EXPERIMENTAL EVALUATION OF SOME MECHANICAL PROPERTIES OF LARGE LIGHTWEIGHT CONCRETE AND CLAY MASONRY AND COMPARISON WITH EC6 EXPRESSIONS

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ABSTRACT:

Reflecting the recent European Directives concerning building energy efficiency, two new envelope masonry systems were developed in Portugal. The main scope was to realise large single leaf external walls with thermal resistance according Portuguese requirements, and enough mechanical capacity to be used as structure in small buildings. The masonry systems are based on large lightweight concrete units and large clay units, bedded on mortar strips joints. Although under a mechanical point of view EC6 provides a methodology that allows to estimate the main mechanical characteristics of masonry, tests were carried to evaluate the more relevant mechanical properties of units and masonry.

This paper describes the mechanical experimental evaluation of these units and masonry systems. Laboratory tests were made, namely masonry compressive and shear according to standards EN 1052-1, EN 1052-3 and ASTM E 519. The tests results allowed to evaluate the shear strength, compressive strength, shear modulus and modulus of elasticity. A comparison is presented between the experimental results and the default values given by EC6 methodology, and a few differences are pointed out. Based on the experimental results, expressions are suggested to allow for a proper evaluation of the mechanical properties of this kind of masonry systems.

Keywords: *mechanical performance; single leaf wall, lightweight materials, laboratory tests, EC6*

NOTATION

f_b normalised average compressive strength of units [N/mm^2];
f_m average compressive strength of mortar [N/mm^2];
f_k characteristic compressive strength of masonry [N/mm^2];
f average compressive strength of masonry [N/mm^2];
f_i individual compressive strength of a masonry test sample [N/mm^2];
f_{vk} characteristic shear strength of masonry [N/mm^2];
f_{v0k} characteristic initial shear strength of masonry, under zero compressive stress [N/mm^2];
f_{v0} average initial shear strength of masonry, under zero compressive stress [N/mm^2];
f_{vi} individual shear strength of a masonry sample, under compressive stress [N/mm^2];
f_{pi} individual compressive stress applied perpendicular to the bed joints [N/mm^2];
g total of the widths of the mortar strips [mm];
t thickness of the wall [mm];
α internal angle of friction, in degrees;
μ_k characteristic friction coefficient;
σ_d design compressive stress perpendicular to the shear [N/mm^2];
E average modulus of elasticity [N/mm^2];
G average shear modulus [N/mm^2];
E_i individual modulus of elasticity of a test sample [N/mm^2];
G_i individual shear modulus of a test sample [N/mm^2].

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1 INTRODUCTION

Two masonry wall systems made from clay and lightweight concrete units were recently developed in Portugal through two research projects that evolved the participation of FEUP (Faculty of Engineering of the University of Porto) and the construction industry.
The main scope of these masonry systems was to realise single leaf external walls with enough thermal resistance, according Portuguese requirements, without the use of specific thermal insulation products, and with enough mechanical capacity to be used as structural masonry in small buildings.

2 DEVELOPMENT OF MASONRY SYSTEMS

A study of the thermal behaviour of both masonry systems was made through computer simulations by the finite element method. An optimization of the thermal transmittance of masonry was made through modifications on the geometry of the units (considering different shapes for the holes, number of holes and rows and unit width) and the density of the materials intended to be used on those units.

In this optimization process, the requirements to be applied to masonry walls, units and mortar according to Portuguese regulations, European Standards and other references were considered.

Some of the most important requirements considered in the development of both masonry systems were:

- Portuguese reference values for thermal transmittance of walls (Portuguese rule [1]);
- density of the unit materials to control thermal conductivity (estimated through the NP EN 1745 [2]);
- minimum compressive strength of the units (Portuguese NDP - National Determined Parameters- of EC8 [3]);
- geometrical requirements for group 2 units (EC6 [4] and Portuguese NDP of EC8);
- maximum weight of the unit to ensure minimum safety and health in manual handling work (Portuguese rule [5]).
- maximum slenderness of the wall (Portuguese NDP of EC8);
- minimum thickness of the wall to ensure watertightness (according to French standard [6]).

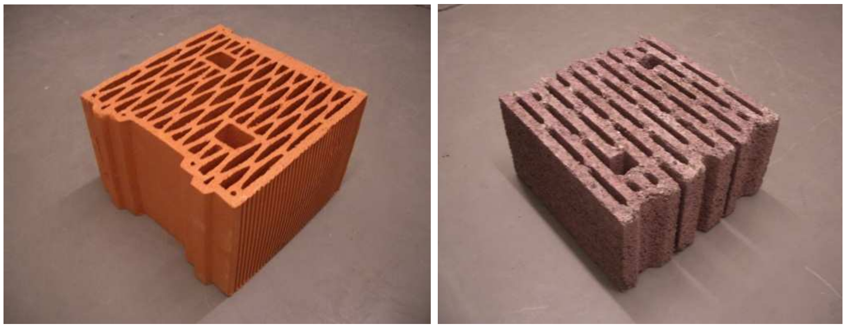
Considering these aspects, the result was the development of two masonry systems made from large units with lightweight materials, such as clay and lightweight concrete (clay density lower than 1850 kg/m^2, mixed with polystyrene aggregates and concrete density lower than 1200 kg/m^2, mixed with lightweight expanded clay aggregates).

The main characteristics of clay and lightweight concrete masonry are:

- the width clay and lightweight concrete units is 300mm and 350mm, respectively;
- both units have vertical holes and are classified as group 2 units according to EC6 geometrical requirements;
- both units have 2 grip holes to help handling the units during construction works;
- the concrete unit has a blind face (5 mm thick) for laying the mortar joints;
- the units are bedded on mortar strips joints with an overlap of half of the length of the unit.
- the thickness of the horizontal joints is 10mm;
- the vertical joints represent 40% of the width of the unit and are filled with mortar to the full height of the joints;
- the vertical and horizontal joints in the clay masonry are made from general purpose mortar and in the lightweight concrete masonry the joints are made from lightweight mortar (factory made mortar).

Several experimental productions of these units were made in factory by two different manufacturers until the desired values for compressive strength and density of the units were achieved.

Examples of clay and lightweight concrete units are presented in Figure 1 and examples of masonry details are presented in Figure 2 and in Figure 3 for both masonry systems.



(a) (b)

Figure 1. Masonry units developed: (a) clay unit and (b) lightweight concrete unit

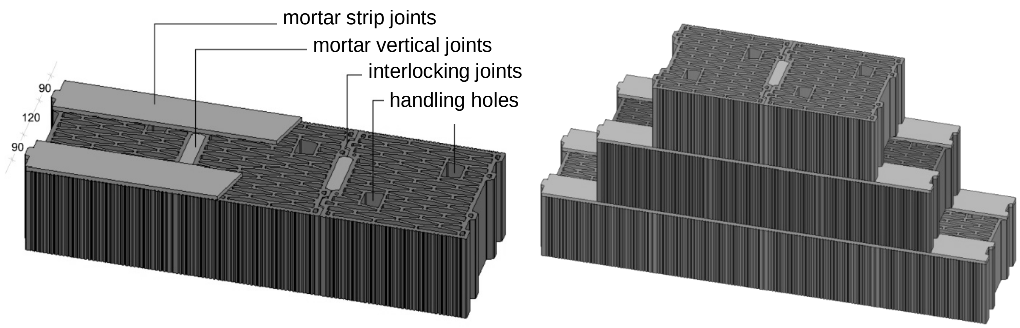


Figure 2. Masonry details schematics for clay masonry (dimensions in mm)

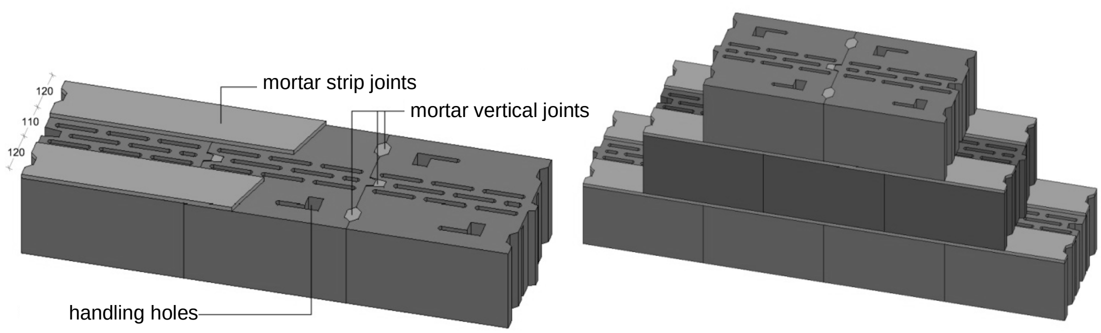


Figure 3. Masonry details schematics for lightweight concrete masonry (dimensions in mm)

3 EXPERIMENTAL EVALUATION OF MASONRY MECHANICAL CHARACTERISTICS

3.1. Tests on masonry elements

An experimental characterization of units and mortar properties was made through laboratory tests, according to European Standards:

- dimensions of masonry units - EN 772-16;
- volume and percentage of voids of masonry units - EN 772-9 and 772-3;
- compressive strength of masonry units - EN 772-1;
- net and gross dry density of masonry units - EN 772-13;

- compressive and flexural strength of hardened mortar - EN 1015-11;
- dry bulk density of hardened mortar - EN 1015-10.

The results for the physical and mechanical proprieties of masonry units and mortar are presented in Table 1.

Table 1. Physical and mechanical proprieties of masonry units and mortar

Proprieties of masonry mortar and units	**Clay masonry**	**Lightweight concrete masonry**
Unit Dimensions (Length x Width x Height)	300x300x190 mm	350x350x190 mm
Volume of all holes in unit (average value)	55% (group 2 unit)	26% (group 2 unit)
Unit weight (average value)	14 kg	18,5 kg
f_b (with mechanical regularization of loading area)	10.4 N/mm^2 (coef. variation=18%) (nº samples=7)	2.6 N/mm^2 (coef. variation=14%) (nº samples=8)
f_b (with regularization of loading area with mortar strips)	7.9 N/mm^2 (coef. variation=14%) (nº samples=7)	2.2 N/mm^2 (coef. variation=11%) (nº samples=8)
f_m	25.8 N/mm^2 (coef. variation=5,8%) (nº samples=12)	11.5 N/mm^2 (coef. variation=25%) (nº samples=12)
Mortar dry density	1800kg/m^3	1300 kg/m^3

3.2. Tests on masonry walls

The scope of the masonry tests was to evaluate some of the most important mechanical characteristics, namely masonry compressive strength and initial shear strength according to European standard test methods defined in NP EN 1052-1 [7] and NP EN 1052-3 [8], respectively.

However, due lack of a European standard test method to determine the masonry shear modulus, *G*, a diagonal tension test was made according to ASTM E 519 [9] to determine this mechanical property.

Test samples of clay and lightweight concrete masonry were constructed in laboratory (Figure 3) according to masonry details defined previously (Figure 2 and Figure 3).

The geometric characteristics and number of test samples were adjusted to laboratory conditions, equipment and number of units produced in factory (Figure 4).

(a) (b)

Figure 4. General view of masonry samples constructed in laboratory: a) clay masonry and (b) lightweight concrete masonry

Some examples of laboratory tests made on the clay masonry and on the lightweight concrete masonry are given bellow:

- compressive tests for evaluation of f_k and E with 4 test samples for each masonry type (Figure 5);
- shear tests for evaluation f_{v0k} and μ_k with 9 test samples for clay masonry and 12 samples for concrete masonry (Figure 6);
- diagonal tension tests for evaluation of G with 4 test samples for each masonry type (Figure 7).

(a) (b)

Figure 5. Example of compressive test set-up: (a) clay and (b) lightweight concrete masonry

(a) (b)

Figure 6. Example of shear test set-up: (a) clay and (b) lightweight concrete masonry

(a) (b)

Figure 7. Example of diagonal tension test set-up: (a) clay and (b) lightweight concrete masonry

As defined in NP EN 1052-3, f_{v0} and α were determined through a linear regression analysis technique.

Considering the small number of test samples, a simple statistical approach was used to calculate the characteristic values of some properties (according to NP EN 1052-1 and NP EN 1052-3, f_k= f/1.2, f_{v0k}= $0.8f_{v0}$ and μ_k= 0.8tan(α)).

The mechanical proprieties of masonry determined from laboratory tests results are presented in Table 2 and in Table 3.

Table 2. Mechanical proprieties of masonry determined from compressive strength tests and diagonal tension tests

Masonry type	**Ref. sample**	**f_i** [N/mm^2]	**f** [N/mm^2]	**f_k= f/1.2** [N/mm^2]	**E_i** [N/mm^2]	**E** [N/mm^2]	**G_i** [N/mm^2]	**G** [N/mm^2]
Lightweight concrete	1	1.79	1.76	1.47	3825	3245	1544	1269
	2	1.74			3041		1389	
	3	1.84			3186		1031	
	4	1.69			2927		1112	
Clay	1	3.75	3.96	3.30	3472	2510	762	944
	2	4.30			2172		1068	
	3	3.78			2211		1088	
	4	4.00			2186		860	

Table 3. Mechanical proprieties of masonry determined from shear strength tests

Masonry type	**Ref. sample**	f_{pi} [N/mm^2]	f_{vi} [N/mm^2]	**Fracture pattern**	f_{v0} [N/mm^2]	$f_{v0k}= 0.8f_{v0}$ [N/mm^2]	$\mu_k = 0.8\tan(\alpha)$ [N/mm^2]
Lightweight concrete	1-A	0.15	0.44	Mortar joint and unit interface (1 face)	0.30	0.24	0.81
	2-A	0.18	0.41				
	3-A	0.16	0.45				
	4-A	0.17	0.50				
	5-B	0.47	0.84				
	6-B	0.45	0.89				
	7-B	0.46	0.65				
	8-B	0.49	0.79				
	9-C	0.78	0.97				
	10-C	0.76	1.16				
	11-C	0.75	1.10				
	12-C	0.78	1.04				
Clay	1-A	0.17	0.42	Mortar joint and unit interface (1 face)	0.24	0.20	0.80
	2-A	0.17	0.41				
	3-A	0.17	0.44				
	4-B	0.52	0.76				
	5-B	0.52	0.72				
	6-B	0.52	0.83				
	7-C	0.85	1.11				
	8-C	0.85	1.23				
	9-C	0.85	0.97				

4 MECHANICAL PROPERTIES OF MASONRY ACCORDING TO EC6

When results from tests are not available, EC6 gives reference values and expressions for calculation of the mechanical properties of masonry according to the mechanical and geometric characteristics of blocks and joints.

This approach can be used provided that some requirements are satisfied (e.g., type of material used on units and mortar, strength limits and coefficient of variation of units, strength limits for mortar, masonry joints details, amongst other aspects).

Considering the mechanical and geometrical characteristics of the blocks and joints of the two developed masonry systems (although the test results of the compressive strength of mortar joints are higher than the values defined by EC6), the expressions according to EC6 for calculation of the mechanical properties for shell bedded masonry are:

- clay and lightweight concrete masonry

$$f_k = K.f_b^{\alpha}.f_m^{\beta} = 0.45.f_b^{0.7}.f_m^{0.3} \quad (1)$$

$$E= 450.f_b^{0.7}.f_m^{0.3} \quad (2)$$

$$G= 180.f_b^{0.7}.f_m^{0.3} \quad (3)$$

- characteristic shear strength of clay masonry

$$f_{vk}= g/t.f_{v0k}+\mu_k.\sigma_d = 0.18+0.4\sigma_d\ (\leq 0.045f_b= 0.47\ N/mm^2) \quad (4)$$

- characteristic shear strength of lightweight concrete masonry

$$f_{vk}= g/t.f_{v0k}+\mu_k.\sigma_d = 0.10+0.4\sigma_d\ (\leq 0.045f_b= 0.12\ N/mm^2) \quad (5)$$

5 COMPARISON BETWEEN EXPERIMENTAL TESTS AND EC6 METHODOLOGY

5.1. Test results and EC6 values

Table 4 summarizes the test results and EC6 values for clay masonry and lightweight concrete masonry, and the ratios between these mechanical properties (ratio Test/EC6).

Table 4. Mechanical characteristics of masonry according to experimental tests and EC6 results

Proprieties	**Clay masonry**			**Lightweight concrete masonry**		
	Test values	EC6 values	Ratio Test/EC6	Test values	EC6 values	Ratio Test/EC6
f_k (N/mm^2)	3.30	5.07	0.65	1.47	1.63	0.90
E (N/mm^2)	2510	5070	0.49	3245	1626	2.00
G (N/mm^2)	944	2028	0.47	1269	650	1.95
G/E (-)	0.38	0.40	0.94	0.39	0.40	0.98
f_{v0k} (N/mm^2)	0.20	0.30	0.67	0.24	0.15	1.60
μ_k (-)	0.80	0.40	2.00	0.81	0.40	2.00

5.2. Result analysis

Comparing the EC6 values with the test results, some remarks about the mechanical properties of the developed masonry systems are given:

- except for μ_k, the EC6 overestimate the mechanical properties considered for clay masonry (ratios from 0.47 to 0.94);

- except for f_k, the EC6 underestimate the mechanical properties considered for lightweight concrete masonry (ratios from 1.6 to 2);
- G, E and μ_k are the properties that have the highest differences in both masonry systems, followed by f_{v0k} ;
- G/E relationship proposed by EC6 is adequate for both masonry systems;
- the maximum value for f_{vk} established by EC6 for shell bedded masonry (0,045.f_b according to the Portuguese NDP - see expressions (4) and (5)) is lower than f_{v0k} test value for lightweight concrete masonry.

6 CONCLUSIONS AND SUGESTIONS

Although the masonry systems resulted from an experimental production, that needs yet small adjustments in some properties of the units, it is possible to note that, in general, the results obtained applying EC6 expressions seem inadequate to estimate the mechanical properties of the masonry systems presented in this study.

Therefore, an adjustment of EC6 expressions to the experimental results was made, and the following expressions are obtained:

- clay masonry

$$f_k = 0.30.f_b^{0.72}.f_m^{0.28} \qquad (6)$$

$$E = 735.f_k \qquad (7)$$

$$f_{vk} = 0.20+0.80.\sigma_d \qquad (8)$$

- lightweight concrete masonry

$$f_k = 0.45.f_b^{0.76}.f_m^{0.24} \qquad (9)$$

$$E = 2212.f_k \qquad (10)$$

$$f_{vk} = 0.24+0.81.\sigma_d \qquad (11)$$

For calculation of G value, the relationship G/E proposed by EC6 is accurate enough for both masonry systems, but expressions for f_k are not.

Finally, some final notes about this study are given:

- although the compressive strength used on mortar joints was higher than the values defined by EC6 to estimate f_k and f_{v0k}, however this fact seems not enough to justify the differences between the EC6 values and the test results;
- it is possible that the type of clay and lightweight concrete used in the units can explain some of this differences, since these materials were developed trough specific mixtures to give an improved thermal performance, therefore providing different mechanical behaviour than expected from more conventional materials used in structural masonry;
- the EC6 underestimate f_{vk} of both masonry systems, and the maximum value for f_{vk} seems inadequate for lightweight concrete masonry since f_{v0k} is always higher than f_{vk} (the main objective of this maximum value is to prevent cracking in masonry due tensile stress in units cause by combined shear and compression loads).

The authors underline that the data given, the conclusions and the expressions referred in this study should be only used for investigation purposes, since these were formulated through a small number of masonry test samples.

Nevertheless, since differences were found between the test results and the EC6 methodology, the authors suggest, as future work, that more experimental tests should be carry out in shell bedded masonry systems to strongly sustain the conclusions made in this study.

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