity obtained by mechanical tests on samples with identical characteristics, i.e. with dry joints, presents a considerable decay [9].

After filling in the joints with mortar, the velocity increases again, but without reaching the values of the single stone (granite). An exception is made for the case of stone C, which seemed to be in worst physical conditions than the other stones. In this case the echo sonic tests showed a higher propagation velocity for the triplets with mortar when compared to the single stones, suggesting that the mortar improve the compactness, or the stiffness of the stone.

Finally, although the mortar curing process of lime mortar is slow and extends over a long period of time, both, sonic direct and sonic echo tests presented a tendency for the wave propagation velocity to increase with curing time.

REFERENCES

[1] BSI. Testing Concrete - Part 203: Recommendations for measurement of velocity of ultrasonic pulses in concrete. BSI; 1986.
[2] Abbaneo MP, Binda L, Fatticcioni A. Non Destructive Evaluation of bricks-masonry Structures: Calibration of Sonic wave propagation procedures. Int Symposium Non-Destructive Testing in Civil Engineering. Berlim1995. p. 253-60.
[3] Berra M, Binda L, Anti L, Fatticcioni A. Utilisation of sonic tests to evaluate damaged and repaired masonries. USA. Colorado1992. p. 329-38.
[4] Berra M, Binda L, Anti L, Fatticcioni A. Non-destructive evaluation of the efficacy of masonry strengthening by grouting techniques. 9th Int Brick/Block Masonry Conf. Berlin1991. p. 1457-64.
[5] Binda L, Berra M, Baronio G, A. AF. Repair of masonries by injection technique: effectiveness, bond and durability problems. In: ICCROM, editor. Conf on Structural Conservation of Stone Masonry. Atene1989. p. 431-41.
[6] Baronio G, Berra M, Binda L, Fontana A. Effectiveness and durability of masonry strengthening by injection techniques. In: IABSE-AIPC-IVBH, editor. IABSE Symp on Durability of Structures. Lisboa1989. p. 755-60.
[7] Carino NJ. The Impact-echo method: an Overview. Gaithersburg: Building and Fire Research Laboratory - National Institute of Standards and Technology; 2001.
[8] Carino NJ. Handbook on Nondestructive Testing of Concrete. In: Malhotra VM, Carino NJ, editors. Stress wave Propagation Methods. 2nd Edition ed. Barr Harbor Drive: ASTM - International
[9] CRC Press LLC; 2004.
[10] Vasconcelos GdFMd. Experimental investigations on the mechanics of stone masonry: Characterization of granites and behavior of ancient masonry shear walls. Guimarães: Universidade do Minho; 2005.