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Mechanical characterization of concrete block used infill masonry panels

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# MECHANICAL CHARACTERIZATION OF CONCRETE BLOCK USED ON INFILL MASONRY PANELS

## INTRODUCTION

Recent earthquakes have warned the scientific community that the old structures are not the only ones to have high seismic vulnerability, the reinforced concrete structures have shown also insufficient behavior, particularly conditioned by the presence of the infill masonry walls in their structural response because normally they are not taken into account in the structural design for being considered non-structural elements [1-6].

This building system, which includes ceramic brick masonry or concrete block infill walls, confined or not by the reinforced concrete elements, still lacks adequate characterization so that a correct evaluation of its seismic performance is possible in terms of its in plane and out of plane behavior [7-9]. Although the infill walls are mostly considered non-structural elements, recent earthquakes showed that they play a decisive role in the structural response of a building, according to their design and arrangement in height and/or plan [10-13].

Mechanical characterization tests available throughout the literature are quite scarce, and complete characterization of the different masonry panels with the different testing methodologies are not usually performed. These information is very useful to calibration of the numerical models and to help the structural designs during the design process of new structures considering the infill mechanical properties. Different masonry units and mortars can result in large results variations.

The current work presents results of experimental tests of mechanical characterization of masonry wallets composed of concrete blocks produced on the Archipelago, in Portugal. It were performed material characterization tests of concrete blocks and the mortar used, and four types of mechanical characterization tests for this type of masonry walls, in particular compressive strength tests, tensile strength tests (diagonal) and shear and flexural tests (parallel and perpendicular to the vertical and settlement joints). The manuscript reports some experimental results of the blocks and specimens, restricted to standardized tests in blocks, mortar and small walls, under simple compression, diagonal compression and flexural according to a parallel plan to the settlement joints and according to a perpendicular plan to the settlement joints. More detailed information about all tests can be found in [14].

## MECHANICAL CHARACTERIZATION OF ELEMENTS OF CONCRETE BLOCK MASONRY

One experimental campaign was conducted with the aim of mechanically characterize concrete blocks masonry samples. For this study were performed compression tests on concrete blocks and flexural and compression tests in mortar specimens. It was also carried out several experimental tests in full scale masonry concrete wallets, according to the constructive methodology used, of which here are referred the compressive strength tests, tensile diagonal shear and flexural strength tests according to a parallel and a perpendicular plan to the settlement joints. Throughout this section will be presented information regarding the material and mechanical tests, namely information about experimental test setup, instrumentation and main results.

### MATERIALS AND CONSTRUCTIVE ASPECTS

Blocks Characterization Tests

Compressive strength tests were performed to determine physical and mechanical properties of the constituent blocks of the masonry samples. The concrete blocks from this island are typically composed with lapilli, and the nominal geometric dimensions are $400 \times 270 \times 200mm^3$ (length, thickness and height), with $400 \times 270mm^2$ in the settlement face.

The compressive strength of the masonry units was determined according to the European standard NP EN 772-1 [15]. Following the principles presented in the test standard, it was calculated the standard compression resistance, from the gross and effective areas of each block, being the percentage of effective area of 62.0%. During the construction process of the masonry wallets it was used concrete blocks from two different lots. Samples were tested for each lot in order to evaluate parameters such as compressive strength, elasticity modulus. From the results it was obtained for the concrete blocks from lot 1 a mean compressive strength of 3.1 $N/mm^2$ (Coefficient of variation (COV) of 22.3% and standard deviation (SD) of 0.7$N/mm^2$) and elasticity modulus of 519.1$N/mm^2$. Regarding the ones from the lot 2 a mean compressive strength of 4.3$N/mm^2$ (COV=16.5% and SD=0.7$N/mm^2$) and elasticity modulus of 1019.8$N/mm^2$.

From the compressive strength tests it can be observed that the mean compressive strength of the concrete blocks from lot 2 was almost 40% higher and the elasticity modulus 96% higher. This is due to the inexistent quality control during the construction process of the blocks. Vertical cracks and spalling were observed during the tests, in particular in the blocks corners. For the construction of the masonry wallets that were subjected to the compression strength test and diagonal tensile shear test it was used concrete blocks of lot 1, being the remaining of lot 2 used for the flexural strength tests.

Mortar Characterization Tests

The mortar used in the construction of the specimens for testing were prepared with a cement used in the islands of the central group: CEM II / A-L 32.5 N. In all the specimens constructed for the different tests it was used mortar with this type of cement.

All the mortars were produced with 1:4 trace with medium granulometry sand, similar to the one used in the Azores Archipelago. Various mortar specimens were tested to determine flexural and compression strength tests according to EN 1015-11 standard [16]. Four different groups of mortar specimens were divided according to their use in the constructive process of masonry wallets for each type of test.

Four groups of mortar specimens were tested (Table 1). The first group of mortar specimens were collected during the construction process of the masonry wallets that will be subjected to compression strength tests. For these mortar specimens it was obtained a flexural mean strength of 3.8N/mm$^2$ (COV= 17.5% and SD=0.7N/mm$^2$) and a mean compressive strength of 16.1N/mm$^2$ (COV=2.9% and SD=0.5N/mm$^2$). The second group of mortar specimens were collected during the construction process of the masonry wallets that will be subjected to compression strength tests. From these samples it was obtained a flexural mean strength of 4.0N/mm$^2$ (COV= 44.8% and SD=1.8N/mm$^2$) and a mean compressive strength of 17.1N/mm$^2$ (COV=13.3% and SD=2.3N/mm$^2$). The third group of mortar specimens were destined for the wallets that were to be tested to obtain the flexural strength in a plan parallel to the settlement joints. From these samples it was obtained a flexural mean strength of 5.1N/mm$^2$ (COV= 18.9% and SD=1.0N/mm$^2$) and a mean compressive strength of 15.5N/mm$^2$ (COV=20.1% and SD=3.1N/mm$^2$). The fourth and last group of mortar specimens were destined for the wallets that will be tested to obtain the flexural strength according to a plan perpendicular to the settlement joints. From these samples it was obtained it was obtained a flexural mean strength of 4.6N/mm$^2$ (COV= 8.2% and SD=0.4N/mm$^2$) and a mean compressive strength of 12.9N/mm$^2$ (COV=5.4% and SD=0.7N/mm$^2$).

Table 1: Material test results obtained for Mortar specimens.

| Group | Mortar used in: | Mechanical properties | Statistical Parameter | Unit | Result |
|---|---|---|---|---|---|
| 1 | Compression strength test masonry wallets | Flexural strength | Mean | ($N/mm^2$) | <u>*3,8*</u> |
| | | | S.D. | ($N/mm^2$) | 0,7 |
| | | | C.O.V. | (%) | 17,5 |
| | | Compression strength | Mean | ($N/mm^2$) | <u>***16,1***</u> |
| | | | S.D. | ($N/mm^2$) | 0,5 |
| | | | C.O.V. | (%) | 2,9 |
| 2 | Diagonal tensile strength tests | Flexural strength | Mean | ($N/mm^2$) | <u>*4,0*</u> |
| | | | S.D. | ($N/mm^2$) | 1,8 |
| | | | C.O.V. | (%) | 44,8 |
| | | Compression strength | Mean | ($N/mm^2$) | <u>*17,1*</u> |
| | | | S.D. | ($N/mm^2$) | 2,3 |
| | | | C.O.V. | (%) | 13,3 |
| 3 | Flexural strength tests according to a parallel settlement joints plan | Flexural strength | Mean | ($N/mm^2$) | <u>*5,1*</u> |
| | | | S.D. | ($N/mm^2$) | 1,0 |
| | | | C.O.V. | (%) | 18,9 |
| | | Compression strength | Mean | ($N/mm^2$) | <u>*15,5*</u> |
| | | | S.D. | ($N/mm^2$) | 3,1 |
| | | | C.O.V. | (%) | 20,1 |
| 4 | Flexural strength tests according to a perpendicular to the settlement joints plan | Flexural strength | Mean | ($N/mm^2$) | <u>*4,6*</u> |
| | | | S.D. | ($N/mm^2$) | 0,4 |
| | | | C.O.V. | (%) | 8,2 |
| | | Compression strength | Mean | ($N/mm^2$) | <u>*12,9*</u> |
| | | | S.D. | ($N/mm^2$) | 0,7 |
| | | | S.O.V. | (%) | 5,4 |

S.D. - Standard deviation

C.O.V. – Coefficient of variation

From the results it is apparent that the mortar used to build the specimens for the diagonal compression test has a high COV associated with the average flexural strength, resulting in two of the specimens tested with resistance much lower than the others, probably due to the presence of small holes at the spacemen surface (poor workmanship) which affected the specimens tensile strength.

## Compression Strength Tests on Concrete of Block Masonry Specimens

The compressive strength specimens tests were performed in the samples, according to the NP EN 1052-1 [17], adopting the dimensions $600 \times 1000 \times 270 mm^3$ (length x height x thickness) illustrated in Figure 1.

The test setup is composed by a hydraulic actuator with the maximum capacity of 1500 kN ($\pm 150\ mm$ stroke). This actuator was coupled with a hinge device. To accommodate possible instabilities during the application between the top of the specimen and the hinge device was used a highly rigid steel profile to distribute the loading uniformly to the wallet.

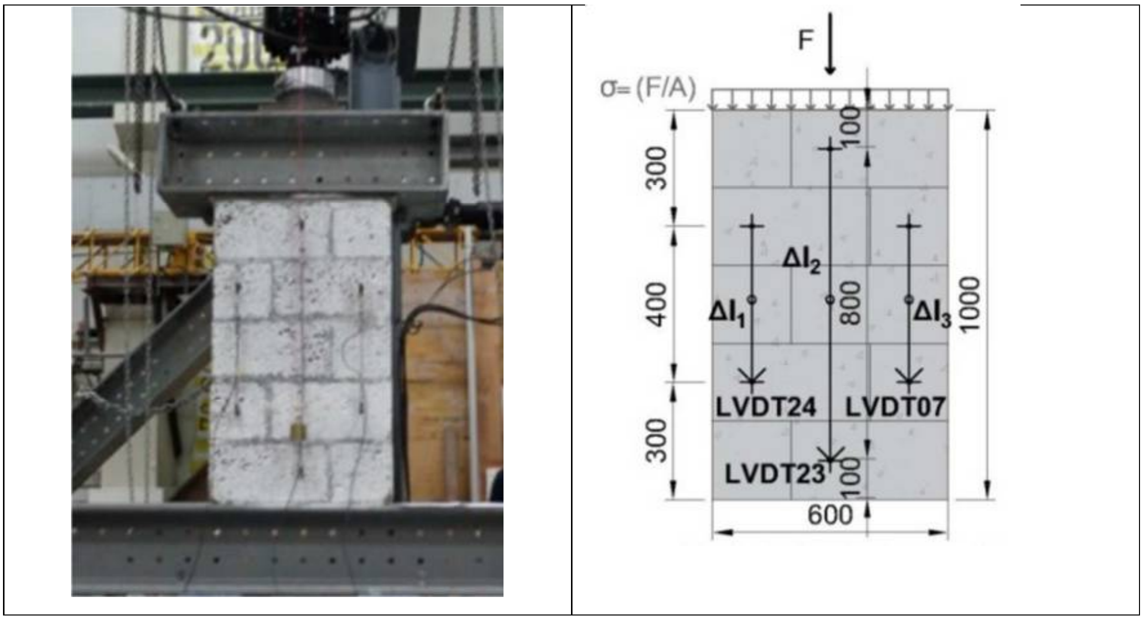



Figure 1: Configuration of the simple compression of masonry specimens: (a) Experimental setup; (b) Setup scheme.

The instrumentation adopted for the compression strength it was used in simple compression tests used LVDT transducers (Linear Variable Displacement Transducer) to record the evolution of vertical displacements in the samples. Following the testing standard NP EN 1052-1 [17] four LVDT's were placed on the front and back faces of the specimens (near the lateral edges), adding a central vertical LVDT on each side, to have results redundancy against those provided in the standard.

According to the NP EN 1052-1 [17], the compression resistance, $f_i$, and the elastic modulus, $E_i$, of each sample can be determined through the following equations:

$$f_i = F_{i,max}/A_i \ (N/mm^2)$$ Equation (1)

$$E_i = \frac{F_{i,max}}{3\varepsilon_i A_i} (N/mm^2)$$ Equation (2)

$$\varepsilon_i = \sum_{j=1}^{4} \varepsilon_j /4 = (\varepsilon_1 + \varepsilon_2 + \varepsilon_3 + \varepsilon_4)/4$$ Equation (3)

$$\varepsilon_j = d_j/h_{dj}$$ Equation (4)

Where $F_{i,máx}$ is the maximum load applied, $A_i$ the loaded area of the $i$ sample, $d_j$ the displacement measured by the $j$ transducer (of the four placed in the lateral position) for a third of the maximum strength, $h_{d,j}$, the length between the two points fixing the same transducer, $\varepsilon_j$, and the arithmetic mean of the extensions obtained in the transducers, $\varepsilon_i$. For each specimen it was calculated the compression stresses and corresponding relative displacement measured during the test, thus allowing to trace the stress-strain curve, from which is obtained the elastic modulus (secant), $E_i$, of each specimen, for a stress equal to $1/3$ of the maximum stresses reached and corresponding average extension obtained from the four lateral measures of the LVDTs. It was also found the characteristic compressive strength, $F_k$, of the masonry specimens using Equation (5):

$$f_k \leq f/1{,}2 \wedge f_k \leq f_{i,min} \; (N/mm^2)$$ Equation (5)

Where $f$ is the average compressive strength of all the masonry specimens and $F_{i,min}$ is the minimum value of the compressive strength of the masonry specimens. Table 2 shows the results obtained for compressive strength of the three specimens, and in Figure 7 is illustrated the corresponding compressive stress-strain curve obtained during the tests.

For the compression strength tests of the three specimens tested it was obtained an average value of $2{,}4N/mm^2$ with a coefficient of variation of $15{,}5\%$, which is acceptable and consistent with the obtained value range (2,01 to $2{,}74N/mm^2$), due to inevitable slight differences in the performance of the test specimens; the corresponding characteristic value is $2{,}0N/mm^2$.

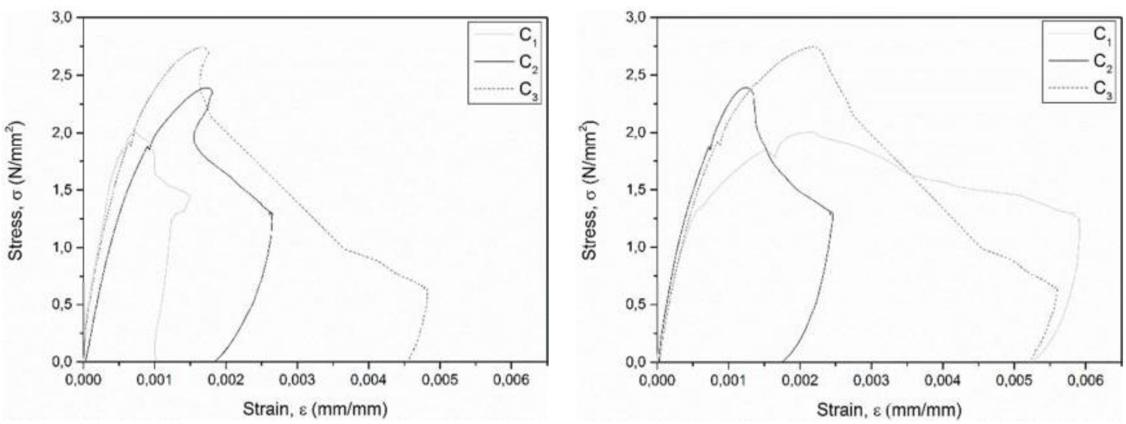
Table 2 includes the values of the modulus of compression $E_i$ calculated for each of the 3 test specimens of this standard testing procedure (NP EN 1052-1) ranging from $3375{,}8$ to $6810{,}2\ N/mm^2$, with average value of $5432{,}1N/mm^2$ and coefficient of variation of $34{,}4\%$. The higher dispersion is associated with the lower accuracy obtained for all the displacements recorded by all LVDTs.

Additionally, Table 2 also presents the elastic modulus calculated from the extents measured along the central axis of the specimens (even though this is not provided in the standard), which corresponds to a range from $3724{,}4$ to $4523{,}5N/mm^2$ with a mean value of $4138{,}2N/mm^2$ and $9{,}7\%$ coefficient of variation, showing greater deformability than that obtained according to the standard and in line with the largest number of horizontal joints involved in the deformation.

It is emphasized that were obtained very high values of secant elastic modulus of the samples 1 and 3, using the side LVDTs (second standard), that was studied in more detail in [4] and concluded that existed deficiencies in the initial readings of the LVDTs placed on the side of the specimens in these tests. The results obtained by the LVDTs placed on the test specimen in the vertical axis are more consistent, as shown in the stress-strain curves plotted in Figure 2.

Table 2: Results obtained in the compression strength tests of masonry wallets.

| **Specimen** | **$F_{max}$ (N)** | **$f_i$ (N/mm$^2$)** | **E (N/mm$^2$)** | **$E_{linear\ regression}$ (N/mm$^2$)** | **$E_{central}$ (N/mm$^2$)** | **$E_{central,\ linear\ regression}$ (N/mm$^2$)** |
|---|---|---|---|---|---|---|
| $C_1$ | 324853,52 | 2,01 | 6810,2 | 5349 | 3724,4 | 2822,9 |
| $C_2$ | 387500,00 | 2,39 | 3375,8 | 3062,9 | 4523,5 | 3629,5 |
| $C_3$ | 444616,70 | 2,74 | 6110,4 | 3155 | 4166,6 | 3155,0 |
| **Mean** | **385656,7** | ***2,4*** | **5432,1** | **3855,6** | **4138,2** | **3610,5** |
| **S.D. (N/mm$^2$)** | 59902,9 | 0,4 | 1814,9 | 1294,1 | 400,3 | 426,7 |
| **C.O.V. (%)** | 15,5 | 15,5 | 33,4 | 33,6 | 9,7 | 11,8 |




(a) (b)

Figure 2: (a) Compressive stress-strain curve according to the standard; (b) Compressive stress-strain curve for the central strains.

Regarding the cracking pattern it can be observed that the three specimens showed similar cracking pattern, the principal variations occurred especially by the instant of appearance of the cracks, existing some specimens with almost instantaneous breakage while others with slow-breaking and gradual opening of slits. It should be noted that the cracking shown in the front and back faces of the specimen was similar and that the slits in the sides of the test pieces were visible, especially along the specimen height.

Analyzing the final damage of all the specimens, it could be concluded that most cracks occurred in the areas of the blocks where there is a combination of two or three openings in the same direction. The lateral cracks occur mainly in the zone in which the masonry units have shorter length.

### DIAGONAL COMPRESSION TENSILE STRENGTH TESTS (SHEAR)

This test was prepared and conducted in accordance with ASTM E 519-02 Standard Method for Diagonal Tensile (Shear) in Masonry Assemblages [18], satisfying all the requirements for the construction and curing of the specimens referred to in the standard.

The test consists on the application of a compression load, continuously, on a square sample, rotated 45° from the horizontal (parallel to the specimen diagonal), until it reaches the breakdown, measuring the deformations undergone by the sample throughout the process allowing determine the shear resistance, $\tau$, shear modulus, $G$, and response curves of the masonry samples when requested to cut in its plane.

With this testing configuration, the cross section aligned with the horizontal diagonal is subjected to a compressive stress, "theoretically" uniform, in which the shear stress is null (pure compression). Based on the Mohr circle classical theory, the cross section along the vertical diagonal is subjected to a pure traction condition (with intensity equal to the vertical compression and without shear) which then causes breaking by traction; For this reason, such stress is sometimes also referred as diagonal tensile strength (see Figure 3).

Figure 3: Configuration of the diagonal compression of masonry specimens

Still based on the Mohr circle properties, the cross-section inclined at $45°$ towards vertical/horizontal, are subjected to pure shear stress state in which the intensity of the tangential stress is equal to the compressive and tensile stress in the horizontal and vertical diagonal sections, respectively. It follows that, in parallel to the settlement and top joints sections, it mobilizes pure shear, with the same limit strength to diagonal pull and also called diagonal shear strength.

In view of the above, the data obtained by this test will allow to determine the diagonal tensile strength and the corresponding shear modulus of the test specimen. Combining the average value of the elasticity modulus obtained in the compression test ($E$) with the average value of the shear modulus calculated in the diagonal compression test, for samples constructed in the same way, it is even possible to estimate the Poisson's ratio of the masonry blocks.

In this test were used to measure the horizontal displacements three LVDTs and one LVDT to measure the vertical displacement of the specimen, in the front and rear faces. The position of the transducers follow the standard ASTM E 519-02 [18].

Although the bibliography reports two ways of processing and interpreting the results of this test, in this study we adopted the method described in ASTM 519-02 [18], whereby it is possible to calculate the tensile strength and diagonal shear as well as the shear modulus of the specimens using the following equations:

$$f_i = 0{,}707\, F_{max}/A_n \qquad \text{Equation (6)}$$

$A_n = ((l_s + h_s)/2) \times t_s \times n$ Equation (7)

$n = (100 - \%_{furação})/100$ Equation (8)

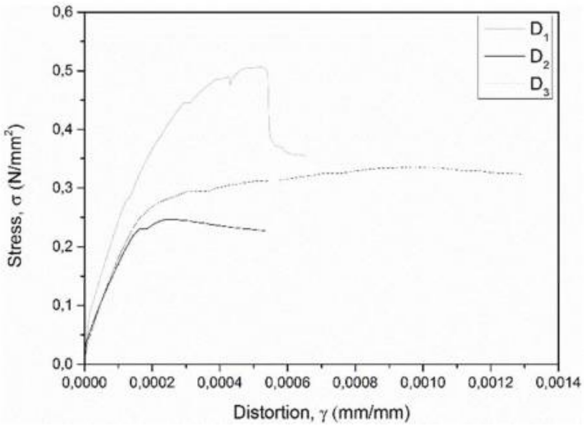
$\gamma = (\Delta v + \Delta h)/L$ Equation (9)

$G_i = f_i/\gamma$ Equation (10)

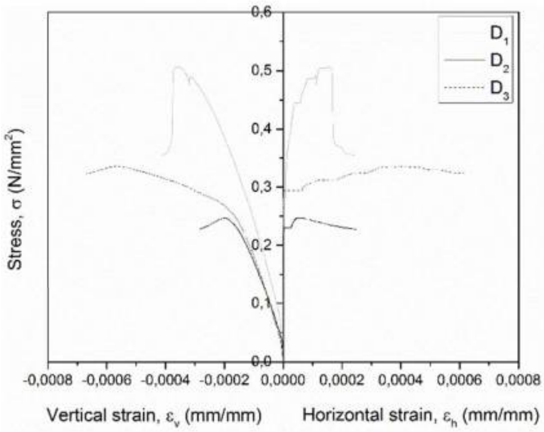
Where $f_i$ represents the tensile/diagonal shear strength of the i specimen, $F_{max}$ the maximum load applied, $A_n$ the net area obtained of the length ($l_s$), height ($h_s$) and thickness ($t_s$) of the sample and the fraction ($n$) of blocks net area, $\gamma$ the distortion of the specimen obtained from the vertical $\Delta v$ (shortening) and horizontal $\Delta h$ (stretching) displacements, to $1/3$ of the maximum force, $L$ the vertical distance between measurement points of $\Delta v$ and $G$ the shear modulus.

In a similar way of what was adopted when calculating the longitudinal modulus of elasticity, it was assumed a $G_i$ value obtained in the elastic range based on the distortion values for one third of the maximum shear or rupture stress.

The Figure 4 presents the stress-distorsion and stress-vertical and horizontal strain from the diagonal tensile shear strength tests from which it was possible to obtain mechanical characteristics included in Table 3, the strength $f_i$ and the shear modulus$G_i$.



(a)



(b)

Figure 4: Diagonal compression tensile strength test results: (a) Shear stress vs distorsion curves; (b) Shear stress vs vertical and horizontal strains curves.

Table 3: Summary of the diagonal compression tensile strength test results.

| Specimen | $f_i$ (N/mm$^2$) | G (N/mm$^2$) | $G_{linear\ regression}$ (N/mm$^2$) |
|---|---|---|---|
| $D_1$ | 0,51 | 2901,1 | 2167,8 |
| $D_2$ | 0,25 | 2535,2 | 1736,9 |
| $D_3$ | 0,34 | 2098,4 | 1698,4 |
| **Mean (N/mm$^2$)** | ***0,4*** | **2511,6** | **1867,7** |
| **S.D. (N/mm$^2$)** | 0,1 | 401,9 | 260,6 |
| **C.O.V. (%)** | 33,0 | 16,0 | 14,0 |

Analyzing the obtained results, an average diagonal tensile strength, $f$, of $0{,}4\ N/mm^2$ with a C.O.V. of 33%, coupled with the fact that the first specimen, $D_1$, showed higher resistance when compared to the other two. For the shear modulus, $G$, it was obtained an average value of $2511{,}6\ N/mm^2$, with C. O.V. of 16%, much lower than the associated with shear strength, which is consistent with the greater proximity of 3 the curves stress-distortion of the three specimens until $2/3$ of the maximum strength.

By combining the shear modulus, $G$, determined value for the diagonal compression test specimens, and the modulus of elasticity, $E$, obtained from the simple compression test in masonry specimens, it can be calculated the Poisson's ratio using equation Equation (11), yielding the value of 0,08, therefore well below the generally accepted value for current concrete $\nu_{concrete} \approx 0{,}2$.

$$E/2G - 1 = (5432{,}1\ /\ ((2 \times 2511{,}6)\ )) - 1 = 0{,}08 \qquad \text{Equation (11)}$$

Regarding the cracking pattern and the final damage observed throughout the tests it was observed that that the cracking starts nearest the vertical joint close to the load application zone at the bottom vertex, thence up through the vertical and horizontal joints.

## FLEXURAL STRENGTH TEST

It was conducted an experimental campaign with aim of evaluate the flexural strength of concrete masonry wallets according to NP EN 1052-2 2002 [19]. These tests aims to determine the flexural strength, $f_{xi}$, of small masonry specimens according to the two main axes of load application. For it, it was applied a load on the largest surface of the sample, perpendicular to this, according to a parallel and perpendicular rupture plane to the horizontal joints, registering weathered maximum load.

Parallel to the Joints Flexural Strength Test

In this test it was used a hydraulic actuator which has a maximum capacity of 100 kN. At this actuator were coupled found a hinged system in the load cell specimen to accommodate possible shifts resulting, as already said, for the construction of irregularities. Displacement control was adopted for the test procedure with a displacement velocity of $0{,}02 mm/s$. The specimens' dimensions are 600mm length and 1000mm height.

It was used a set of four LVDTs, placed on the sample front face subject to the load acting perpendicularly to this, as shown in Figure 5, although not required by the standard, but to facilitate the tracing of the force-displacement curve.


(a)

Figure 5: Flexural strength tests parallel to the horizontal bed joints: test setup.

The standard presents a series of equations (Equation 12 and 13) that allows to process the data results and determine the parallel flexural strength to the horizontal joints of the masonry wallet.

$$f_{xi} = \frac{3F_{i,máx}(l_1 - l_2)}{2bt_u^2}$$ Equation (12)

Where $F_{i,máx}$ corresponds to the maximum load applied to the specimen, $l_1$is the distance between supports and $l_2$ the distance between load application areas, $b$ is the specimen width perpendicular to the direction of the will and $t_u$ the specimen thickness.

The characteristic flexural strength, $f_k$, rounded to $0{,}01\ N/mm^2$ can be calculated for the case of five test specimens, according to the equation Equation (13).

$$f_k = \frac{f_{average}}{1{,}5} \qquad \text{Equation (13)}$$

Where $f_{average}$ corresponds to the average flexural strength according to a parallel to the vertical joints break plane. The dimensions of $l_1$ is $900mm$, $l_2$ is $360mm$, $b$ is $605mm$ and $t_u$ is $270mm$.

Figure 6 illustrates the distribution of the load-displacement response of the five tested specimens during the tests and in Table 4 are summarized the values of the rupture load of each specimen as well as the flexural strength according to a parallel to the joints plane. The average of the flexural strength according to a parallel plane to rupture horizontal joints is $0{,}25N/mm^2$ and has a C.O.V. of 33,8%. The high C.O.V. value is due to the high breaking strength offered by $FPl_3$ specimen, also visible in the graph of Figure 6. If observed, the flexural strength results of the mortars used in the construction of the specimens, and taking into account that the rupture of the masonry specimens usually occurs by the joints of settlement, there is also a slightly higher C.O.V. for these mortars due to high resistance of two samples, then the specimen that has endured more, was constructed with only these mortars.

Thus this high variability is due to the fact that the failure mode involving the adherence between the block and the mortar and this zone have high variability. Frictional forces between the blocks and mortar are the conditions for the rupture of the specimens. The characteristic strength was determined has it is represented in equation Equation (14).

$$f_k = \frac{0{,}25}{1{,}5} = 0{,}17N/mm^2 \qquad \text{Equation (14)}$$

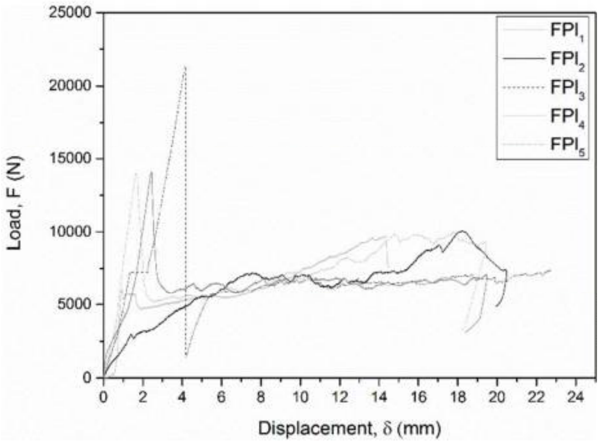



Figure 6: Parallel to the Joints Flexural Strength Test results: Force-displacement curves.

Table 4: Flexural strength in a plane parallel to the joints.

| Specimen | $F_{máx}$ | $f_{xi}$ (N/mm$^2$) |
|---|---|---|
| $FPl_1$ | 9712 | 0,18 |
| $FPl_2$ | 10077 | 0,19 |
| $FPl_3$ | 21356 | 0,39 |
| $FPl_4$ | 14101 | 0,26 |
| $FPl_5$ | 14021 | 0,26 |
| **Mean (N/mm$^2$)** | **13853,4** | ***0,25*** |
| **S.D. (N/mm$^2$)** | 4685,0 | 0,09 |
| **C. O.V. (%)** | 33,8 | 33,8 |

From the observation of the specimens' failure it can be concluded that the rupture occurred mainly due to the detachments between the mortar and masonry units, as expected. Three of the five test pieces in a slot opened by the third horizontal joint counting from the base and two from the second joint. The respective deformed to the first position and the second, show what has been evident during the rupture of the specimens, the rotation of the elements occurred around the line resulting of the intersection of the load application plane and the surface and the joint where the crack occurred.

Perpendicular to the Joints Flexural Strength Test

The specimens dimensions adopted are 560mm length and 800mm height. The instrumentation used was similar to that described for bending test according to a direction parallel to the joints, described in previous section.

The flexural strength tests according to a perpendicular to the horizontal joints rupture plane were performed according to the European standard. From the tests, the force-displacement curves, the characteristic flexural strength were determined and it was also observed the cracking start in the obtained graphic through the small force breaks before reaching the breakage point of the test specimen.

From the force-displacement results, plotted in Figure 7 it is possible to see the maximum force the specimen can withstand, as well as the displacements suffered. The dimensions of $l_1$ is $1100mm$, $l_2$ is $560mm$, $b$ is $834mm$ and $t_u$ is $270mm$. Table 5 presents the values of the rupture load of each specimen as well as the flexural strength according to a perpendicular to the joints plane.

From an analysis of Table 5 it can be extracted the average flexural strength according to the direction considered in this test of $0{,}32N/mm^2$, with a C.O.V. of $14{,}1\%$. This C.O.V. value is acceptable, with only a slight variation of the flexural resistance of each specimen. In the tests it was found that the breakage of the specimen when subjected to bending stress according to a perpendicular to the horizontal joints rupture plane, is given by the vertical joints between the load application area ($l_2 \times b$), and the blocks, can thus affirm that if the masonry units contributes to flexural strength in addition to the friction between the blocks and mortar.

The characteristic strength to bending was obtained by equation Equation (15). The average flexural strength according to a rupture plane perpendicular to the horizontal joints is $1{,}28$ times the average flexural strength according to a parallel plane to rupture the horizontal joints, which would be expected as in the case of the sample in a rupture plane parallel to the horizontal joints test offers least resistance for load application that is perpendicular to the horizontal joint rupture test. In the case of bending test according to a direction perpendicular to the horizontal joints, both the blocks and the mortar interface / block offer resistance to loads requesting the sample.

$$f_k = \frac{0{,}32}{1{,}5} = 0{,}21N/mm^2 \qquad \text{Equation (15)}$$

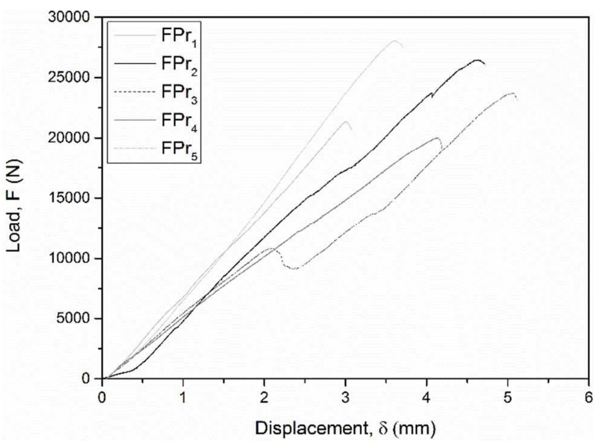


Figure 7: Perpendicular to the Joints Flexural Strength Test results: Force-displacement curves.

Table 5: Flexural strength according to a perpendicular to the joints plane.

| Specimen | $F_{máx}$ | $f_{xi}$ (N/mm$^2$) |
|---|---|---|
| FPr1 | 21383 | 0,29 |
| FPr2 | 26467 | 0,36 |
| FPr3 | 23748 | 0,32 |
| FPr4 | 20036 | 0,27 |
| FPr5 | 28088 | 0,38 |
| **Mean (N/mm$^2$)** | **23944,5** | ***0,32*** |
| **S.D. (N/mm$^2$)** | 3369,4 | 0,05 |
| **C. O.V. (%)** | 14,1 | 14,1 |

From the observation of the specimen's damages throughout the tests it was observed the specimens' breakage took place under the central vertical rows (vertical symmetry axis) of the specimen, extending up from the mortar to the blocks, reaching through these by the septa zone.

The rotation of the test pieces took place around the line of intersection of the load application face and the plane passing through the cracking zone obtaining an approximately symmetric deformed.

It was found that rupture of the samples was mainly caused by the vertical symmetry axis, with small inclinations to the right or left, making an analysis from top to bottom of the test pieces, as shown in Figure 8.

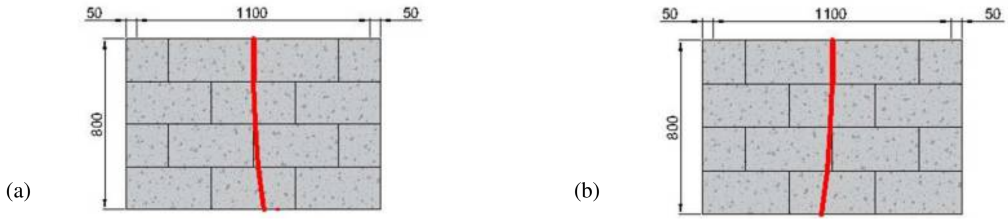



Figure 8: Major failure mechanisms identified (dimensions in mm).

## CONCLUSION

Based on data obtained from the mechanical characterization tests of the concrete masonry blocks, it can be seen that in simple compression the masonry specimens ($f = 2{,}4\ N/mm^2$; $E \approx 4 - 5kN/mm^2$) average strength is about 6 times higher than the average strength to diagonal shear/tension ($F = 0{,}4N/mm^2$; $G \approx 2{,}5kN/mm^2$), while the stiffness is almost doubled. In simple compression tests, it was observed that the masonry specimens cracked in areas of higher drilling of the blocks. In the tensile tests by diagonal compression it was found that the test specimens mainly cracked by the block/mortar joint interfaces, following the delineation of settlement and top joints.

With the achievement of the bending tests it can be concluded that the strength of masonry wallets essentially depends on the bonding strength between the mortar and blocks.

The minimum strength of masonry units in high seismicity areas, $f_{b,min}$ (as for example the island of Faial where the tested masonry units are used) and other islands of Central and Eastern group of Açores, is $4N/mm^2$ (perpendicularly to settlement joints in the wall plane), according to Eurocode 8 [20]. Analyzing the average strength values obtained for compression, it can be said that the blocks from the Lot 1 do not meet this criterion ($f_{b,normalized} = 3{,}5N/mm^2 < 4\ N/mm^2$) and blocks from lot 2 satisfy ($f_{b,normalized} =$

$4{,}7N/mm^2 > 4\,N/mm^2$. So it can be said that these masonry units should be improved to fulfill the minimum criteria imposed by the Eurocodes for design and to avoid collapses of walls and buildings.

A minimum compression strength is also required, $f_{m,min}$, for mortar for simple or confined masonry according to Eurocode 8 of $5N/mm^2$ [20]. By analyzing the mean values of compressive strength obtained for each of the mortars used, it can be seen that all the values satisfy this criterion and are far above (the lowest value is $12{,}9N/mm^2$ and still it is $2{,}58$ times the minimum required).

The specimens of masonry to be tested at compression, have an average compressive strength, $f$, of $2{,}4N/mm^2$ and a modulus of elasticity, $E$, between $4138{,}2N/mm^2$ and $5432{,}1\,N/mm^2$, and the average value of compression resistance is about six times the average resistance to shear (diagonal tension), $f$, of $0{,}4\,N/mm^2$. The stiffness is about two times higher in samples when tested in compression compared to specimens tested shear (medium value of shear modulus, $G$, is $2511{,}6N/mm^2$).

Concerning the failure mode of masonry specimens subjected to compressive load, it found to be primarily under the septa of concrete blocks. In the case of masonry specimens tested in shear, it was observed that the failure was primarily at the block/mortar joints interface, following the outline of the settlement and top joints.

For masonry specimens tested under a flexural rupture plane perpendicular to the horizontal joints gave an average flexural strength, $f_{xi}$, $0{,}32N/mm^2$ and $1{,}28$ times the average compressive strength according to a plan breaking the parallel horizontal joints ($0{,}25N/mm^2$). The superiority of this value has to do with the fact that the flexural strength test according perpendicular to the horizontal joints plane both the vertical joints and the blocks support the loads whereas in the case of the bending test according to a plane parallel to the horizontal joints the horizontal joints are practically the only ones who resist the forces to which the specimen is subjected.

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**Conflict of Interest**: The authors declare that they have no conflict of interest.

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