Seismic Vulnerability of Old Masonry Buildings – SEVERES Project

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I. INTRODUCTION

OLD masonry buildings are integral and very important parts in most of the European cities. These buildings are still being used, for housing and services, as their main function. In Lisbon and other Mediterranean cities, old masonry buildings are generally exposed to a very high seismic risk due to high probability of earthquake occurrence. Only recently, a special attention has been paid on the need to protect and preserve this architectural heritage, which requires a significantly different approach to be adopted in contrast to the one used for new constructions.

The structure of old buildings with historical value requires special interventions, which should be based on diagnostic studies and surveys in order to provide adequate decisions about the intervention methodologies and techniques to be adopted. No action should be undertaken without detailed examination of benefits and disadvantages of adopted methodologies to the building. Some recommendations for the analysis and conversation of building can be found in [3]. Therefore, it is needed to physically and mechanically characterize the resistance of the walls of old buildings, as well as to evaluate the states of stress they could face under gravity loads and seismic actions.

Focusing on the traditional buildings in the south of Portugal, including Lisbon, the common approach requires to build and test the prototypes of the walls in the laboratory. The prototypes for test should be built with different types of mortar, in limestone masonry, and have to be representative of the traditional walls. Furthermore, in order to identify the mechanical behavior of masonry, different tests may be carried out, *e.g.*, diagonal compression test, cyclic shear test, triplet test and compression test.

The specimens, which is going to be tested, were specially built by our experiment using the traditional materials. The experimental work presented herein mainly refers to ASTM E519-02 standard [4], which defines the standard test method to determine diagonal tension (shear) in masonry walls, commonly designated as *diagonal compression test*. Corradi [5] previously carried out in-situ diagonal test, together with compression test, on panels made with roughly cut stones. In the recent past, Brignola [6] applied in-situ diagonal compression test on panels, which are mainly characterized by multiple roughly cuts stone masonry.

Moreover, different wall prototypes will also be subjected to the *triplet test*, which is defined by UNI-EN 1052-3 standard [7]. Prota [8] carried out the triplet test on the wall samples built with tuff units, which significantly differs from the present work that considers the wall samples built in roughly cut stone (limestone) masonry. Also, Lourenço [9] triplet test has performed, but in that case walls were built with clay units.

Furthermore, we will also conduct a set of experiments on the small walls, which are subjected to the *compression test*, defined by NP EN 1052-1998 (*Methods of test for masonry – Part 1: Determination of compressive strength*) standard [2]. As previously referred, Corradi [5] carried out compression test on panels made with roughly cut stones.

The general objectives of the work presented herein are to determine: i) shear strength of masonry via diagonal compression test, ii) initial shear strength, cohesion and friction angle of the joints by performing triplet test, and iii) compressive strength and Young modulus of elasticity through compression test. The experiments are conducted in the laboratory, using the above-mentioned test methodologies on the wall prototypes, especially constructed for this purpose. Namely, this research project includes 16 masonry panels with different dimensions and different type of mortars (hydraulic mortar and air lime mortar), which are subjected to diagonal compression, triplet and compression test.

Nevertheless, the *specimens of mortar* are also tested. For each type of mortar, 9 prismatic and 3 cylindrical specimens were tested following the indications of EN 1015-11 [10] standard. The aim of these tests is to obtain the flexural and compressive strength of prismatic specimens, and compressive strength and modulus of elasticity for cylindrical specimens.

To the best of our knowledge, current state of the art in the area usually applies the triplet test on regular stone masonry, which differs from our work, as each of above-mentioned tests will be carried out on rubble stone masonry.

Fig. 1. General layout of the loading shoe.

II. Description of the Tests

A. Diagonal compression test

The diagonal compression test is carried out with a procedure similar to that described in ASTM E519-02 (*Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*)[4], which provides the accurate means to measure the diagonal tensile (shear) strength of masonry walls. In fact, the masonry assemblages will be loaded in compression along one diagonal of the specimen, causing a diagonal tension failure with the specimen splitting apart parallel to the direction of the load. Actually, the specimens will be placed into the testing machine with diagonal axis position. The load on the specimen will be increased until failure of the specimen occurs. Treatment of the load should be in suitable increment rates. The increments should be chosen so that at least ten deformation or strain readings will be obtained to determine definitely the stress-strain curve. Such readings should be obtained for loads as close to the ultimate load as feasible. The failure pattern of each specimen will be registered and ultimate shear strength as well as shear elastic modulus (modulus of rigidity) will be calculated.

For diagonal compression test, two steel loading shoes are used and placed on two diagonally opposite corners of the panels. The general layout of the loading shoe is depicted in Figure 1. To avoid premature splitting and failure of panel edges, the space between the specimen and steel plates is filled with appropriate type of mortar. During the testing, load is applied to the panel by a hydraulic jack action on steel shoe placed at the top corner and transmitted to a similar shoe at the bottom corner, as shown in Figure 2.

In this document, the bearing dimension of the loading shoe is 150×150×15 mm, with the total loading shoe length of 722 mm. According to the ASTM E519-02 standard [4], maximum length of the bearing of the shoe should be approximately 1/8 of the length of the specimen edge to avoid excessive bearing stress. Number and spacing of stiffeners depend on the thickness of the tested wall specimen, according to the ASTM E519-02 standard [4]. In this case, due to the dimension of the wall 1200×1200×700 mm, the adopted number of stiffeners is four.

The shortening of the vertical diagonal and the lengthening of the horizontal diagonal under load were measured with linear displacement transducers (TSV and TSH, respectively). In our case, eight linear displacement transducers were used. As depicted in Figure 3, five transducers were instrumented on one side of the specimen, while the remaining three transducers were placed on the other side of specimen.

For the tested wall specimens, both with hydraulic mortar and with air lime mortar, the load is applied in increments of 10.0 kN/s. Furthermore, two masonry specimens with dimensions of 1200×1200×700 mm were prepared for each type of mortar and cured in laboratory air at the ambient temperature range from 10°C to 28°C (from August to March).

1) Calculation: According to the ASTM E519-02 [4], the shear strength, shear strain and modulus of rigidity are evaluated from the experimental results assuming that the diagonal compression test produces a uniform shear stress. In this case the Mohr's circle is centered in the origins of the Cartesian axis and the value of the shear stress τ is equal to the principal tensile stress.

- *Shear stress calculation*

  The shear stress of specimen is calculated as follows:

$$\tau = \frac{0.707 \times P}{A_n} \tag{1}$$

  Where:

  - τ is shear stress on net area in [MPa],
  - P is applied load in [N],
  - A_n is net area of the specimen in [mm^2], calculated as follows:

$$A_n = (\frac{W + h}{2}) \times t \times n \tag{2}$$

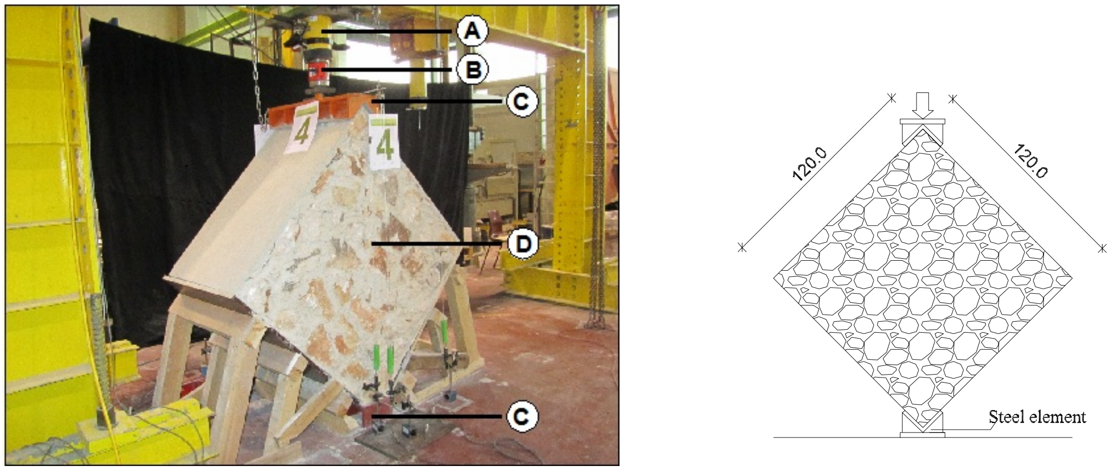
    Where:

    - W is specimen width in [mm],
    - h is specimen height in [mm],
    - t is total thickness of specimen in [mm],
    - n is percent of the unit's gross area that is solid, expressed as a decimal. In this experimental campaign n=1 was adopted.

- *Shear strain calculation*

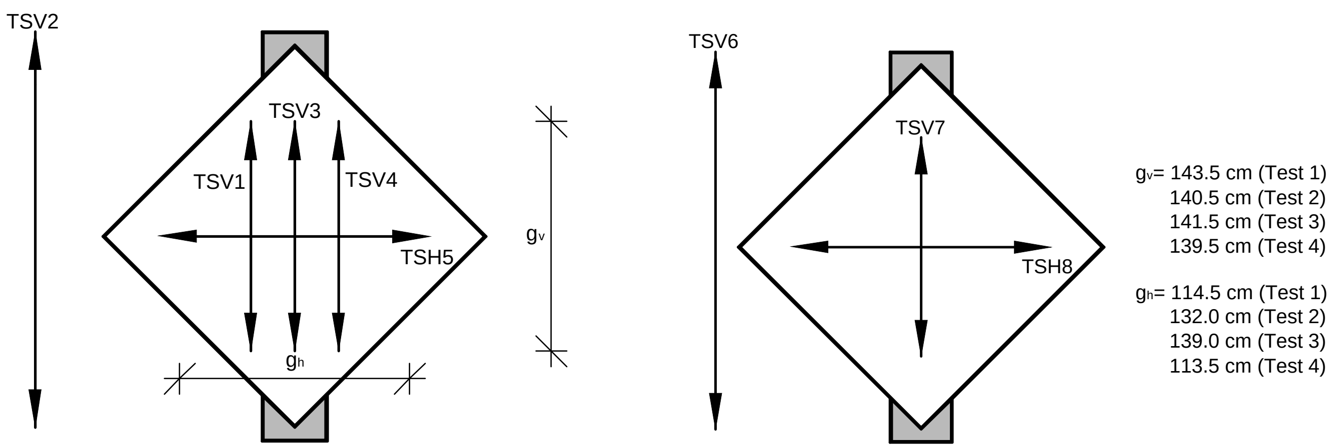
  When required, the shear strain is calculated as follows:

$$\gamma = \frac{\Delta v}{g_v} + \frac{\Delta h}{g_h} \tag{3}$$



(a) (b)

Fig. 2. Test setup for diagonal compression test (dimensions in [cm]) A Hydraulic jack; B Load cell; C Loading shoes; D Masonry specimen.



(a) (b)

Fig. 3. Transducers position: (a) wall front side (b) wall back side (dimensions in [cm]).

Where:

- γ is shearing strain in [mm/mm],
- Δv is vertical shortening in [mm],
- Δh is horizontal extension in [mm],
- g_v is vertical gage length in [mm],
- g_h is horizontal gage length in [mm],

Consequently, the shear strength τ_0 (f_{v0} according to Eurocode 6 [11]) and the tensile strength are defined as:

$$\tau_0 = f_t = \frac{0.707 \times P_{max}}{A_n} \tag{4}$$

Where:

- P_{max} is the maximum load applied by the jack.

- *Modulus of rigidity*

Modulus of rigidity (modulus of elasticity in shear) can be calculated as follows:

$$G = \frac{\tau_{1/3}}{\gamma_{1/3}} \tag{5}$$

Where:

- G is modulus of rigidity in [MPa].
- $\tau_{1/3}$ is the shear stress for a load of 1/3 of the maximum load P_{max},
- $\gamma_{1/3}$ is the shear strain,

B. Triplet test

For this type of test nine wall specimens were built and subdivided into two groups, depending on the type of mortar used for their construction. The walls from the first group were built using hydraulic mortar, whereas the

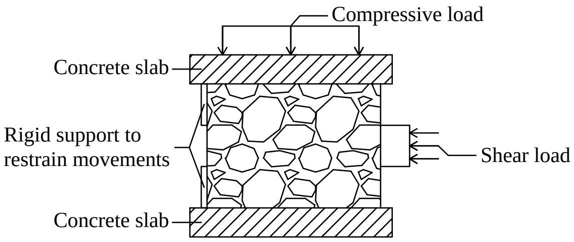
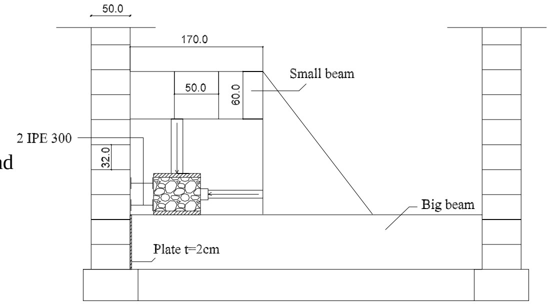


Fig. 4. Triplet test procedure according to EN 1052-3.



(a)

(b)

Fig. 5. Triplet test setup (dimensions in [cm]).

walls belonging to the second group were built using air lime mortar. Dimensions and evolution of construction of these walls can be seen in Section III.

According to EN 1052-3 [7] standard, will be specimens of three layers of masonry units subjected to a vertical pre-compression load, as presented in Figure 4. The top and bottom masonry layers will be kept under constant pressure, while a horizontal load will be applied to the middle layer of the wall. At the end of this procedure, the value of the shear strength of the masonry joints is obtained.

In order to define the cohesion and the coefficient of friction, three different pre-compression stress levels are adopted, namely 0.1 N/mm^2, 0.2 N/mm^2, 0.3 N/mm^2 and 0.5 N/mm^2. These reference values of pre-compression are based on the real state of stress of masonry walls in two typical old buildings in Lisbon, namely Pombalino and Gaioleiros buildings. Pombalino buildings represent typical masonry for the period after Lisbon earthquake (1755) and before the first decade of the XX century. This masonry type is superseded by Gaioleiros buildings, which were used until the end of the third decade of XX century, when the reinforced concrete starts to be used and the stress levels are kept constant during the complete test duration.

The specimens from hydraulic mortar were subdivided into three series:

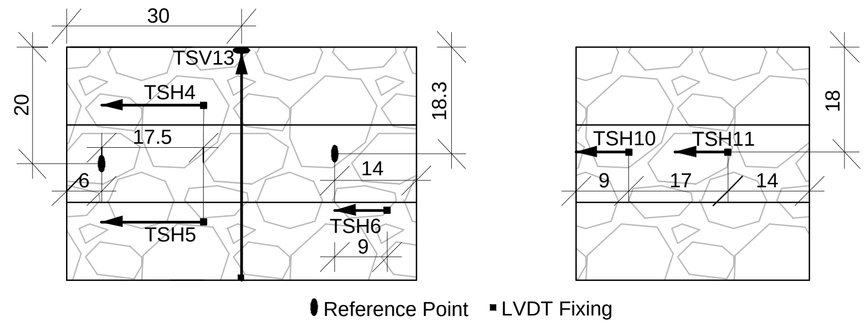
(a) T1 and T2 panels – for a pre-compression level of 0.1 N/mm^2,
(b) T5 panel – for pre-compression level of 0.2 N/mm^2, and
(c) T3.H and T4.H panels – for a pre-compression level of 0.3 N/mm^2.

Correspondingly, the specimens from air lime mortar were subdivided into three series :

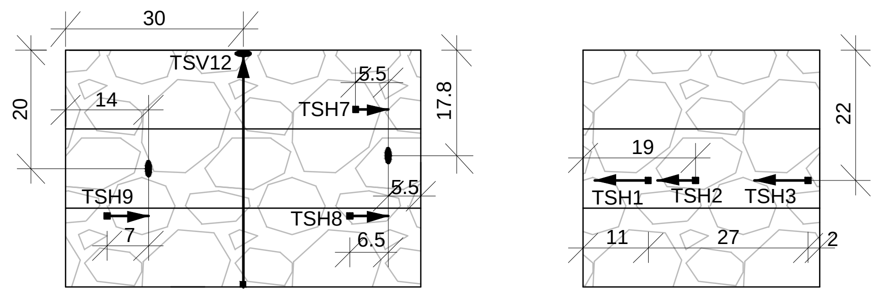
(a) T6 and T7 panels – for a pre-compression level of 0.1 N/mm^2,
(b) T8 panel – for pre-compression level of 0.3 N/mm^2, and
(c) T9 panel – for a pre-compression level of 0.5 N/mm^2.

The test setup is shown in Figure 5. Two horizontal supports are used to restrict the movement of the top and bottom courses of the panel (see Figure 4). The horizontal and vertical loading system consist of two independent actuators. The horizontal actuator is applied directly to the middle course and the vertical actuator is applied to a steel beam, so that the load can be distributed in the panel.

Initially, the vertical compressive load is applied by the vertical hydraulic actuator. The maximum loading capacity of the vertical actuator is 30 tons. The force of the hydraulic actuator is kept under control, which results in an almost constant vertical load. It is worth to emphasize that the vertical load is approximately constant during the complete test duration by means of some small unloading steps. After the selected pre-compression level is applied, the hydraulic actuator of a maximum loading capacity equal to 30 tons is used to apply and increasing the horizontal load until the specimen's rupture. The displacements of the specimens were recorded with thirteen linear displacement transducers (LVDTs) placed on four faces of the specimen. Six transducers were placed to measure the horizontal displacements on the front and back faces (transducers TSH4, TSH5, TSH6 on the front face and transducers TSH7, TSH8, TSH9 on the back face) and two transducers were placed on the front and back faces to measure the vertical displacements (transducer TSV13 on the front face and transducer TSV12 on the back face). On the specimen face where the horizontal load is applied (lateral face) it was placed one transducer at the horizontal actuator (transducer TSH2) and two transducers to measure the horizontal displacements (transducers TSH1 and TSH3). On the opposite lateral face two other horizontal transducers were placed (transducers TSH10 and TSH11). The positions of the transducers are shown in Figure 6.



(a) Front and lateral face of the specimen



(b) Back and lateral face of the specimen

Fig. 6. Position of transducers for triplet test (dimensions in [cm]).

1) Calculation: The test evaluation was conducted according to the EN 1052-3 [7] standard. Namely, for each specimen the shear strength can be calculated as follows:

- *Shear strength calculation*

$$\tau_0 = \frac{F_{i,max}}{2 \times A_i} \tag{6}$$

Where:
  - $F_{i,max}$ is the maximum horizontal force (shear load), that has to be divided two times by the corresponding shear area [N],
  - A_i is the cross - sectional area of a specimen parallel to the bed joints [mm^2],

As described in EN 1052-3 [7] standard, the characteristic values for cohesion and for the coefficient of friction are about 80% of the experimental values.

Coulomb friction law, for moderate pre-compression levels, describes the joint strength behavior, and provides a linear relation between the shear stress τ and the normal compression stress σ, given by:

$$\tau = \tau_0 + \mu \times \sigma \tag{7}$$

- τ_0 is cohesion or initial shear strength of the joint in [MPa], and
- μ is the coefficient of friction.

C. Compression test

Only two walls, one with hydraulic mortar and one with air lime mortar, were built for compression test. The details related to these walls are presented in Section III. The major goal of the compression test is to determine the compressive strength and the modulus of elasticity of masonry. The test is conducted using the procedure described in BS EN 1052-1 1998 (*Methods of test for masonry – Part 1: Determination of compressive strength*) [2] standard.

The wall specimens are loaded uniformly in compression and the maximum achieved load is recorded. The characteristic compressive strength of the masonry is derived from the strength of the individual specimens. If the masonry units, or the mortar, are not capable of achieving the exact specified strength, then it is permitted to adjust the measured values, as specified in BS EN 1052-1 [2] standard.

During the testing procedure, the testing machines are used to apply load to a specimen, such that displacements are uniformly distributed across the loaded surfaces. Specimen should be put centrally in the testing machine. The top and bottom of the specimen have to be in full contact with the testing machine. Load should be applied uniformly to the top and bottom of the specimen and increased constantly.

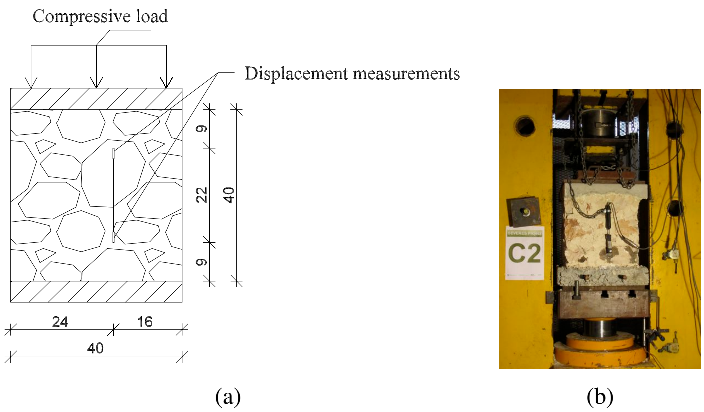


Fig. 7. Position of transducers and Test setup for compression test (dimensions in [cm]) .

According to BS EN 1052-1 [2] standard, in order to determine the modulus of elasticity, the compression force is applied in three equal stages up to 50% of maximum estimated force. After each step, the compressive force should be kept constant for 2±1 min in order to determine the changes in height. After the completion of the measurement in the last step, the compressive force should be increased at a constant rate until failure of the tested specimen.

In order to measure the modulus of elasticity, displacement measurements should be taken at the four measuring points up to about 50% of the maximum load, as shown in Figure 7.

1) Calculation:
For calculation of the compressive strength and modulus of elasticity of each wall, following formulas should be used:

- *Calculation of the compressive strength*:

$$\sigma_0 = \frac{F_{i,max}}{A_i} \tag{8}$$

  - $F_{i,max}$ is the maximum load reached on an individual masonry specimen in [N],
  - A_i is loaded cross-section of an individual masonry specimen in [mm^2], and
  - σ_0 is compressive strength of an individual masonry specimen in [N/mm^2].

- *Calculation of the modulus of elasticity*:

$$E_i = \frac{F_{i,max}}{3 \times \varepsilon_i \times A_i} \tag{9}$$

  - $F_{i,max}$ is the maximum load reached on an individual masonry specimen in [N],
  - A_i is loaded cross-section of an individual masonry specimen in [mm^2],
  - ε_i is the strain in an individual masonry specimen correspondent to a load of 1/3 of the maximum load achieved, and
  - E_i is modulus of elasticity of an individual masonry specimen [N/mm^2].

D. *Test of cubic samples*

Regarding the test of cubic samples, the results from [1] are adopted due to the fact that both experiments rely on the same type of stone taken from the same quarry, thus the values for compressive strength and the modulus of elasticity of cubic samples are presented in Section IV in respect to the results obtained in [1].

III. Construction of stone masonry walls

A. *General considerations*

In order to represent the behavior of the stone masonry walls in the old buildings of Portugal, *i.e.*, Pombalino and Gaioleiros buildings, the construction and testing of specifically designed rubble stone masonry walls is performed.

Definition and description of specimen construction and used materials is presented herein regarding the testing procedure. Namely, four big wall specimens were built in order to assess their behavior under the diagonal compression test, ten smaller wall specimens were constructed in order to perform triplet test and two smaller wall specimens were built in order to perform compression test.

Moreover, the walls from each group are further subdivided into two equal subgroups, depending on the type of mortar used for their construction: hydraulic mortar and air lime mortar were used for each subgroup, corresponding to different mechanical characteristics and different speed of hardness.

For triplet and compression tests, small concrete slabs with reinforcement bars were built in the top and in the base of the specimens to facilitate transportation of the walls.

The walls are built and tested in the *Laboratório de Estruturas e Resistência de Materiais* at the Civil Engineering Department of the Instituto Superior Técnico (IST), Lisbon, Portugal.

B. *Delivery and storage of the materials*

On 26th of July, 2010, the materials were transported to the Laboratory, including stone, hydraulic lime, river sand and sand quarry.

Both types of sand, river sand and sand quarry, and stone (depicted in Figures 8 and 9, respectively) were

Fig. 8. River sand and sand quarry.

Fig. 9. Traditional stone.

Fig. 10. Boxes of hydraulic lime.

Fig. 11. Cooked stone.

(a) (b)

Fig. 12. Walls for diagonal compression test with hydraulic mortar: (a) Wall with horizontal layers, and (b) Wall with diagonal layers.

(a) (b)

Fig. 13. Walls for diagonal compression test with air lime mortar with diagonal layers: (a) Rear side, and (b) Front side.

stored outside of the Laboratory, paying special attention on ensuring their weatherproofing. The other materials, boxes of hydraulic lime and cooked stones, shown in Figures 10 and 11 respectively, were stored inside the Laboratory near the construction place of the walls.

The walls were built during the summer (July - August) and were constructed using the two types of mortar, one based on hydraulic lime and the other on air lime.

C. Construction of large walls specimens

The specimens construction started on 26th of July, 2010, trying to reproduce the common features of the traditional construction methodology employed for the rubble stone masonry walls in old buildings in Lisbon.

The stones were carefully chosen, in order to secure their best application, to maximize the fitting and minimize the oscillations between them, but also to leave the fewest voids as possible. The remaining voids were filled with mortar and small stones. During the construction period, a special attention was paid on choosing the larger stones as the basic building units, especially for the wall edges, which are further locked together by applying the mortar and small stones in order to make wall solid and stable.

Before the actual placement, the dimensions of the stone were usually physically altered to ensure better placing to the surrounding stones. The dimension alternation was usually requiring to test the stone fitting by placing it on the wall surface (without applying mortar), and to repeat the dimension adjustment, if needed. After ”the best” fitting had been found, the stone was placed onto the wall structure by applying the mortar, and by hitting it with the hammer until ensuring even better placing with the mortar joints.

For diagonal compression test, the first wall was constructed by applying the stones in horizontal layers, whereas the other three walls were built with diagonal stone layers, as depicted in Figures 12 and 13, respectively.

Moreover, the four specimens, built for diagonal compression test, were also constructed with different type of mortars, namely, two walls with hydraulic mortar and two walls with air lime mortar. The specimens were constructed with the dimension of 1200×1200 mm with cross-section thickness of 700 mm, according to the ASTM E519-02 standard [4].

After the specimens with hydraulic mortar were finished, the process of strengthening of the mortar on the external face of the specimen lasted one more day. For the walls with air lime mortar, more than two days were required in order to ensure that the mortar becomes strong on the external faces on specimens. Based on the experience, walls specimens built with hydraulic mortar can be tested after two months, whereas walls specimens built with the air lime mortar can be tested after five - six months.

It is also worth noting that it is very important to put hydraulic mortar in the first layer when building the walls with air lime mortar. Without applying the hydraulic mortar in the first layer, it might happen that the wall will fall down with removal of sheeting.

Evolution of construction for walls with hydraulic mortar can be seen in Figure 14, whereas the evolution of construction for walls with air lime mortar is presented in Figure 15.

D. Construction of small walls specimens

In order to perform triplet and compression tests, twelve smaller walls, with different dimensions, were built with the similar characteristics as the larger specimens, namely ten specimens for triplet test and two specimens for compression test. For both type of tests specimens were built using both hydraulic mortar and air-lime mortar. In case of triplet test, the group of five specimens was constructed using hydraulic mortar, whereas the remaining five specimens were built using air lime mortar. Correspondingly, for compression test, one wall with hydraulic mortar and one with air-lime mortar were built.

The dimensions of the walls were based on average dimensions of the faces of the stones, according to Table I of BS EN 1052-1 1998 (*Method of test for masonry – Part 1: Determination of compressive strength*) [2] standard.

Ten specimens (five with hydraulic mortar, and five with air lime mortar) are tested with triplet test. Two specimens (one with hydraulic mortar, and one with air lime mortar) are tested with compression test. The specimens are shown in Figures 16 and 17.

Table II presents dimensions of the specimens used for triplet test. According to EN 1052-3 standard [7], the specimens consist of three horizontal layers of stone units, due to the strict requirement imposed by the specification of triplet test. Also, a special attention was paid on preserving the more or less regularly shaped form of horizontal layers.

The evolution of construction for walls with hydraulic mortar is presented in Figure 18, wheres the construction of walls with air lime mortar for triplet test can be seen on Figure 19.

Table III presents dimensions of specimens for compression test. Figure 20 presents the construction of

(a) Model of sheeting

(b) Placing of the first stone

(c) After half an hour of work

(d) After seven hours of work

(e) After one day and a half of work

(f) After two days of work

Fig. 14. Evolution of construction for walls with hydraulic mortar and horizontal stone layers.

TABLE I
DIMENSIONS OF THE SMALL SPECIMENS FOR COMPRESSION TEST – BS EN 1052-1 [2]

Dimensions of block		**Dimensions of specimen**			
l_u [mm]	h_u [mm]	**Length** l_s	**Height** h_s		**Thickness** t_s
≤ 300	≤ 150	$\geq (2 \times l_u)$	$\geq 5\ h_u$	$\geq 3\ t_s$ e $\leq 15\ t_s$ e $\geq l_s$	$\geq t_u$
	> 150		$\geq 3\ h_u$		
> 300	≤ 150	$\geq (1.5 \times l_u)$	$\geq 5\ h_u$		
	> 150		$\geq 3\ h_u$		

walls with hydraulic mortar, and Figure 21 follows the evolution of walls with air lime mortar for compression test.

E. Mortar characterization

1) Preparation of hydraulic mortar: The mortar mix proportion adopted for specimens with hydraulic lime was as follows:

- 20 l of hydraulic lime,

(a) Model of sheeting

(b) First layer with hydraulic mortar

(c) After half an hour of work

(d) After four hours of work

(e) After six hours of work

(f) After one day and a half of work

(g) After two days of work

Fig. 15. Evolution of construction for walls with air lime mortar and diagonal stone layers.

TABLE II
DIMENSIONS OF THE SPECIMENS FOR TRIPLET TEST

Masonry typology	Panel	Type of mortar	Size [cm]
Roughly cut stone masonry	T1.H	Hydraulic	60 × 40 × 40
Roughly cut stone masonry	T2.H	Hydraulic	60 × 40 × 40
Roughly cut stone masonry	T3.H	Hydraulic	60 × 40 × 40
Roughly cut stone masonry	T4.H	Hydraulic	60 × 40 × 40
Roughly cut stone masonry	T5.H	Hydraulic	60 × 40 × 40
Roughly cut stone masonry	T1.A	Air Lime	60 × 40 × 40
Roughly cut stone masonry	T2.A	Air Lime	60 × 40 × 40
Roughly cut stone masonry	T3.A	Air Lime	60 × 40 × 40
Roughly cut stone masonry	T4.A	Air Lime	60 × 40 × 40
Roughly cut stone masonry	T5.A	Air Lime	60 × 40 × 40

(a) (b)

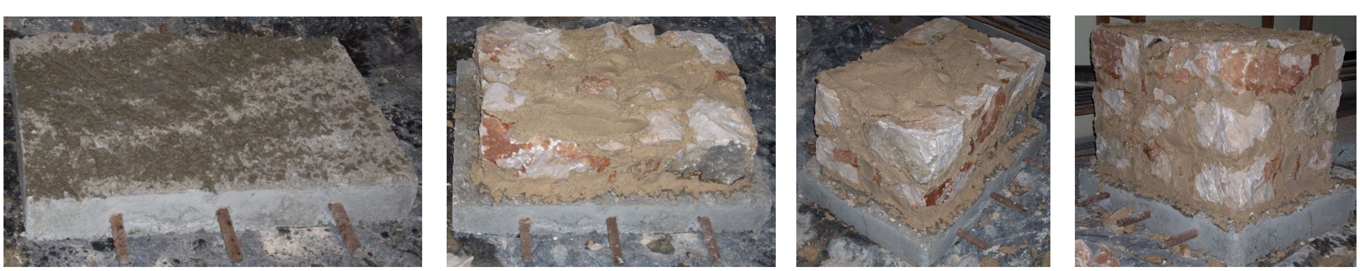
Fig. 16. Walls for triplet test: (a) With hydraulic mortar, and (b) With air lime mortar.

(a) (b)

Fig. 17. Walls for compression test: (a) With hydraulic mortar, and (b) With air lime mortar.

(a) Concrete slab (b) First layer (c) Second layer (d) Third layer

Fig. 18. Evolution of construction for walls with hydraulic mortar for triplet test.



(a) Concrete slab (b) First layer (c) Second layer (d) Third layer

Fig. 19. Evolution of construction for walls with air lime mortar for triplet test.

TABLE III
ADOPTED DIMENSIONS OF THE SPECIMENS FOR COMPRESSION TEST

Masonry typology	**Panel**	**Type of mortar**	**Size [cm]**
Roughly cut stone masonry	C1.H	Hydraulic	$40 \times 40 \times 40$
Roughly cut stone masonry	C1.A	Air Lime	$40 \times 40 \times 40$

(a) Concrete slab (b) First layer (c) Second layer (d) Third layer

Fig. 20. Evolution of construction for walls with hydraulic mortar for compression test.

(a) Concrete slab (b) First layer (c) Second layer (d) Third layer

Fig. 21. Evolution of construction for walls with air lime mortar for compression test.

- 30 l of river sand,
- 30 l of sand quarry, and
- 15 l of water.

Procedure of preparation is listed in the following:

- Firstly, 20 l of river sand was put, followed by the addition of 10 l of hydraulic lime and 10 l of water;
- Remaining 10 l of river sand and 10 l of hydraulic lime was added and mixed with remaining water and 30 l of sand quarry. All ingredients are further mixed in the electric mixer;
- During the complete process the water was added as needed. Sometimes during the preparation of hydraulic mortar, it is required to use more than 15 l of water. It is worth noting that quantity of water depends on the humidity of sand. If the sand is wet, less quantity of water should be applied, whereas in the case where sand is dry, more water is needed.

Hydraulic mortar was prepared at the following average temperatures:

- inside temperature of 23.8°C, and
- outside temperature of 26.5°C.

The procedure of hydraulic mortar mixing is presented in Figure 22.

For this work the same mortar and procedure of preparing mortar like in old buildings are adopted.

2) Preparation of air lime mortar: Before providing the detailed explanation of the process of obtaining air lime mortar, it is worthwhile to elaborate the process of obtaining cooked lime stone and air lime.

- *Process of obtaining cooked stone:*
  Lime stone is put in the oven at the temperature between 200°C and 300°C, and during this process, the black smoke from the oven can be seen. After approximately 24 hours, stone is cooked and obtains the white color. Comparing the weight of cooked stone and the weight of the not-cooked stone, it

Fig. 22. Hydraulic mortar preparation.

Fig. 23. Air lime mortar preparation.

Fig. 24. Boiling of mass.

Fig. 25. First phase: Sand mix preparation.

can be evidenced that the cooked stone has less weight and is not as strong as the stone which is not cooked, thus can be broken very easily.

- *Process of obtaining air lime:*
  For this procedure a big barrel is needed, where the cooked stone should be added slowly to the already introduced amount of water. All the time it should be mixed with the big piece of wood, as seen in Figure 23. After one or two minutes, the mass starts to boil, as depicted in Figure 24, which designates the point where more water and stone should be added alternately. The color of this mass is white, and at very high temperature all the time.
  In our case, the explained process is conducted at the outside temperature of 29°C. When boiling is finished, temperature of the mass was about 90°C – 95°C. The obtained mass cannot be used immediately, and has to be left to mature for one more day to reach the adequate temperature to be used in mortar preparation. After the process is finished, the cap is put on the barrel. At the same day, after eight hours, the temperature in the barrel was about 40°C – 45°C.

- *Preparation of air lime mortar:*
  For the preparation of air lime mortar, the adopted mortar mix proportion was as follows:
  - 20 l of air lime,
  - 30 l of river sand,
  - 30 l of sand quarry,
  - 3 l of water (sometimes it is necessary to add even bigger amount of water).

  During the process of making this type of mortar, the mixer was not employed. This mortar was completely prepared manually, in a big plate of rectangular shape. The process of obtaining the air lime mortar consists of three phases, namely:
  - *First phase:* River sand and sand quarry are alternately put as needed, (Figure 25).
  - *Second phase:* Air lime is added and everything is mixed together, (Figure 26).
  - *Third phase:* In this phase it is necessary to add water and to mix everything together, while the compact mass is not attained, (Figure 27).

  After concluding these three phases, the obtained mass can be used for construction of the wall specimens.

F. Implementation and testing of specimens of mortar

1) General considerations: As already mentioned, the walls were constructed using the two types of mortars, *i.e.*, hydraulic mortar and air lime mortar. Mortar test should be conducted according to ASTM E519-02 standard [4] to provide the characteristic of mortar, which is important for walls specimens where this mortar is used. For each type of mortar nine prismatic specimens with dimensions 160×40×40 mm are used, following the indications of the EN 1015-11 (*Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar*) [10], and also three cylindrical specimen of 150 mm in diameter and 300 mm in height are considered. The prismatic specimens are designed to obtain the flexural strength, and the half-prisms resulting from this test is used to test compressive strength. The cylindrical specimens are tested to determine the compressive strength and modulus of elasticity.

2) Implementation of prismatic specimens: Nine prismatic molds were filled with each type of mortar. The excess mortar on the surface of the mold was removed in the smoothing operation using the edge of a metal spatula. The excess mortar removal was performed by moving the edge of spatula horizontally, along the longer dimension of the mold. The molds are shown in Figure 28.

(a) Both sand types and air lime

(b) Start of material mixing

(c) Further mixing of materials

(d) Mixing before addition of water

Fig. 26. Second phase: Preparation of air lime mortar

(a) Adding water

(b) Mixing with water

(c) Further material mixing

(d) Further material mixing

(e) Air lime mortar

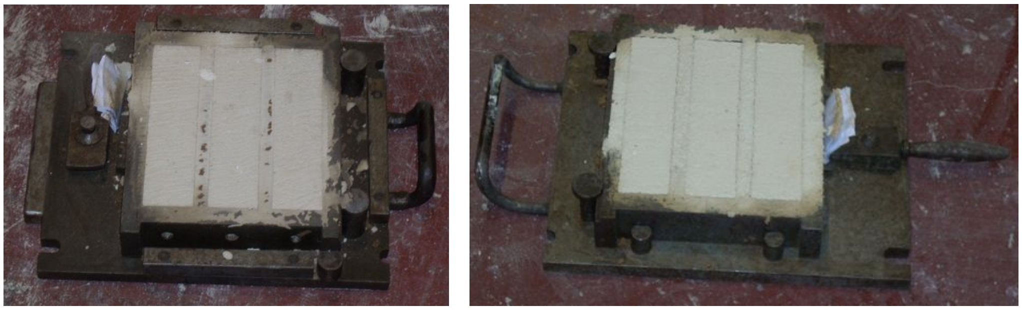
Fig. 27. Third phase: Preparation of air lime mortar.

3) Implementation of cylindrical specimens: The cylindrical molds were filled with a trowel and the pressure exerted on the top of the cylinder is applied to compress the material. Excess mortar was removed in the smoothing operation, by horizontal movements over the material surface. Cylindrical molds are shown in Figure 29.

Both type of specimens, prismatic and cylindrical, were put next to the wall and at the same temperature as the wall, according to the ASTM E519-02 standard [4].

It worth noting that molds with hydraulic mortar can be tested after two months, whereas the molds with air lime mortar can only be tested after six months.

4) Testing of prismatic specimens: The procedure for testing the flexural and compressive strength of prismatic mortar specimens is based on EN 1015-11 (*Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened*



(a) (b)

Fig. 28. Prismatic test tubes of mortar: (a) Mold of hydraulic mortar, and (b) Mold of air lime mortar.

(a) (b)

Fig. 29. Cylindrical test tubes of mortar: (a) Mold of hydraulic mortar, and (b) Mold of air lime mortar.

Fig. 30. Prismatic specimens with hydraulic mortar.

Fig. 31. Prismatic specimens with air lime mortar.

Fig. 32. Specimen weight measuring.

mortar) [10] standard. On 13th of January, 2011, the prismatic specimens with hydraulic and air lime mortar were taken out from the mold, as shown in Figure 30. One prismatic specimen with air lime mortar was broken before testing, as can be seen in Figure 31.

Before prismatic specimen testing, the weight of each specimen was measured, as depicted in Figure 32.

For both mortar types, the prismatic specimens are made to obtain the flexural strength, and the half-prisms resulting from this test are used to test compressive strength. The general procedure is depicted in Figures 33 and 34.

In order to obtain the flexural and compressive strength of mortar specimens, the general testing procedure requires to perform different phases, as shown in Figures 35 and 36.

It is important to emphasize that the broken specimen (which is broken on his right side) with air lime mortar was also tested, as in shown in Figure 37 and the obtained results are surprisingly better comparing to the results for some of not destroyed specimens. For all specimens, except the destroyed one, the crack in the flexural strength test has appeared more or less in the specimen's middle.

- *Determination of flexural strength*

The apparatus for determination of flexural strength

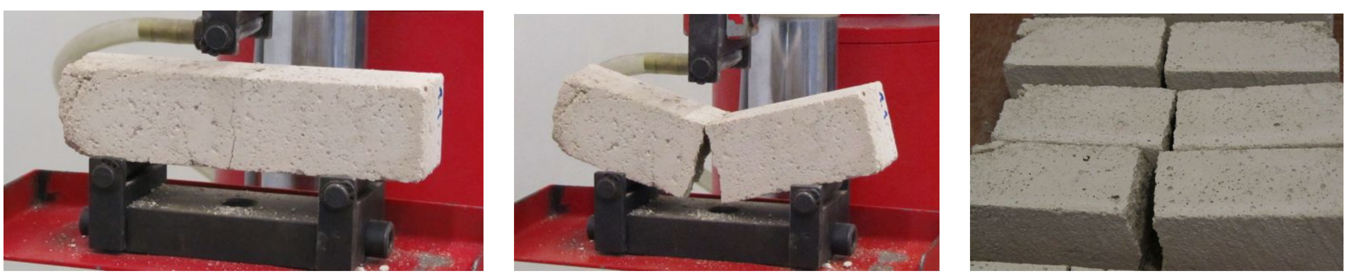
(a) (b)

Fig. 33. Test of hydraulic prismatic specimens: (a) Flexural strength test, and (b) Compressive strength test.

(a) (b)

Fig. 34. Test of air lime prismatic specimens: (a) Flexural strength test, and (b) Compressive strength test.

(a) Test preparation (b) Specimen in the machine

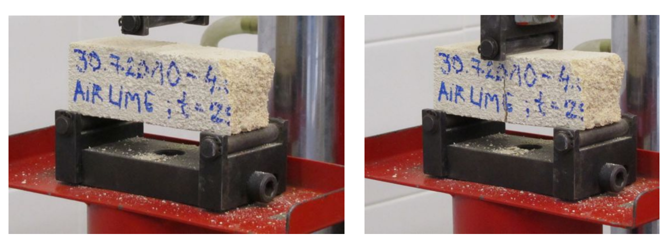


(c) Crack has appeared (d) Destroyed specimen (e) Specimen after the testing

Fig. 35. Flexural strength test: Different phases.

(a) (b)

Fig. 36. Compressive strength test. Different phases: (a) Specimen in the machine, (b) Crack has appeared.



(a) (b)

Fig. 37. Phases during the testing before damaged prismatic specimens to obtain flexural strength: (a) Specimen in the machine, (b) Crack has appeared.

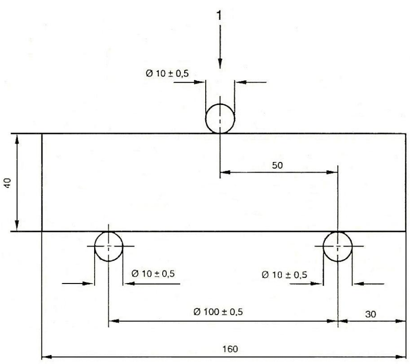


Fig. 38. Flexural strength test according to EN 1015 – 11 (dimensions in [mm]).

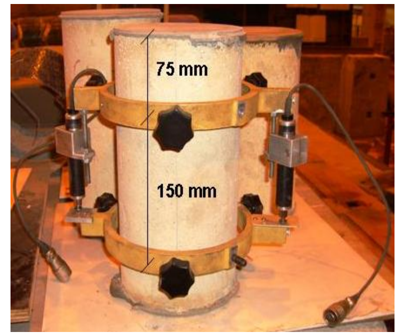


Fig. 39. Assembly of deflections for modulus of elasticity test [1].

consists of a machine with two steel supporting rollers of length between 45 mm and 50 mm and 10±0.5 mm diameter, spaced 100±0.5 mm apart, and a third steel roller of the same length and diameter located centrally between the support rollers, as can be seen on Figure 38. The three vertical planes through the axes of the three rollers should be parallel and remain parallel, equidistant and normal to the direction of the prism under test. One of the supporting rollers and the loading roller should be capable of tilting slightly to allow a uniform distribution of the load over the width of the prism without subjecting it to any torsional stresses.

(a) *Preparation*
Before testing, the bearing surfaces of the roller and the sides of specimen should be wiped with a clean cloth to remove any loose grit or other material. Specimen should be placed with one of its sides on the supporting rollers.

(b) *Loading*
Load should be applied without shock, at a uniform rate in the range of 10 N/s to 50 N/s, so that failure occurs within a period of 30 s to 90 s. After the load application, the broken specimen should be returned to the storage chamber and kept for compressive strength measurements.

(c) *Calculation and expression of results*
Flexural strength, f, is calculated using the following expression:

$$f = 1.5 \times \frac{F \times l}{b \times d^2} \text{ [N/mm}^2\text{]} \qquad (10)$$

- F is the maximum load applied to the specimen in [N],
- l is distance between the axes of the support rollers in [mm],
- b is width of specimen [40 mm], and
- d is depth of specimen [40 mm].

- *Determination of compressive strength*

(a) *Loading*
Load should be applied without shock and increased continuously at a rate within range 50 N/s to 500 N/s, so that failure occurs within a period of 30 to 90 s.

(b) *Calculation and expression of results*
The value of the compressive strength, f_c, was calculated using the expression:

$$f_c = \frac{F}{A} \text{ [MPa]} \qquad (11)$$

- F is the maximum load applied to the specimen in [N], and
- A is contact area in [mm^2].

It is worth noting, that compressive strength test was performed with half-prisms resulting from flexural strength test. The specimens have been placed in the half-prisms machine with contact area of 1600 mm^2. The samples were placed so that the load was applied at one side, which was in contact with the metal mold.
Table IV and Table V presents the test results for prismatic specimens of hydraulic mortar and of air lime mortar, respectively.

5) Testing of cylindrical specimens: The cylindrical specimens are tested to determine the compressive strength and modulus of elasticity, and should be tested at the same day as the large walls.

After the top and bottom of the cylindrical specimens are rectified, two rings are placed at a distance of 75 mm from the top, and then the reading through deflections (150 mm) is performed for the modulus of elasticity, as it can be seen on Figure 39.

In order to perform this test, a hydraulic press is used with maximum capacity of 250 kN and accuracy of

TABLE IV
RESULTS FOR HYDRAULIC MORTAR PRISMATIC SPECIMENS

Hydraulic mortar	**Weight [g]**	F_{crack} **[N]**	**Flexural strength** f **[N/mm^2]**	**Half prism**	F_{crack} **[N]**	**Compressive strength** f_c **[N/mm^2]**
Prism 1	456.5	160	0.38	1A	2240	1.4
				1B	2080	1.3
Prism 2	460.3	146	0.34	2A	2230	1.39
				2B	2410	1.51
Prism 3	458.8	139	0.33	3A	2340	1.46
				3B	2240	1.40
Prism 4	465.9	157	0.37	4A	2460	1.54
				4B	2460	1.54
Prism 5	464.2	135	0.32	5A	2370	1.48
				5B	2500	1.56
Prism 6	468.5	169	0.39	6A	2750	1.72
				6B	2930	1.83
Prism 7	464.9	154	0.36	7A	2310	1.44
				7B	2330	1.46
Prism 8	459.3	174	0.41	8A	2050	1.28
				8B	2080	1.30
Prism 9	466.5	133	0.31	9A	2140	1.34
				9B	2410	1.51
Average			0.35			1.47

TABLE V
RESULTS FOR AIR LIME MORTAR PRISMATIC SPECIMENS

Hydraulic mortar	**Weight [g]**	F_{crack} **[N]**	**Flexural strength** f **[N/mm^2]**	**Half prism**	F_{crack} **[N]**	**Compressive strength** f_c **[N/mm^2]**	**Length [cm]**
Prism 1	435.7	106	0.25	1A	890	0.56	
				1B	880	0.55	
Prism 2	426.2	111	0.26	2A	860	0.54	
				2B	910	0.57	
Prism 3	430.6	51	0.12	3A	860	0.54	
				3B	860	0.54	
Prism 4	423.1	113	0.26	4A	890	0.56	
				4B	870	0.54	
Prism 5	434.6	126	0.295	5A	910	0.57	
				5B	940	0.59	
Prism 6	429.1	127	0.297	6A	890	0.56	5.20
[broken]				6B	920	0.58	5.50
Prism 7	427.1	115	0.27	7A	860	0.54	8
				7B	910	0.57	8
Prism 8	428.2	104	0.24	8A	940	0.59	8
				8B	910	0.57	8
Prism 9	426.6	119	0.28	9A	840	0.53	8.4
				9B	840	0.53	7.6
Average			0.25			0.56	

0.01 kN. The load application is controlled at 0.1 kN/s and the applied forces, elapsed time and deformations by those deflections are recorded.

IV. Mechanical characterization of rubble stone masonry using other research works

In the recent past, Carvalho [1] conducted in Instituto Superior Técnico (IST), Lisbon, Portugal a set of experiments using the same type of materials, used in the present work, *i.e.* the walls specimens were built using the traditional stone from Portugal, obtained from the same quarry. Hydraulic mortar, air lime mortar and air lime with cement were also used for the construction of wall specimens in [1]. In the above-mentioned work several tests were performed, such as mortar and stone tests, compression test on the small specimens, and flat jack test for big specimens. The following sections summarize the achievements and results presented in [1].

A. *Tests of mortar, cubics and small wall specimens*

1) Tests of mortar specimens:

- *General considerations*
  As mentioned, the ordinary masonry walls specimens were made with different mortars: air lime mortar, hydraulic lime mortar and mortar with hydraulic lime and cement. Correspondingly, mortar tests were also performed. For each type of mortar, six prismatic specimens with dimensions 160×40×40 mm were used, following the indications of the EN 1015-11 (*Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar*) [10], and a cylindrical specimen of 150 mm in diameter and 300 mm in height was considered. The prismatic specimens were designed to obtain the flexural strength of the mortar and the half-prisms, resulting from this test, were used to test the mortar compressive strength. The cylindrical specimens were tested to determine the compressive strength and modulus of elasticity of the mortar.

- *Testing of prismatic specimens*
  The procedure for testing flexural and compressive strength is based on EN 1015-11 (*Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar*) standard [10].
  The tests were performed after 28 days and 6.5 months, respectively for prismatic specimens of the mortar used in big and small walls. Results presented in Table VI are the average values of flexural and compressive strength, obtained by testing the prismatic specimens.

TABLE VI
Averaged results obtained for prismatic specimens [1]

Type of Mortar	Days	R_f [MPa]	R_c [MPa]
Air Lime Mortar	28	0.13	0.21
	195	0.32	0.63
Hydraulic Mortar	28	0.25	1.27
	195	0.29	1.09

R_f – Flexural strength
R_c – Compressive strength

- *Testing of cylindrical specimens*
  The cylindrical specimens were tested after 6.5 months. A sample of each mortar (air lime mortar and hydraulic mortar) was tested to determine modulus of elasticity and compressive strength. To perform the test, hydraulic press was used with maximum capacity of 250 kN and accuracy of 0.01 kN. The applied load was controlled at 0.1 kN/s and the applied forces, elapsed time and deformations by deflections were recording using the connected computer equipment, as presented in Figure 40.
  Table VII presents the results of ultimate stress and the modulus of elasticity obtained in [1] for compression test. The ultimate stress was calculated by dividing the recorded ultimate load with the area of the specimen. The module of elasticity was calculated for a load level of 30% of ultimate load, *i.e.*, when the specimen was still in the regime of linear elastic behavior.
  Based on the obtained results, Carvalho [1] suggests that for each type of mortar modulus of elasticity

TABLE VII
Estimated results obtained for cylindric specimens [1]

Cylindrical specimens	Ultimate load [kN]	Ultimate stress [MPa]	Modulus of elasticity [GPa]
Air lime mortar	7.1	0.40	1.22
Hydraulic mortar	18.81	1.06	0.77

TABLE VIII
Flexural and compressive strength for each type of mortar [1]

Type of mortar	Flexural strength [MPa]	Compressive strength [MPa]
Air lime mortar	0.25	0.60
Hydraulic mortar	0.25	1.00

Fig. 40. Cylindrical specimen prepared for modulus of elasticity testing [1].

Fig. 41. Cubic specimens [1].

Fig. 42. Testing of cubic specimens [1].

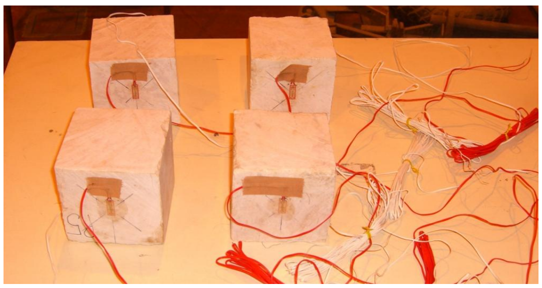


Fig. 43. Cubic specimens with strain gauges [1].

Fig. 44. Modulus of elasticity testing [1].

Fig. 45. Rupture test [1].

of 1.20 GPa should be considered and the values for flexural and compressive strength as indicated in Table VIII.

2) Testing of stone samples:

- *General considerations*
  Simultaneously with the construction of the walls, the used cubic pieces of stones were taken to assess their compressive strength and the modulus of elasticity. For construction of these specimens, test procedures and their calculations, NP EN 772-1 2002 (*Métodos de ensaio de blocos para alvenaria – Parte 1: Determinação da resistência à compressão*) standard [12] was used. The six cubic specimens with 10 cm of length were built, and an extra cube due to a fault occured at the edge of one of the six cubes (cube 1), as shown in Figure 41. After cutting, the cubes were stored and air-dried in the laboratory.

- *Testing of cubic stones*
  Before performing the test for determining the modulus of elasticity of the stone cubes, the three out of the seven cubes are taken and testing until rupture, in order to assess their compressive strength. The three cubes are presented in Figure 42. Since the literature presents a very wide range for the ultimate stress for this stone type [13], a gradual force was applied to the cubic pieces of stone, with a speed of 8 kN/s until the failure was achieved. Furthermore, the values of the crushing forces of compression are also recorded. As presented in Table IX, the compressive strength obtained by test is 28 MPa, which is relatively low in comparison to the limits indicated by the state of the art research works.
  It is worth noting that the disintegration of the stones was in the form of small stone pieces, showing the few signs of crushing. After finishing the tests on three samples in order to measure the average value of compressive strength, the testing of other specimens was conducted in order to determine the modulus of elasticity. For each of the cubes, two TML "electric" gauges were placed, type PL-10-11 (*Tokyo Kenkyujo Sokkia Co., Ltd.*), 10 mm in length, at each side on the half height of the cube, as depicted in Figure 43.
  The modulus of elasticity was determined by using the hydraulic press with maximum capacity of 250 kN and precision of 0.01 kN, connected to a computer equipment for recording the applied forces, elapsed time and extensions of these gauges, as shown in Figure 44.
  The modulus of elasticity test was carried out according to LNEC E397 standard, and with three cycles of charge/discharge for each specimen. The first and second cycle were performed at a rate of

TABLE IX
TEST RESULTS OF COMPRESSION STRENGTH FOR CUBIC SPECIMENS - I [1]

Specimens		Test Date	Ultimate Load [kN]	Compression Strength [MPa]	
N○	Section [cm^2]			Individual Values	Average
1	100	23-03-2007	417	42	**28**
2	100	23-03-2007	248	25	
3	100	23-03-2007	183	18	

TABLE X
TEST RESULTS OF COMPRESSION STRENGTH FOR CUBIC SPECIMENS - II [1]

Specimens		Compression Strength [MPa]	1/3 of Compression Strength [MPa]
N°	Section [cm^2]		
4	100	41	14
5	100	71	24
6	100	91	30
7	100	47	16

TABLE XI
AVERAGE VALUES OBTAINED WITH TESTS PERFORMED ON CUBIC SPECIMENS [1]

Cubes	Ultimate load [kN]	Compressive strength [MPa]	Modulus of elasticity E (1/3 of ultimate load) [GPa]
Average values	478	48	74

1 kN/s, until 70 kN (1/3 of estimated ultimate load) and the third cycle was conducted at a speed of 2.5 kN/s, until 250 kN (estimated force to put the specimen into rupture). It is worth to emphasize that the specimen 6 was the only one on which two cycles of loading/unloading were performed, namely, the first cycle at a speed of 1 kN/s, until 140 kN and the second at a speed of 2.5 kN/s, until 250 kN. However, despite applying the estimated load of 250 kN (corresponds to the stress of 25 MPa) in the last cycle, which was supposed to be theoretically sufficient to put the cubic specimens into failure, this amount of load was not sufficient to bring the specimens to rupture. Limited by 250 kN of the maximum force that can be applied with the used press, the specimens were again subjected to compression but using another type of press capable of providing higher amounts of force. The first three specimens were initially tested until failure, in order to determine the compression strength and to identify the modulus of elasticity (1/3 of compression strength), as depicted in Figure 45.
Table X summarizes the results obtained with four tests conducted on cubic stone samples. It was possible to calculate the modulus of elasticity for 1/3 of compression strength for all samples except for sample 6. In case of sample 6 the calculated modulus of elasticity is higher than 25 MPa, which supersedes the attainable modulus of elasticity by the used press calculated for the maximum stress, *i.e.*, 250 kN corresponding to 25 MPa stress for 10 cm cubic sample.
Table XI presents the average values obtained from tests performed on the cubic specimens. After performing the compression tests, it was found that the results greatly varied and that the tests on the same stone type can provide different values for the compression strength, which correspondents to the range of values presented by *Tabelas Técnicas* [13].

3) Compression test on small walls: As mentioned above, compression tests was performed on the two small specimens walls, each constructed with the different type of mortar, namely, with air lime mortar and with hydraulic mortar. The tests were conducted in order to determine the modulus of elasticity and the walls compression strength, according to NP EN 1052-1 2002 *(Método de ensaio para alvenaria – Parte 1: Determinação resistência à compressão)* standard [14].

The tests were performed on a press with a maximum force of 3000 kN, and four deflectometers were placed on each wall (pairs of two deflectometers at each side of the specimen). After the wall was placed and centered on the machine, a load cell was mounted at the top of the specimen, capable to record the applied load (until

TABLE XII
THE RESULTS OBTAINED WITH COMPRESSION TEST FOR THE SMALL WALLS SPECIMENS [1]

Small Walls	Estimated values		Average values		
	Ultimate load [kN]	Compression strength [MPa]	Ultimate load [kN]	Compression strength [MPa]	Modulus of elasticity E (1/3 of ultimate load) [GPa]
Air Lime Mortar	900	5.62	397	2.48	0.25
Hydraulic Mortar	1500	9.37	1108	6.92	0.48

TABLE XIII
OBTAINED MODULUS OF ELASTICITY FOR SMALL AND BIG WALLS SPECIMENS [1]

	Modulus of elasticity	
	Small walls [GPa]	Big walls [GPa]
Air Lime Mortar	0.25	0.41
Hydraulic Mortar	0.48	1.65

TABLE XIV
RESULTS OBTAINED BY SINGLE FLAT-JACK TEST ON BIG WALLS [1]

Big walls	Single flat-jack test	
	$\sigma_{Installed}$ [MPa]	$\sigma_{Average}$ [MPa]
Air lime mortar	0.5	0.78
Hydraulic mortar	0.75	0.8

3000 kN) and the release times, as shown in Figure 46.

The first tested wall specimen was built with air lime mortar and the ultimate load of 900 kN was obtained, which corresponds to compression strength of 5.6 MPa, as determined in [15]. Furthermore, the second wall specimen under the test was built with hydraulic mortar, which ultimate load is obtained to 1500 kN, which corresponds to compression strength of 9.4 MPa, as found in [15].

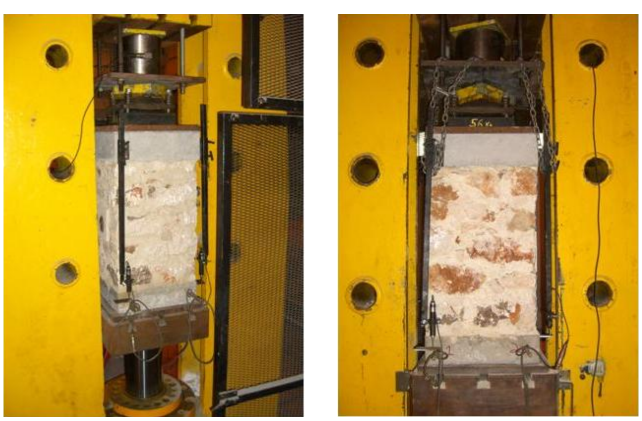
Table XII presents the results obtained when performing compression test of two small wall specimens.

B. Flat-jack tests on big walls

The flat-jack tests are used to assess in situ important mechanical characteristics of masonry. In [1] two types of flat-jack tests were performed on big specimen walls, namely *single flat-jack test* and *double flat-jack test*. The single flat-jack test is used for determination of the local stress state of the wall, whereas double flat-jack test estimates the modulus of elasticity and compressive strength of masonry. These techniques are widely used for large masonry walls, on which the load is applied on top of specimen by hydraulic jack(s), as presented in Figure 47.

1) Initial load application: The initial load applied to the walls built with hydraulic mortar was 600 kN, whereas the walls built with air lime mortar was applied with the load of only 400 kN. The rationale behind adopting the lower load value lies in the fact that the cracks in the walls with the air lime appear even when the walls are subjected to the load of 500 kN.

From the aspect of the modulus of elasticity, which is calculated for the loads close to 1/3 of the ultimate load according to standard NP EN 1052-1 2002 [14], the obtained values which is summarized in Table XIII were



(a) (b)

Fig. 46. Testing of small walls: (a) Wall with air lime, and (b) Wall with hydraulic lime [1].

Fig. 47. Frame used for flat-jack testing of large walls [1].

TABLE XV
TEST RESULTS OBTAINED WITH DOUBLE FLAT-JACK TEST ON BIG WALLS [1]

Big walls	**Double flat-jack test**		
	Compression strength σ_u [MPa]	**Modulus of elasticity E (1/3 σ) [GPa]**	**ν Poisson**
Air lime mortar	2.38	0.08	–
Hydraulic mortar	5.33	0.37	0.18

TABLE XVI
THE RESULTS OBTAINED WITH RUPTURE TEST ON WALLS WITH AIR-LIME MORTAR [1]

Big walls	**Rupture test**		
	Ultimate load F_u [kN]	**Compression strength σ_u [MPa]**	**Modulus of elasticity E (1/3 σ) [GPa]**
Air lime mortar	659	0.82	0.69

consistent with the values obtained for the previously tested small walls specimens.

2) Single flat jack test on big walls: Single flat-jack test is used to determine the state of tension and to evaluate the deformability characteristics of masonry, as regulated by following standards:

- ASTM C1196-04 – *Standard test method for in situ compressive stress Within Solid Unit Masonry Estimated flat-jack measurements*,
- ASTM C1197-04 – *Standard test method for in situ measurement of masonry deformability properties using flat-jack the method*,
- RILEM TC177-MDT.D.4 – *In-situ stress tests based on the flat jack*, and
- RILEM TC177-MDT.D.5 – *In-situ stress-strain behavior tests based on the flat jack*.

The test methodology is based on the following assumptions [16]:

- The local stress state is uniform compression;
- The masonry around the crack is uniform;
- Masonry deforms symmetrically in relation to the crack;
- The stress applied to the masonry by the flat-jack is uniform; and
- The masonry is elastic, namely irreversible damage to the masonry should not be visible.

In order to calibrate the technique for flat-jack testing and to characterize the mechanical behavior of masonry walls, the simple flat-jack tests were performed on each wall specimens. As previous mentioned, the walls specimen were loaded with the initial load of 600 kN (hydraulic lime mortar) and 400 kN (air lime mortar). The results obtained by performing this type of test on big walls specimen are presented in Table XIV.

3) Double flat-jack test on big walls: Double flat-jack test is used to determine the modulus of elasticity and compressive strength of masonry walls.

In [1], the test planning was based on two standards, namely ASTM C1197-04 (*Standard Test Method for In Situ Measurement of Masonry Deformability Properties Using the Flat-jack Method*) [17], and RILEM TC-D5 MDT (*In-situ stress strain behavior tests based on the flat jack*) [18] standards.

Following the single flat-jack testing, double flat-jack testing was performed on each wall. As before the tests were performed with the initial load of 600 kN for the walls specimen built with hydraulic mortar, and 400 kN for the walls specimens built with air lime mortar. The tests results are presented in Table XV.

4) Testing the rupture of the walls with air-lime mortar: After completing the flat-jack tests, the wall specimen made of air-lime mortar was repaired (the holes of the flat-jack were filled with mortar) and subjected to the higher loads in order to provide better understanding of their behavior under higher compression and to register their ultimate load. The results of this destructive test are presented in Table XVI.

REFERENCES

[1] J. Carvalho, "Caracterização mecânica de paredes resistentes em alvenaria de pedra através de ensaios não destrutivos," Master's thesis, Instituto Superior Técnico, 2008.

[2] E. BS, "1052-1: 1998," *Methods of test for masonry-Part 1: Determination of compressive strength*, 1998.

[3] I. Standard, "Recommendations for the analysis, conservation and structural restoration of architectural heritage," *ICOMOS, International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage*, 2003.

[4] A. Standard, “ASTM E519-02, Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages,” *ASTM International, West Conshohocken, PA*, 2002.

[5] M. Corradi, A. Borri, and A. Vignoli, “Experimental study on the determination of strength of masonry walls,” *Construction and Building Materials*, vol. 17, no. 5, pp. 325–337, 2003.

[6] A. Brignola, S. Frumento, S. Lagomarsino, and S. Podestà, “Identification of shear parameters of masonry panels through the in-situ diagonal compression test,” *International Journal of Architectural Heritage*, vol. 3, no. 1, pp. 52–73, 2009.

[7] E. UNI, “1052-3: 2003,” *Methods of test for masonry-Determination of initial shear strength. Ente Nazionale Italiano di Unificazione (UNI)*, 2003.

[8] A. Prota, G. Marcari, G. Fabbrocino, G. Manfredi, and C. Aldea, “Experimental in-plane behavior of tuff masonry strengthened with cementitious matrix–grid composites,” *Journal of Composites for Construction*, vol. 10, p. 223, 2006.

[9] P. Lourenço, J. Barros, and J. Oliveira, “Shear testing of stack bonded masonry,” *Construction and Building Materials*, vol. 18, no. 2, pp. 125–132, 2004.

[10] E. CEN, “1015-11: 1999,” *Methods of test for mortar for masonry-Part 11: Determination of flexural and compressive strength of hardened mortar*, 1999.

[11] EC 6, “Eurocode 6 - Design of masonry structures, part 1-1: general rules for buildings - rules for reinforced and unreinforced masonry.” *ENV 1996-1-1:1995*, 1995.

[12] N. IPQ, “EN 772-1: 2002,” *Métodos de ensaio de blocos para alvenaria Parte I: Determinação da resistência à compressão*, 2002.

[13] J. S. Farinha B, M. Farinha B, J. P. Farinha B, and A. Correia Dos Reis, “Tabelas Técnicas. Edições Técnicas E. T. L,” *LDA*, 2003.

[14] N. IPQ, “EN 1052-1: 2002,” *Métodos de ensaio para alvenaria Parte I: Determinação da resistência à compressão*, 2002.

[15] J. Segurado, *Biblioteca de Instrução Profissional Alvenaria, cantaria e betão*. Livraria Bertrand, Lisboa, 1908.

[16] P. Gregorczyk and P. Lourenço, “A review on flat-jack testing,” 2000.

[17] A. Standard, “ASTM C1197-04, Standard test method for in situ measurement of masonry deformability properties using the flat-jack method,” *ASTM International, West Conshohocken, PA,*, 2004.

[18] R. T. Standard, “RILEM TC 177-MDT.D.5, In-situ stress strain behavior tests based on the flat jack,” *RILEM TC*, 2004.