

Direct Sonic and Ultrasonic Wave Velocity in Masonry under Compressive Stress

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ABSTRACT: Sonic Pulse Velocity Testing and Ultrasonic Testing are widely accepted non-destructive testing techniques that can be used to investigate historical masonry structures. Sonic pulse velocity tests have been used with various set-up configurations to investigate the interior consistency of masonry walls and columns and to assess the effectiveness of grout injection; and ultrasonic tests have been used on masonry materials to estimate their elasticity. The velocity at which a wave passes through the masonry can be influenced by many variables such as the mechanical characteristics of the materials, arrangement of constituents, joints and voids. Due to the irregularity of historical masonry and the large number of variables that can influence the wave velocity, only qualitative results from these tests can be obtained. This paper presents the results of a laboratory test plan aimed at investigating the relationship between wave velocity and the variable of masonry compressive stress. Ultrasonic tests were performed on the constituent materials, granite and mortar blocks, while they were loaded in compression. Then direct sonic tests were performed on small masonry wallets constructed of the same materials while they were loaded in compression. Test results of the masonry are discussed in relation to those of the constituent materials.

Keywords: Sonic Pulse Velocity Testing, Ultrasonic Testing, Non-destructive Testing, Masonry

1 INTRODUCTION

Sonic pulse velocity and ultrasonic non-destructive test methods are common methods employed to determine various characteristics of unreinforced masonry and for such purposes as determining the consistency of the masonry; locations of voids, cracks, and joints; deterioration; success of grout injections; and estimation of the elastic properties of the masonry. These methods are especially useful in investigating historic structures where the masonry must be preserved and destructive tests cannot be used. Historic masonry often has so many irregularities and variable properties that are unknown that the results of the sonic testing also have high variability and low accuracy. Some irregularities of the masonry might be the smoothness of the surface, unknown voids or cracks within the masonry, unknown material properties, irregular and unknown placement of the units, and unknown compressive stresses in the masonry.

This paper presents the results of a study that aimed at determining the effect of compressive stress on directly transmitted sonic and ultrasonic waves in masonry and its constituent materials. If the relationship between the compressive stress and the direct wave velocity is known, the accuracy and confidence of sonic test results can be improved. While further tests should be performed on other types of masonry, the results of this study showed that while the compressive

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stress did have an observable effect on the ultrasonic velocity in the granite; it did not have an observable effect on the direct sonic velocity in the masonry, due to the typology of masonry and variability of the sonic test method.

This paper will give some background into ultrasonic and sonic testing, describe the construction of the test specimens, provide the results of the mechanical characterization of the specimens and constituent materials, present the ultrasonic testing of granite cubes and mortar cubes and the sonic testing of regular masonry wallets constructed of the same granite and mortar, and finally provide some conclusions and ideas for further study and testing.

2 ULTRASONIC AND SONIC TEST BACKGROUND

Sonic testing is the most widely used mechanical wave transmission NDT for investigation of historic masonry. It has been applied to concrete and masonry since 1938 ([1] via [2]). The basic concept of the test is that a mechanical wave pulse is generated in the masonry by hitting the surface with a hammer and a sensor is used on another part of the masonry surface to receive and record the wave (Figure 1). The properties and differences between the transmitted and received waves can provide information about the medium that the wave travelled through.

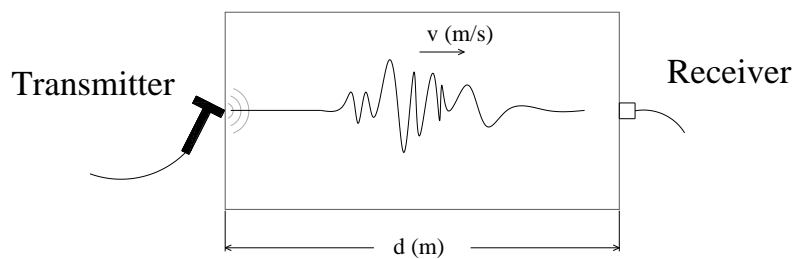


Figure 1. Basic concept of a direct sonic test

The precise velocity, energy and wavelength of each wave are determined by the physical and mechanical properties of the materials through which the wave passes. It follows then that studying the changes in a wave's signal as it passes through a material can provide information about the material's properties. Since wave velocity is the quickest and easiest property to distinguish and it is used most often in sonic testing, it will be the main focus of these studies. The velocity of a wave traveling through a material can be calculated simply using the time that it takes the wave to travel a certain distance, $d(m)$, as shown in Figure 1 and Equation 1.

$$V(m/s) = \frac{d(m)}{t(s)} \quad (1)$$

where: $V(m/s)$ is the velocity of the wave in meters per second, and $t(s)$ is the time in seconds.

Sonic pulse velocity uses mechanical waves in the sonic frequency range. Ultrasonic tests are performed by using higher frequency waves in the ultrasonic range. To produce the higher frequency waves an electronic transmitter, placed on the surface of the masonry, emits an ultrasonic wave that is received by a receptor. In the late 1970s ultrasonics were being developed for the determination of density and dimensions of masonry elements. At this time it was suggested that this test could also be used to detect hidden structural details, location of voids, faults, and cracks [3]. The main focus of the test, as in the other wave tests, was in determining the typology or geometric characteristics of the masonry. One disadvantage to using ultrasonic waves is that the transducers must be directly coupled to the material surface [3]. Small defects or roughness with the surface can affect the results because the short wavelength of the signal prevents it from passing even very small voids between the surface and the receiver. This precision detection is both a blessing and a curse for the test because it means that defects as small as 1-2 inches (2.5-5.0 cm) can be precisely located and sized but only if the material is homogeneous and only has a small number of these anomalies. Heterogeneity of the material, or large voids, result in rapid wave attenuation, prevention of the waves from passing through the material, and poor quality results [4].

Masonry is a complex combination of different materials, sometimes even with various sizes, configurations, and qualities. When waves reach an interface with another material or air, they can be reflected or refracted. Reflected waves remain in the material but propagate in a different direction based on the angle at which they met the material boundary. Refracted waves propagate in the adjacent material but at a different angle and velocity based on the new material properties and the angle at which the wave was introduced to the surface of the new material. Consequently, the sonic pulse velocity test was first used for detecting voids in 1942 ([5] via [2]). Increasing complexity of the masonry typology leads to increasing complexity of both the wave propagation through the material and the analysis of the received wave.

Given this information regarding the influence of voids and material boundaries on wave behavior and velocity, it can be predicted that the homogeneous materials with the least number of voids tested in this study will have the highest wave velocities. The masonry which is composed of both the granite units and mortar joints will have lower wave velocities. In locations where the waves must travel through multiple boundaries between the materials, the more boundaries there are, the lower the calculated average wave velocity. Indeed, studies by Binda, Saisi and Tiraboschi have shown that different material types can be distinguished and that low wave velocity can be correlated with voids and damage [6].

Various studies have been performed in the past to determine if ultrasonic velocities can be correlated with the compressive strength or modulus of elasticity of the material. Penelis et al conducted tests in 1983 and found that there was a low correlation between ultrasonic tests and core compression tests. However, there was a good correlation with the dynamic modulus of elasticity [7]. Schuller, Atkinson, and Noland also reported that there are poor correlations between velocity and compressive strength or other material properties [4]. Little has been done to determine if there is a correlation between the state of compressive stress in the material and the wave velocity.

The focus of this study was on determining if directly transmitted waves are impacted by the compressive stress in the material. Each of the constituent materials was characterized and tested using ultrasonic tests and then the masonry itself was tested.

3 CONSTRUCTION OF SPECIMENS

Small masonry wallets were constructed for the purpose of studying non-destructive tests on masonry loaded in compression in the masonry's elastic range. Three specimens were constructed in accordance with the European Standard for compression testing of masonry specimens [8]. Materials used for the construction were 40 cm by 20 cm by 20 cm granite blocks, cut in accordance with the masonry specimen dimensions, and a low strength cement-lime mortar. The design of the masonry wallets and their construction is shown in Figure 2. The wallets were cured uncovered in the laboratory basement.



Figure 2. Masonry wallet: (a) design showing front and side profiles; and (b) completed construction of the three specimens [dimensions in mm]

Granite cubes were cut to the size of 20 cm by 20 cm by 20 cm, as shown in Figure 3a, for ultrasonic testing while the granite is under compressive loads. Four mortar cubes with dimensions of 15 cm by 15 cm by 15 cm were also cast concurrently with, and using the same mortar as, the construction of the wallets (Figure 3b). The mortar cubes were cured under the same conditions as the wallets and were demolded after 3 weeks.

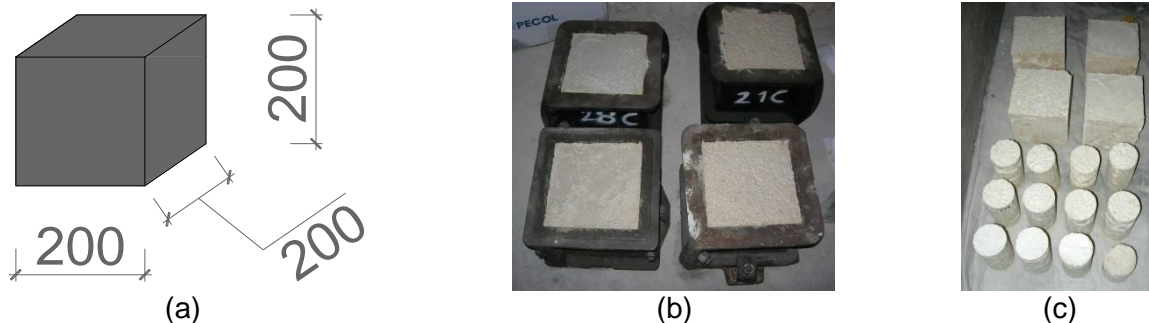


Figure 3. Material specimens: (a) granite cube dimensions [mm]; (b) mortar cubes in molds; and (c) mortar cubes and cylinders curing

To determine the material properties of the granite and mortar used in the masonry wallets, additional cylindrical specimens were made for compression testing. Seven granite cylinders were cored from two granite blocks from the same batch of granite used for the masonry wallets (Figure 4). The cylinders were approximately 73.5 mm in diameter and cut and rectified to approximately 150 mm in height. The cores were dried at 100 °C for 6 hours and then placed in the same curing environment as the masonry wallets. Eight mortar cylinders, labeled R13-R20, were cast concurrently with, and using the same mortar as, the construction of the wallets. The average diameter of the cylinders was approximately 70 mm and the average height approximately 150 mm. The mortar specimens were demolded two weeks after casting and stored in the same conditions as the masonry wallets until testing. Two days before testing the mortar cylinders, thin layer cement caps were added to ensure a smooth transfer of load to both ends of the specimens.

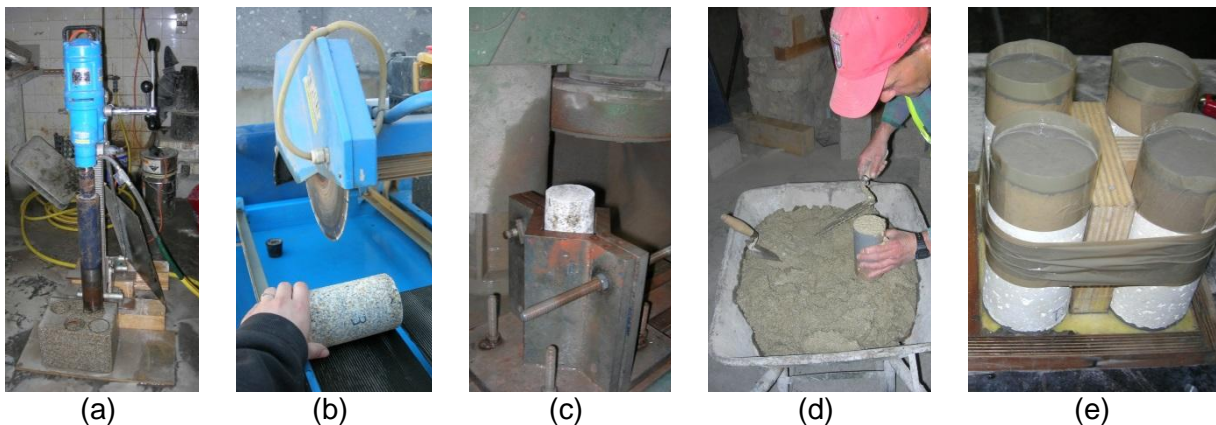


Figure 4. Cylinder preparation: (a) granite coring; (b) sawing granite cores to the correct height; (c) rectifying the granite cylinder ends; (d) casting mortar cylinders; and (e) capping mortar cylinders

4 MECHANICAL CHARACTERIZATION OF THE MATERIALS

4.1. Granite Cylinders

The granite cylinders were tested in uniaxial compression to determine the Young's modulus and compressive strength of the granite. These tests were carried out in a very stiff frame containing a high capacity load cell and closed-loop control system, located at the University of Minho Structural Laboratory (Figure 5b).

The set-up for the Young's Modulus test is shown in (Figure 5a). The Young's Modulus test was performed by applying a 10 kN preload to the specimen and then loading and unloading the specimen three times. An iterative process was used to determine the optimal maximum load and loading rate for the test, however, these variables did not seem to significantly affect the test results. The maximum load ranged from 100 kN to 150 kN and the loading rate ranged from 3 kN/s to 5 kN/s. The results showed an average Young's Modulus of 30 GPa with a standard deviation of 3.14 GPa. This average was taken as the Young's modulus of the granite used in the masonry wallets.

Vertical displacement control and a test speed of 5 $\mu\text{m/s}$ were used for the compression tests. The test set-up and results of the compression to failure test are shown in Figure 5b and c. Due to the variability of the results, a standard deviation of 14 MPa, further testing is planned. For this study, 67.9 MPa was considered the average compressive strength of the granite.

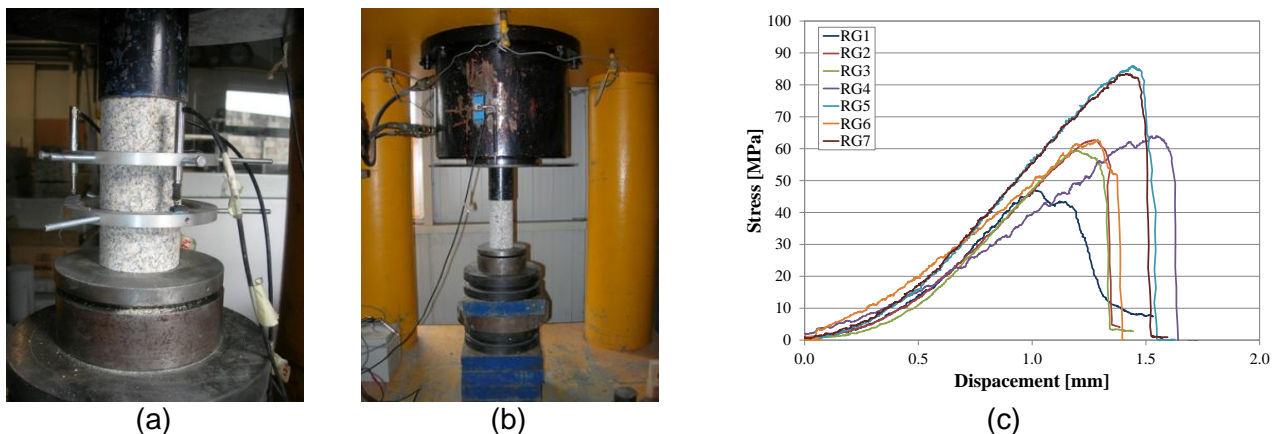


Figure 5. Granite cylinder tests: (a) Young's Modulus test set-up; (b) compression test set-up; and (c) compression test results

4.2. Mortar Cylinders

The mortar cylinders were tested in uniaxial compression to determine the Young's modulus and compressive strength of the mortar. The loading rate was 2 $\mu\text{m/s}$ and was controlled by an external LVDT. The test set-up is shown in Figure 6a and the results of the mortar cylinder compression tests are shown in Figure 6b.

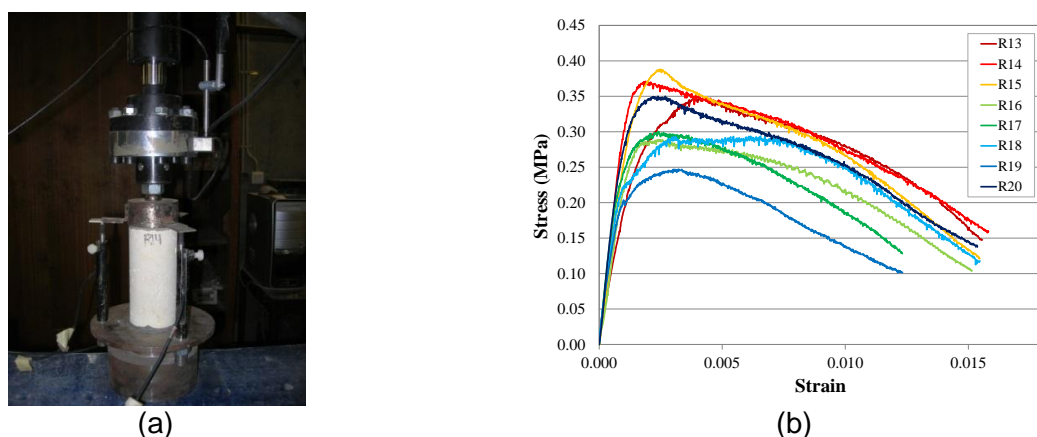


Figure 6. Mortar cylinder compression test: (a) test setup including LVDTs used to measure vertical displacement of the entire specimen for calculation of the Young's Modulus; and (b) results of the eight tests

The average compressive strength was calculated to be approximately 0.32 MPa with a standard deviation of 0.048 MPa. The Young's Modulus was calculated using the portion of the stress strain curve between 5% and 40% of the maximum stress, approximately the linear portion of the graph, for each specimen. The average Young's Modulus was calculated to be 281 MPa with a standard deviation of 57.6 MPa.

4.3. Masonry Wallets

The masonry wallets were tested in compression using a steel frame and a 600 kN load cell to determine their Young's modulus and compressive strength. The positioning of the LVDTs was determined based on British Standard, Methods of test for masonry – Part 1: Determination of compressive strength [8]. The complete test setup is shown in Figure 7a.

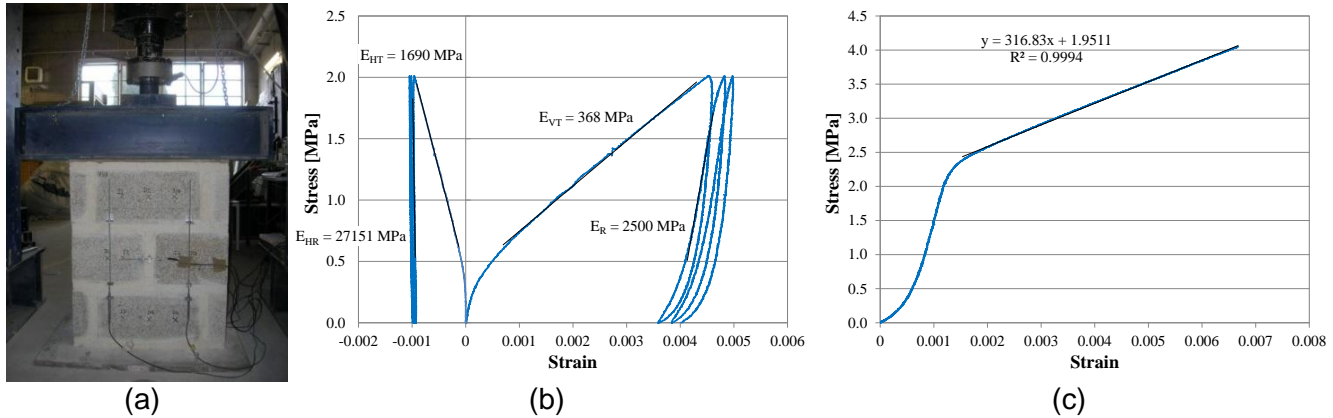


Figure 7. Masonry wallet testing: (a) complete test set-up; (b) RS1 Young's Modulus test results; and (c) RS1 compression test results

Before performing the tests, the compressive strength of the masonry was estimated to be 2.25 MPa using the European Standard 1996-1-1 part 3.6.1.2 [9]. This estimation was used for determining the maximum compressive load for the first Young's Modulus test. Following the first Young's Modulus test, the results of the first compressive test revealed that the compressive strength of the masonry was much higher than the estimated value. The first specimen was tested with a loading rate of 0.1 kN/s and a maximum loading of 60 kN. The second and third specimens were tested with a loading rate of 0.3 kN/s and a maximum loading of 250 kN. The average vertical and horizontal LVDT results for the third specimen tested, the RS1 specimen, are shown in Figure 7b. The tangent loading modulus, E_{VT} , was determined from the linear loading portion of the vertical LVDT data (Figure 7b). Since the RS1 test was the most successful test of the three, the tangent Young's Modulus of the masonry was taken as 368 MPa. The reloading modulus, E_R , was determined to be 2.5 GPa from the first reloading cycle of the vertical LVDT data (Figure 7b). A trend line was also fit to the initial loading of horizontal LVDT data (Figure 7b) and the value of the slope, E_{HT} , displayed. Using the inverse slopes of the trend lines from the initial loading data in the vertical and horizontal directions, the Poisson ratio was calculated to be 0.218.

The compression tests were performed on the masonry wallets following all other tests. The test set-up was the same as for the Young's Modulus tests except that vertical displacement control was used with a loading rate of 5 $\mu\text{m/s}$. For all of the test specimens the maximum compressive strength of the masonry was not reached, with a maximum load of 500 kN applied. The average vertical LVDT results of the compression test on RS1 are shown in Figure 7c along with a fitted trend line for the tangent loading elastic modulus for the stress levels not loaded in the previous tests. The test results indicate that the compressive strength of the masonry is greater than 4.167 MPa.

5 DIRECT ULTRASONIC TESTS

Direct ultrasonic tests were performed on both the granite blocks and mortar blocks while they were under compressive loading. The purpose of these tests was to determine the wave velocity through the materials while they were under different compressive stress states. Ultrasonic equipment was chosen because of the small size of the specimens and since they were made of a single material, either granite or mortar, with no apparent voids or cracks. The short wavelength of the ultrasonic wave allows it to be contained entirely within the small specimen and be measurable with the sensors. The disadvantage of using the ultrasonic equipment is that the equipment automatically

calculates the average wave speed of several induced waves and displays this value. The user has no way of observing the transmitted or received signal and analyzing those signals by hand.

5.1. Granite block test set-up

The granite block tests were conducted in the same frame and with the same load cell as the granite cylinder compression tests as shown in Figure 5b. A schematic of the test setup for the granite block tests is shown in Figure 8a. The load was applied to the specimens vertically in a step-wise procedure. The specimens were loaded at a rate of 4 kN/s. At each load level the load was held constant for 5 minutes while three ultrasonic readings were taken. The three readings were averaged for each load level. The ultrasonic signals were transmitted horizontally through the specimen from the center of the left side to the center of the right side. Vaseline was used to ensure contact between the sensors and the granite surface. The test equipment and set-up are shown in Figure 8b.

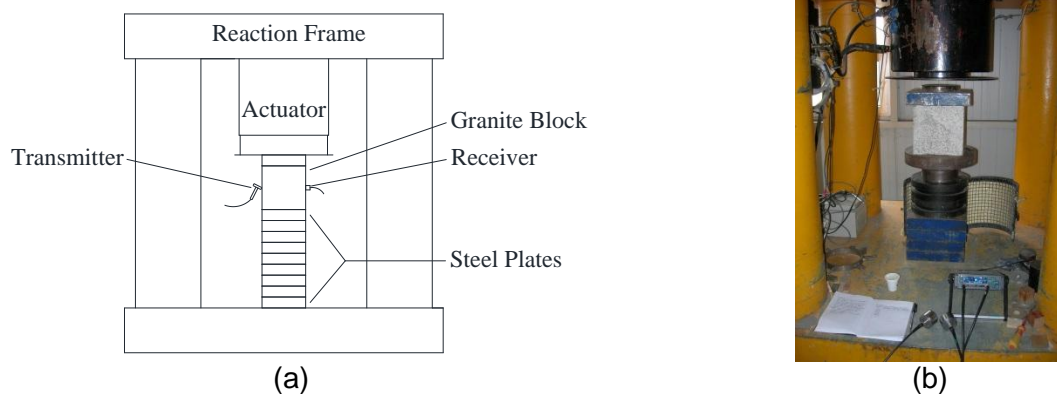


Figure 8. Granite block test setup: (a) schematic; and (b) ultrasonic test equipment

5.2. Granite block results

Two granite block tests were performed on granite cube GCUBE1 and one on GCUBE3. In the first test on GCUBE1 the maximum load was 600 kN and the load steps were 100 kN. Following this test the block was left uncompressed for 48 hours. In the second test on GCUBE1 the maximum load was increased to 1000 kN with load steps of 100 kN. For the GCUBE3 specimen the same load steps were used up to a maximum load of 700 kN. The average standard deviation for the three ultrasonic velocity values taken on each load level was 13 m/s for GCUBE1 and 7 m/s for GCUBE3. The average results are shown in Figure 9. It can be seen in these results that initially as the compressive load or stress in the granite increases, the ultrasonic velocity also increases. As the stress level increases the ultrasonic velocity levels off or even starts to slowly decrease. To confirm these results and determine if the initial trend is linear more tests are necessary. The difference in the initial ultrasonic velocities between the two test specimens can be attributed to the variability of the granite, shown in the results of the cylinder compression tests, the surface roughness of the granite and connection between the sensors and the granite, and any unseen flaws within the material.

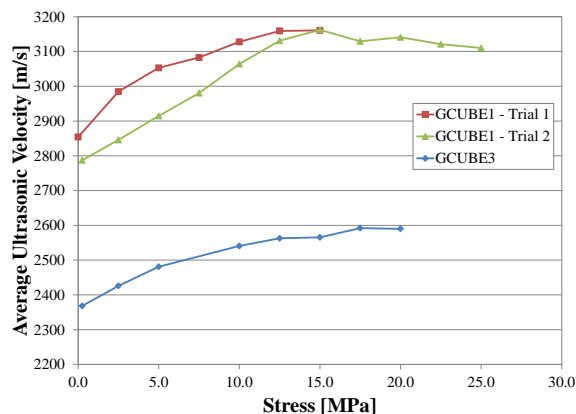


Figure 9. Granite block test results

5.3. Mortar block test set-up

The mortar blocks were tested in the same frame and with the same 50 kN load cell as the mortar cylinders. Figure 10 shows the test setup and the ultrasonic sensors being applied during a test. The load was applied to the specimen vertically in a step-wise procedure. The mortar cubes were compressed at a rate of 5 N/s starting from a preload of 0.3 kN. At each load level the load was held constant for 3 minutes while three ultrasonic readings were taken. The three readings were averaged for each load level. Ultrasonic waves were transmitted horizontally through the specimen from one side to the other as shown in Figure 10. Vaseline was used to ensure contact between the sensors and the mortar surface.



Figure 10. Mortar block test setup including positioning of ultrasonic sensors

5.4. Mortar block results

The four mortar cubes shown in Figure 3b and c were tested as described in the previous section. The cubes were labeled MR1 – MR4. Since the compressive strength of the mortar was determined to be approximately 0.32 MPa, the maximum load was selected to be 3 kN, which is equivalent to a stress level of 0.133 MPa, less than half the compressive strength, ensuring that the specimens would be compressed only in the linear elastic range. Each load step was then set to 0.5 kN. The average standard deviations of the three velocities taken at each of the load levels were 9 m/s, 13 m/s, 7 m/s, and 7 m/s for specimens MR1, MR2, MR3, and MR4, respectively. Test results are shown in Figure 11a.

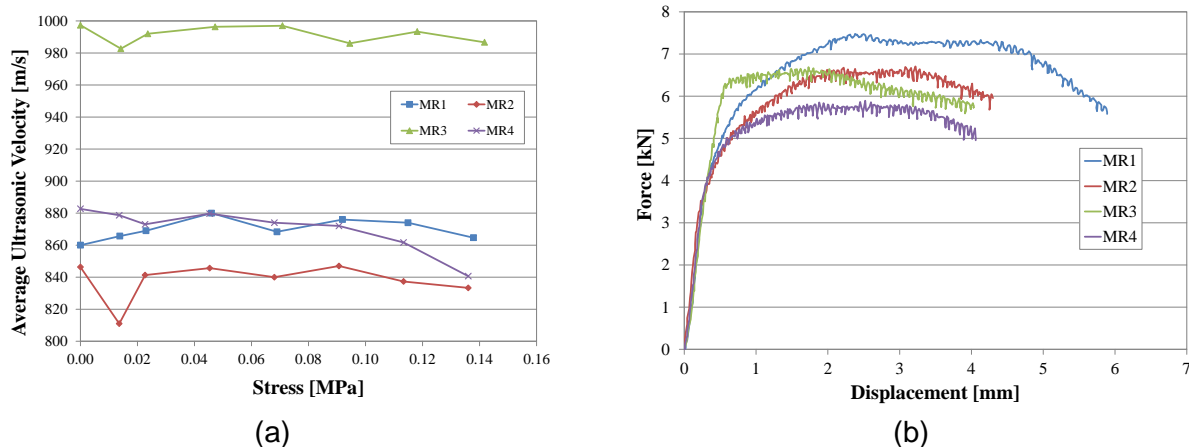


Figure 11. Mortar block test results: (a) Ultrasonic velocity results for mortar cubes under compression; and (b) results of compressive tests on the mortar blocks to failure

The results show that in each of the cubes the sonic waves propagated at different velocities when unstressed. This could be due to the density of the different mortar samples, voids within the material, or contact between the mortar and the sensors. In all cases the sonic velocity varied slightly from its original unstressed value when the specimens were placed under a compressive load. However, only one of the four specimens showed that the increasing stress level had any effect on the sonic velocity. MR4 showed a slight reduction of the sonic velocity as the stress level increased. This could have been the result of the material weakening under the load and microcracks forming. It was found

in compression testing the mortar blocks to failure, following the ultrasonic tests, that block MR4 had the lowest strength, as shown in Figure 11b. In general it can be concluded that for low levels of compressive stress, the compressive stress does not affect or only minimally affects the direct ultrasonic velocity in low strength mortar.

6 DIRECT SONIC TESTS

In the ultrasonic tests on mortar and granite it could be deduced that as the granite and mortar are compressed together, the velocity of the waves will increase as the compressive stress increases due to the relationship between the ultrasonic velocity and the compressive stress in the granite. However, the arrangement of granite blocks and mortar joints in masonry does not necessarily produce the same results as combining the properties of the individual materials. Thus, sonic tests were performed on the three small masonry wallets while they were loaded in compression to determine the effect of compressive stress in masonry on the sonic velocity.

6.1. Masonry Wallets Compression and Sonic Test Set-up

The masonry wallets were tested in the same frame and position as they were tested for the Young's modulus test, as described previously in the paper. Tests were conducted by transmitting a sonic wave through the masonry by hitting the granite with an instrumented hammer and receiving the signal on the opposite side of the specimen with an accelerometer. There were three point combinations to be studied, labelled D5, D6, and D7, corresponding to the top course, middle course, and bottom course of masonry, as shown in Figure 12a and Figure 12b. By measuring the distance between the transmission point and the reception point and calculating the time it took the wave to pass through the masonry by selecting the points in time at which the wave was transmitted and received, the average velocity of each transmitted wave could be determined. For each set of transmission and reception points, ten hammer hits or waves were transmitted through the masonry and recorded. The average of these ten hits was considered the average sonic velocity for that set of points.

The surface of the specimen and connection between the sensors and the material can impact the recorded wave velocity. Thus, measurements were taken in both directions, from left to right and right to left. Since the material is the same between these point combinations it can be assumed that the difference in sonic velocity is due to the surface conditions. The two average values from each point combination for left to right and right to left were averaged to create a single set of data for each point combination.

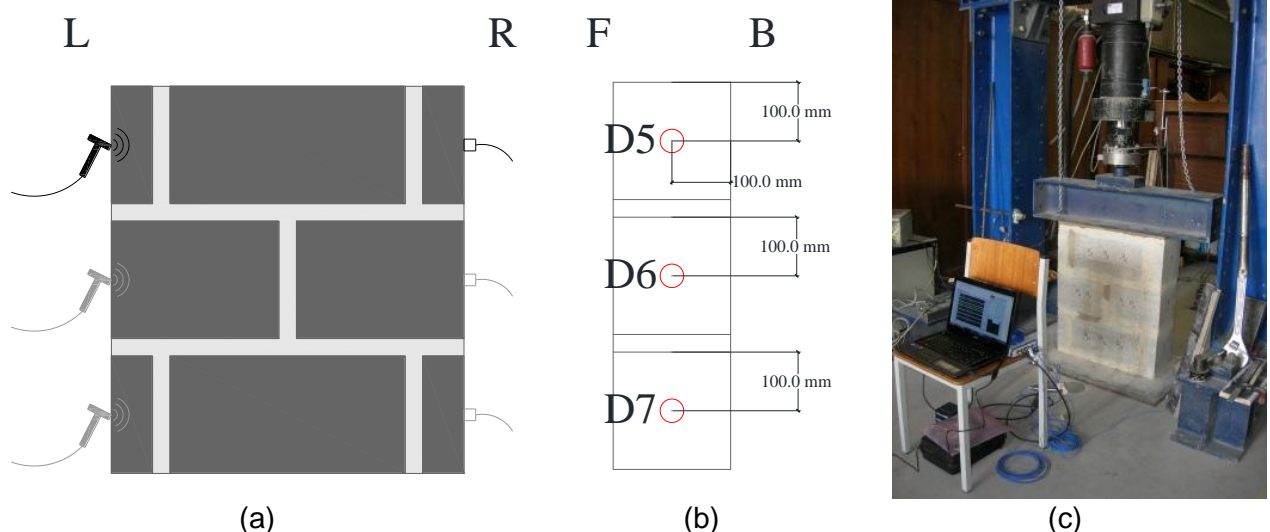


Figure 12. Masonry wallets compression and sonic test setup: (a) direct sonic test transmission and reception points; (b) labels and locations of points; and (c) complete test setup

The sonic tests were performed at various load steps or stress levels. For the first specimen, RS3, a preload was set at 3 kN and the load steps set to 12 kN with a maximum load of 60 kN. This was the same maximum load that was used in the Young's modulus test on this specimen. The loading rate was 0.1 kN/s so that each step was reached after 2 minutes. Each load was held constant for 30 minutes while the sonic tests were conducted.

For specimens RS2 and RS1 the maximum load was increased to 250 kN since it was determined through the compression test of RS3 that the compressive strength of the masonry was greater than 4.167 MPa, equivalent to a 500 kN load. The number of load steps was kept the same so that each load step was 50 kN. The loading rate was increased to 0.3 kN/sec. The RS2 and RS1 tests lasted approximately 3 hours each.

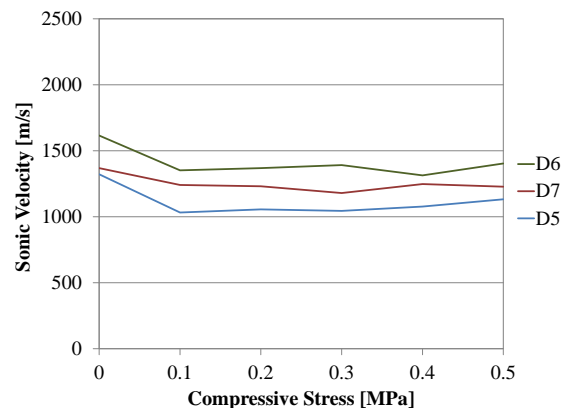
6.2. Results

The data collected from the sonic tests on the three masonry wallets was analyzed using a program developed by the authors which automatically selects the arrival time of the transmitted wave and the received wave and calculates the velocity of the wave, given the input distance between the transmission and reception points. Since there are so many variables that can influence the results of a single hammer hit and resulting wave signal, some signals were not able to be analyzed correctly with the program. These results were checked by hand.

Figure 13a shows the sonic testing being conducted on the first wall, RS3, at the D7 points and Figure 13b shows the results from the tests on the RS3 specimen. The results show that, despite the compressive stress that the masonry is under, the sonic velocity is always greater in the second course of masonry. This is due to the fact that it has only one vertical mortar joint that the wave must pass through, while both the first and third courses have two vertical joints. Each time the wave must pass through a joint, the overall average velocity is reduced because the wave moves slower through the mortar than it does through the granite, as shown in the ultrasonic tests performed through the individual materials.



(a)



(b)

Figure 13. Compression sonic testing of masonry wallet RS3: (a) testing the D7 points; and (b) average results

It can also be seen in the results for the RS3 specimen that the sonic velocity decreases as an initial load is applied. The initial vertical loading causes the horizontal movement of the units outward as shown in the horizontal LVDT data in the Young's Modulus tests (Figure 7). This movement creates cracks or voids in the joints. After the initial drop of the sonic velocity, as the compressive stress is increased there seems to be little influence on the sonic velocity, only the variation due to the variability of sonic testing can be seen. The increasing vertical pressure does not close the initial voids in the joints and the measured sonic velocity remains the same.

It can also be noted that the stress variation in this test was only 0.5 MPa, which is very low. In the ultrasonic tests on mortar cubes, up to 0.14 MPa, there were no changes in the wave velocity. Also, for the corresponding change in compressive stress, 0.5 MPa, there was only an estimated change in

sonic velocity for the granite cubes of about 10 m/s. Just the variation in the sonic test results, due to error and variability of the test, is larger than 10 m/s. Thus, even this small increase could not be discerned in the results of specimen RS3.

The results of the compression and sonic tests on specimens RS2 and RS1 are shown in Figure 14. These results also show that for all stress levels the sonic velocity at the D6 points, through the central masonry course, is higher than for the other two point combinations. This confirms that the number of mortar joints that the wave must pass through impacts the average sonic velocity. These results also show the same drop in sonic velocity from when the masonry is unstressed to when it is compressed.

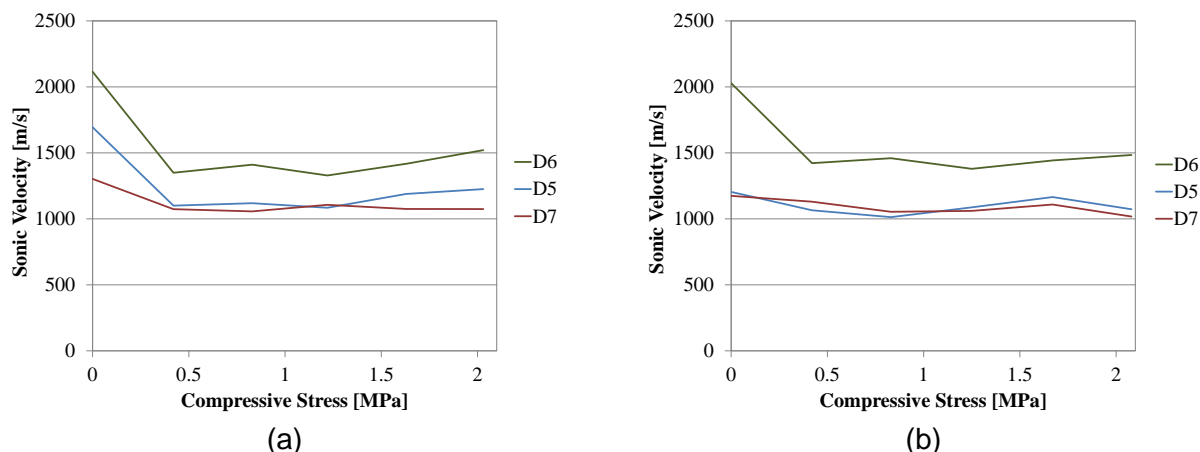


Figure 14. Average results from compression sonic testing of masonry wallets: (a) RS2; and (b) RS1

The results for the RS2 and RS1 specimens show that there could be a slight increase in the sonic velocity for the D6 points as the compressive stress is increased beyond approximately 1.25 MPa. However, this increase is very slight and may only be the random variation of the sonic tests. More tests would need to be conducted to confirm this trend. Additionally, no trends or correlations can be seen for the other points, D5 and D7. Thus, it can be concluded that for regular masonry made of granite and weak mortar, compressive stresses after initial vertical loading and up to approximately 2 MPa do not significantly affect direct sonic test results.

7 CONCLUSIONS

In conclusion, compressive stresses up to 2 MPa did not significantly affect direct sonic wave velocity through single leaf regular masonry constructed of granite and weak cement-lime mortar. However, this study did show that wave velocity did increase in the granite as compressive stress increases. This increase can be seen in the more precise ultrasonic tests conducted but cannot be discerned in the more variable sonic tests. No trends were seen in the ultrasonic tests performed only on the mortar. However, since the mortar strength was so low, this limited the compressive stress which could be applied. Future work could be done to test the effect of compressive stress on other sonic test configurations, such as semi-direct and indirect. Sonic tests on masonry specimens with irregular typologies and with mortars of different compositions and strengths could also be studied. It can be said that for this type of masonry, direct sonic test results do not depend on the compressive stress in the masonry and thus can be used to determine other characteristics of the masonry such as location of voids, joints and deterioration.

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