Experimental Research on Rubble Stone Masonry Walls

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SUMMARY: This paper refers to the results of a research project carried out at Nova University of Lisbon (Pinho [8]), where several experimental models of rubble stone masonry walls were subjected to axial compression and shear-compression tests. The aim of this research project was the experimental evaluation of some structural strengthening solutions for rubble stone masonry buildings.

The results of some tests performed to determine physical, chemical and mechanical properties of the constituent materials of the experimental masonry models are also presented.

This experimental work was made in cooperation with LNEC, and it was sponsored by some industrial companies.

KEY-WORDS: Experimental analysis, masonry, mortar.

INTRODUCTION

According to the National Statistic Institute (INE [4]), there are about 3.160.000 buildings in Portugal. A significant percentage was built with structural masonry walls, namely stone masonry walls. Most of them are located in villages and towns centres, and constitute a reference of their places.

A large number of those masonry walls have a high percentage of lime mortar in their constitution, and, consequently, present poor mechanical behaviour to foundations settlements and, specially, to seismic actions. This last aspect is very important because Portugal is located near the frontier between two important tectonic plaques (African and Euro Asiatic plaques) and, therefore, exposed to strong seismic activity – like the ones occurred at 1755 and, more recently, in some Azores Islands at 1998 –, with devastating human and material consequences.

Sometimes, those mechanical problems are enlarged by disaggregating phenomena that can occur in such masonry walls.

MAIN PROPERTIES OF THE CONSTRUCTION MATERIALS OF THE EXPERIMENTAL MODELS

Some physical, chemical and mechanical properties of the construction materials are presented. These properties are: (i) bulk density, open porosity, volumetric coefficient, chemical constituents and mechanical resistance, for **stones**; (ii) particle size distribution curves, bulk density, loose bulk density, voids volume percentage, content of fine particles and chemical constituents, for **sands**; (iii) particle size distribution curve and chemical characteristics, for **hydrated lime** and (iv) flow table consistency, bulk density, open porosity, capillary absorption coefficient, vapour permeability coefficient, compression resistance, dynamic elasticity modulus and carbonation depth, for **mortar**.

Stones

The models were built with stones from Rio Maior. Some of them, with larger dimensions, were used to obtain bigger units than the others, figure 1. These bigger stone blocks were used in general at 1/3 and 2/3 of the height of the experimental models, corresponding to 0,40 m and 0,80 m up to their bases, respectively. These bigger stones are named by "*perpianhos*". Table 1 present the mean values of the analysed characteristics of stones.

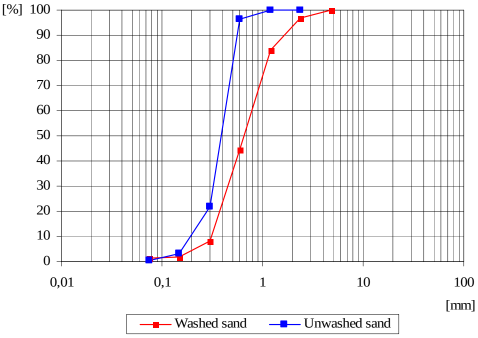
Figure 1 – Preparation of the stones used in the construction the experimental models

Table 1 - Mean values of physical, chemical and mechanical characteristics of stones

Characteristics		**Mean Values**
Physical	Bulk density	2491 kg/m^3
	Open porosity	8,1 %
	Volumetric coefficient	0,26
Chemical	Calcium oxide [CaO]	54,91 %
	Silicon dioxide [SiO_2]	0,52 %
	Aluminium trioxide [Al_2O_3]	0,46 %
	Iron trioxide [Fe_2O_3]	0,12 %
	Magnesium oxide [MgO]	0,33 %
	Potassium oxide [K_2O]	0,02 %
	Loose on ignition (LOI)	43,52 %
Mechanical	Mechanical resistance	47,8 MPa

Sands

The models were built with sands from Rio Maior, which main characteristics are presented both in figure 2 and table 2.



	Yellow pit sand (unwashed)	River sand (washed)
Maxim Dimension (D) [mm]	0,595	2,38
Minimum Dimension (d) [mm]	0,149	0,149
Fineness Modulus (Fm)	1,8	2,7

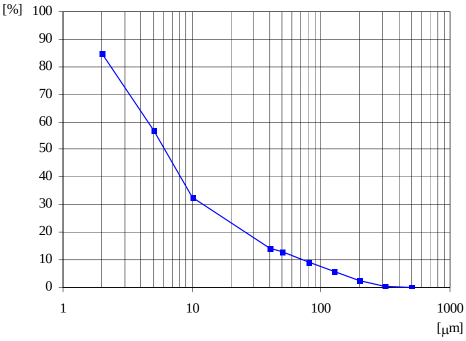
Figure 2 – Particle size distribution curves of both sands

Table 2 - Mean values of physical and chemical characteristics of sands

	Characteristic	Mean Values	
		River sand	Yellow pit sand
Physical (105 ± 5 ºC)	Bulk density	2625 kg/m^3	2647 kg/m^3
	Loose bulk density	1584 kg/m^3	1539 kg/m^3
	Voids volume percentage	38,2 %	39,5 %
	Content of fine particles	1,2 %	7,6 %
Chemical	Silicon dioxide (SiO_2)	98,0 %	87,8 %
	Aluminium trioxide (Al_2O_3)	1,70 %	7,34 %
	Iron trioxide (Fe_2O_3)	0,11 %	0,85 %
	Calcium oxide (CaO)	0,18 %	0,17 %
	Magnesium oxide (MgO)	0,01 %	0,09 %
	Potassium oxide (K_2O)	0,01 %	3,39 %

Lime

The majority of the models were built with hydrated lime produced by Lusical Company. Figure 3 and table 3 show physical and chemical characteristics of the used lime.



Mean diameter = 6,07 μm

Figure 3 – Particle size distribution curve of the lime

Table 3 – Mean values of chemical characteristics of the hydrated lime

	Characteristics	Mean Values [%]
Chemical	Calcium hydroxide $Ca(OH)_2$	93,5
	Calcium carbonate $CaCO_3$	3,86
	Magnesium hydroxide $Mg(OH)_2$	0,52
	Calcium sulphate $CaSO_4$	0,51

Mortar

The models were built with lime mortar, using a volumetric composition 1:3 (lime:sand), figure 4. This composition was defined according to researches about the composition of mortars used in Lisbon Pombaline Old Town (Nero [2]) and the analysis of several mortars (Veiga [14]). The ratio water/lime was equal to 1,2, and sands had two origins: river and yellow pit sands, as mentioned in figure 2.

Figures 5 and 6, and table 4, shows physical and chemical characteristics of the mortar.

Figure 4 – Lime mortar production using a mechanical mixer

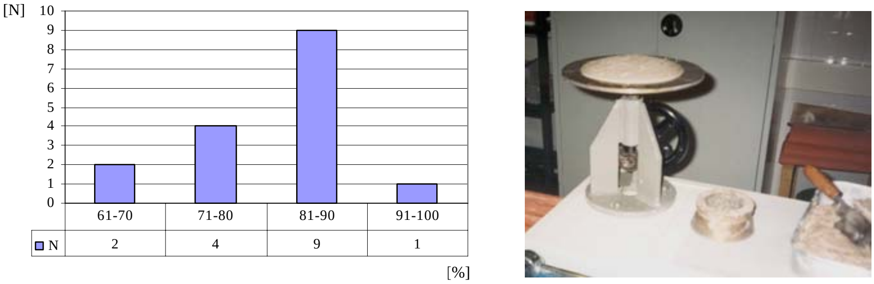


Figure 5 – Flow table consistency of the mortar

Table 4 – Main values of physical, mechanical and chemical characteristics of the mortar

	Characteristics (90 days)	Mean Values
Physical	Bulk density	1743 kg/m^3
	Open porosity	32,7 %
	Absorption coefficient	17,4 $kg/m^2.h^{1/2}$
	Permeability coefficient	$17,74\times10^{-12}$ kg/m.s.Pa
Mechanical	Compression resistance	0,65 MPa
	Dynamic elasticity modulus	2310 MPa

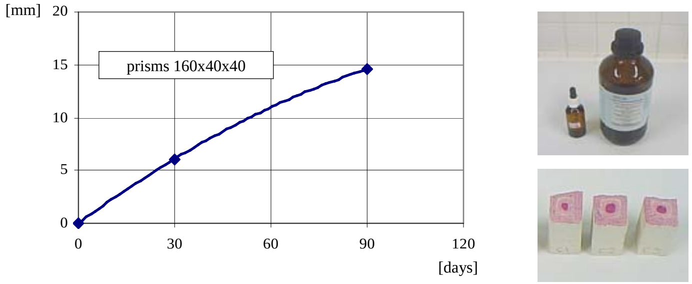


Figure 6 – Carbonation depth of the lime mortar’s prismatic specimens

The results of mechanical parameters of the mortar, presented in table 4, were achieved at 90 days of curing. However, in this research (Pinho [8]), the mean values (σ=0,6MPa) considered to analyze the mechanical behavior of the reference models were taken at 607 and 739 days, during the experimental tests of such reference models. It must also be said that the maximum value of mechanical resistance of the lime mortar, obtained at 1101 days, was 0,82 MPa.

According to European Standard EN 998 - Specification for mortar for masonry - Part 2: Masonry mortar (CEN [2]), mortars with those resistances belong to class M1.

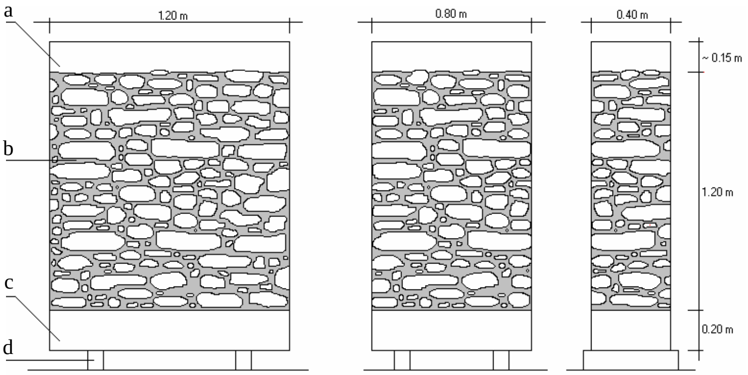
MAIN PROPERTIES OF THE EXPERIMENTAL MODELS (RUBBLE STONE MASONRY)

The experimental models of rubble stone masonry were made with 75% of limestone and 25% of lime mortar per m^3 of masonry, figure 7 (Appleton [1], Nero *et al* [6] and Pinho [8, 9]). Sixty two models were constructed using traditional techniques, divided into two groups: 20 models, numbered from 1 to 20, with 1,20m high, 1,20m wide and 0,40m thick, for shear-compression load tests, identified by “large models”, and 42 models, numbered from 21 to 62, with 1,20m high, 0,80m wide and 0,40m thick, to compression load tests, identified by “small models”, according to figure 8 (Pinho [10]).

Some of the models were also used for water absorption under low pressure tests.

1 – construction of the experimental models, using traditional techniques; 2 – curing place of the models; 3 – inside of the curing place

Figure 7 – Rubble stone masonry models



(large models) *(small models)* *(transversal cut)*

a-concrete lintel; b-masonry; c- concrete base; d-support of the models

Figure 8 – Geometry of the experimental rubble stone masonry models

Physical properties of the experimental models

Physical properties of the mortar, taken directly from the masonry of the experimental models, are presented in table 5.

Figure 9 presents the linear dimension variations of three models, along time. This figure includes also the relationship between such variations and the involving humidity-temperature inside the curing place of the models. Humidity values are amplified “10×”.

Table 5 – Mean values of the mortar obtained directly from the experimental models

Characteristics (90 days of curing)	**Mean Values**
Bulk density	1807 kg/m^3
Open porosity	26,9 %

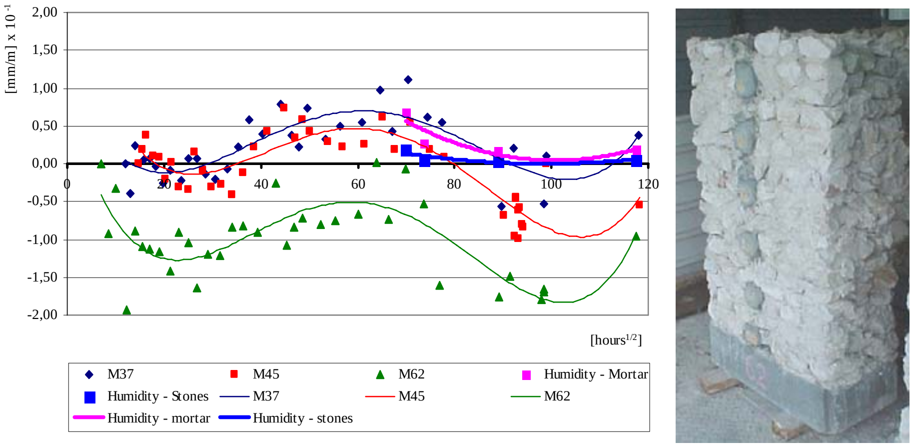


Figure 9 – Relationship between linear dimension variations of three experimental models (M37, M45, M62), along time, and the ambiance humidity-temperature

The experimental model M62, presented in figure 9, has only 75% of the mortar used in the other models (M37 and M45). This figure illustrates an important relationship between linear dimension variations of the models and the ambiance humidity-temperature.

The mean bulk density of the masonry of all tested models (small and large) is 1758 kg/m^3. Using this value, theoretical bulk density of the masonry (Tbd^m) can be defined according to expression (1), considering:

i) the bulk density of the mortar acquired directly from the masonry of the experimental models, of 1807 kg/m^3;

ii) the bulk density of stones, of 2491 kg/m^3;

iii) the referred mean percentages of mortar and stones, per m^3 of masonry, of 25% and 75%, respectively;

$$\mathrm{Tbd}^m = 0{,}25\times1807\ \mathrm{kg/m^3}+0{,}75\times2491\ \mathrm{kg/m^3} = 2320\ \mathrm{kg/m^3} \tag{1}$$

According to these values, the voids volume percentage of the rubble stone masonry, Vv, is given by expression (2):

$$\mathrm{Vv} = 1-\frac{1758\ \mathrm{kg/m^3}}{2320\ \mathrm{kg/m^3}} \cong 24\% \tag{2}$$

To evaluate the effects of the water in contact with the masonry, several water absorption tests under low pressure were done, using the *Carsten* tubes on the mortar joints. Although these tests do not distinguish between water absorbed by stones or by mortar joints, they are usually used to analyse the global behaviour of the wall (Santos *et al* [12]) in the presence of the water.

Figure 10 shows the obtained results in ten models at about 90 days. Other ages, not present here, were also analyzed (Pinho [8]).

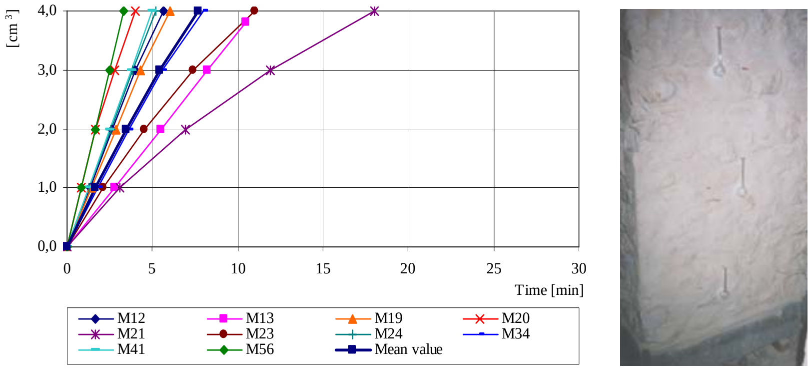
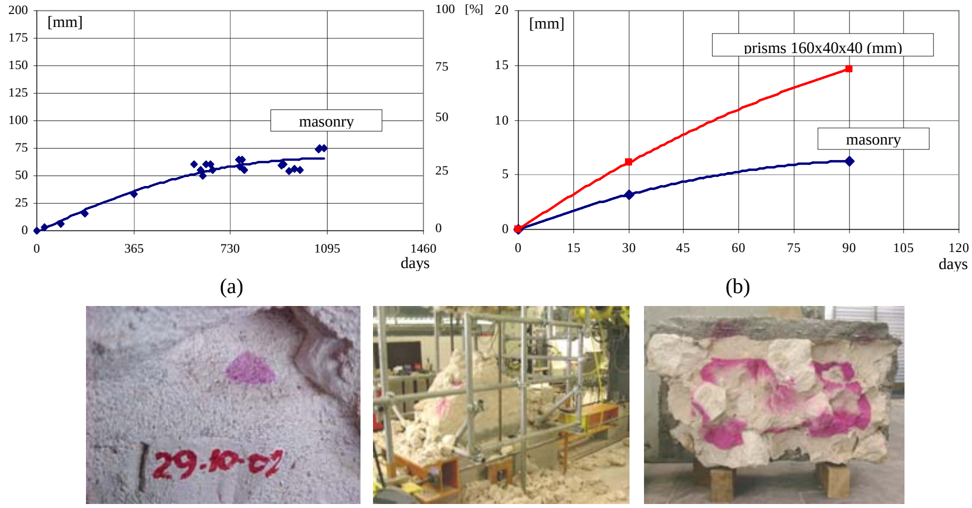


Figure 10 – Water absorption tests under low pressure, using *Carsten* tubes

Chemical properties of the experimental models

Carbonation depth of the lime mortar, obtained in prismatic models of 160x40x40 (mm) is presented in figure 11.



(a)

(b)

(a) directly from the experimental models; (b) comparing this characteristic from prismatic models of 160x40x40 (mm) and the mortar of the masonry, until 90 days

Figure 11 – Evolution of the carbonation depth on the lime mortar

Mechanical properties of the experimental models

Axial compression and shear-compression testing system

Two different types of loading systems were designed and built up for this research: one for axial compression tests (small models) and another for shear-compression tests (large models), figure 12.

In the axial compression testing system, the load was applied monotonically up to the collapse of the experimental models. The load was applied by a hydraulic cylinder placed between the steel frame and a load spreading steel beam placed over the model. The vertical displacements were measured (on the top of the experimental models) with two LVDTs, fixed to the concrete base of the models.

In the shear-compression testing system the horizontal load was applied monotonically, cyclically or alternately on the tested models. However, the reference models were submitted only to monotonic loading. In this loading system loads were applied in two different phases: first a prescribed vertical load was applied and, subsequently, horizontal displacements were imposed by an actuator standing on a strong wall, till the collapse of the models. The vertical and horizontal displacements were measured with seven LVDTs fixed to the concrete base of the models.

Figure 12 – Axial compression and shear-compression testing systems

Analysis of the experimental results

The experimental work started with the test of 3 small models and 3 large models without any strengthening, also named by “reference models” which mechanical characteristics, used as reference to compare with the test results of the strengthened models, are presented next. Figure 13 show the axial force-vertical displacements diagrams and the final stages of the three experimental testes under compression.

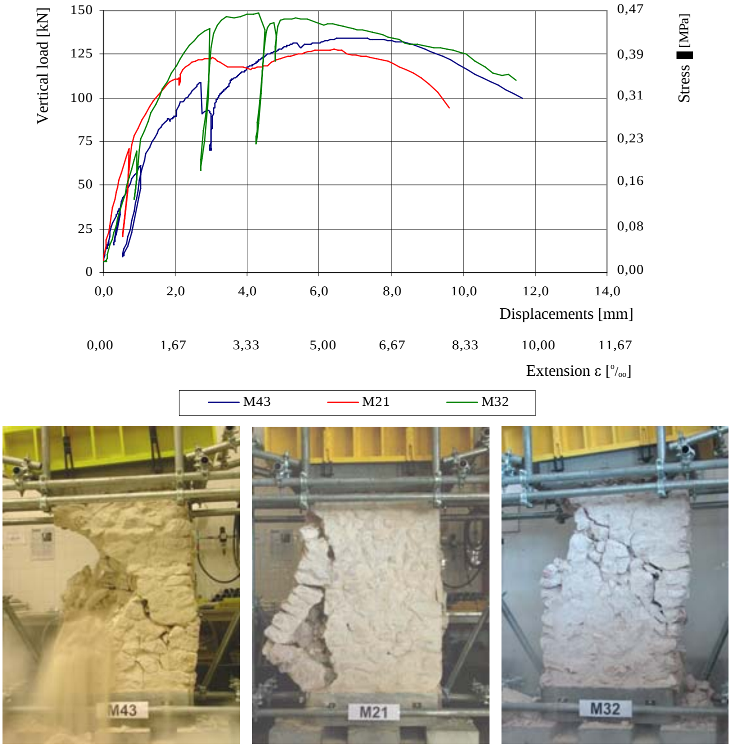


Figure 13 – Results of the three experimental testes under axial compression loads

Table 6 presents the main parameters obtained from these tests. Such parameters are: the maximum force (F_{max}); the vertical displacement corresponding to the maximum force (δ_v^{Fmax}); the axial stiffness at 30% of the maximum force and dissipated energy (E_{diss}) at F_{max} and at 85% F_{max} (at 15% F_{max} drop after F_{max} is reached).

Table 6 – Main values obtained under axial compression loading tests

Model	**L_V^{max} [kN]**	**σ^{max} [MPa]**	**δ_V^{Fmax} [mm]**	**ε_V^{Fmax} [$^o/_{oo}$]**	**E [MPa]**	**Axial Stifness [kN.m/m]**	**Dissipated energy [kN.mm]**	
							100% F_V^{max}	**85% F_V^{max}**
M43	134,2	0,42	6,8	5,7	239	76×10^3	686,5	1143,5
M21	127,7	0,40	6,4	5,3	409	131×10^3	686,8	1005,2
M32	148,5	0,46	4,3	3,6	267	86×10^3	459,8	1230,2
Mean Values	**136,8**	**0,43**	**5,8**	**4,9**	**305**	**98×10^3**	**611,0**	**1126,3**

Figure 14 shows the horizontal force-horizontal displacements diagrams of the three tested unstrengthened models (large models) under shear-compression tests (with a mean vertical load of 109,2 kN), and table 7 presents the obtained results.

These results are: the resultant of the main vertical and the maximum horizontal forces (L_V^{med}; F_H^{max}; R_{max}), the horizontal displacements corresponding to the maximum horizontal loads, the transversal stiffness and the dissipated energy.

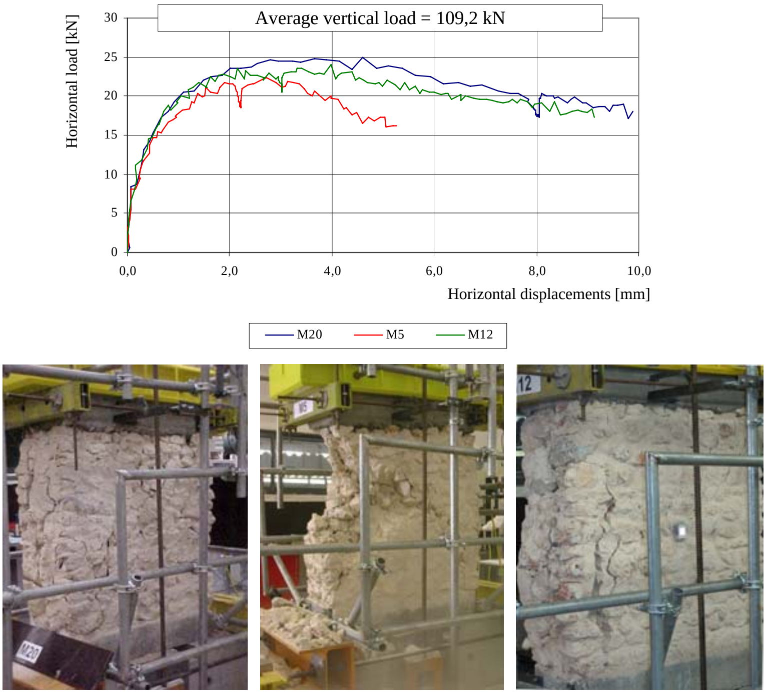


Figure 14 – Results of the three experimental testes under compression-shear loads

Table 7 – Main values obtained in under compression-shear loading testes

Model	**L_V^{med} [kN]**	**F_H^{max} [kN]**	**R^{max} [kN]**	**δ_H^{Fmax} [mm]**	**Transversal stiffness [kN.m/m]**	**Dissipated energy [kN.mm]**	
						100% F_H^{max}	**85% F_H^{max}**
M20	108,9	25,0	111,7	4,6	163×10^3	99,0	152,0
M5	109,8	22,4	112,1	2,7	145×10^3	48,6	79,7
M12	108,9	24,0	111,5	4,0	113×10^3	81,0	124,7
Mean Values	**109,2**	**23,8**	**111,8**	**3,8**	**140×10^3**	**76,2**	**118,8**

MAIN CONCLUSIONS

1. Considering that the carbonation depth of the masonry (lime mortar) was about 27,5% when the reference models were tested in the axial testing system (627 days of age), the mean values of mechanical resistance of such models (0,43 MPa), tend to be *comparable* to the ones obtained *in situ* by J. Roque *et al* [11], of about 1 MPa, and in laboratory, by R. Valluzzi [13], using experimental models built with hydraulic lime, of about 0,99 and 1,97 MPa. The elasticity modulus, 305 MPa, is also *comparable* to the obtained *in situ* by A. Costa [3], in a building placed in Faial Island, of 0,23 GPa, and by C. Oliveira *et al* [7] in another building located in Angra do Heroísmo, with values between 0,2 GPa and 0,5 GPa.

2. In the shear-compression testing system, the maximum horizontal forces of the reference models was near to their mean value, of 23,8 kN, for a mean vertical load of about 109 kN. On the contrary, the transversal stiffness and the deformation in rupture presented some variability, even though rather significant, due to the typical heterogeneity of the rubble stone masonry.

3. The average value of the bulk density of the masonry (17,6 kN/m^3) is similar to other values, namely those obtained *in situ* by A. Costa [3] and C. Oliveira [7], both of 18 kN/m^3.

4. The values of the mortar's resistance, obtained along time (during the tests of the reference and strengthened models) were influenced by the fact that such mortar was done in work environment (and not in the laboratory), even though all the careful used in it.

5. The developed analysis (Pinho [8]) gave also a Poisson coefficient, $\nu = 0{,}24$. This value is quite comparable to the one mentioned in Eurocode 6 (EC6) [5], of $\nu = 0{,}25$.

6. However, considering the mechanical resistance of both mortar (0,6 MPa), obtained during the experimental tests of the reference models (figure 13), and stones (47,8 MPa), the value given by the expression 3.1 of EC6, for the quantification of the masonry resistance to compression (4,35 MPa), is far from the mean experimental one (0,43 MPa), *confirming* that EC6 must not be used to analyze this kind of masonry.

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