Assessment of compressive behavior of concrete masonry prisms partially filled by general mortar

Vladimir G. Haach[1]
Graça Vasconcelos[2]
Paulo B. Lourenço[3]

Abstract. The usage of general mortar for embedding and partially filling of units in masonry prisms is evaluated through compressive tests. Filled and unfilled prisms were tested in order to verify the differences on their compressive behavior. Four mortar mixes with three water/cement ratios for each mix were used in tests. Results indicated small differences between filled and unfilled masonry prisms. Mortar had a small influence in the compressive strength of the masonry. However, a more significant influence could be observed on secant elastic modulus, compressive fracture energy and deformations of masonry prisms. Besides, an analytical model to represent the stress *vs.* strain diagram of masonry prisms is proposed. The analytical model depends on the compressive strength of mortar and masonry prism. Furthermore, results indicated that the usage of general mortar for embedding and filling masonry prisms can be a solution in terms of building technology.

Key words: compression, stress strain relations, mortar, masonry.

1 – Professor, School of Engineering of São Carlos, University of São Paulo, Av. Trabalhador Saocarlense, 400, 13566-590, São Carlos-SP, Brazil, E-mail: vghaach@sc.usp.br (corresponding author)
2 – Assistant Professor, ISISE, Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, PORTUGAL, E-mail: graca@civil.uminho.pt
3 – Professor, ISISE, Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, PORTUGAL, E-mail: pbl@civil.uminho.pt

Introduction

The evaluation of compressive behavior takes a major role on the characterization of masonry as structural and constructive system since the compression is a primary action to which structural walls are submitted. Besides, the compressive behavior is also important when masonry is subjected to lateral loading since the in-plane behavior depends on the compressive properties of masonry, mainly if flexural resisting mechanism predominates (Haach et al., 2012).

In case of structural masonry used in seismic prone regions, it is usual to add vertical reinforcements on the hollow cells of the masonry units and fill these cells with grout, so that adequate bonding behavior between masonry and reinforcements can be achieved. In other cases, the filling of holes of units by grout is also performed in order to increase the cross section of masonry elements and consequently to improve their load capacity. Several authors studied the compressive behaviour of grouted and ungrouted concrete block masonry (Hamid and Drysdale, 1979; Khalaf *et al.*, 1994; Ramamurthy, 1995; Koksal *et al.*, 2005; Thanoon *et al.*, 2008). Hamid and Drysdale (1979) found that grouted specimens exhibited lower compressive behavior, which was attributed to the incompatibility of the deformation characteristics for the grout and concrete blocks. In fact, large lateral expansion of the grout leads to premature tensile splitting failure of the blocks´shells. Similar behavior was found by Koksal *et al.* (2005) in case of strength of grout is lower than the compressive strength of concrete units. Thanoon *et al.* (2008) pointed out that grouted masonry carries higher load compared to ungrouted prisms. However, as the cross sectional area of the grouted prism is higher than the ungrouted prism, the stresses become lower. Furthermore, the full capacity of grout strength is not achieved due to the web-shell splitting failure. The axial compressive load in the grout produces bilateral expansion of the grout which is confined by the web-shell faces of the block. This creates additional tensile stresses at the web-shell interface leading to a splitting crack.

In terms of construction technology, the substitution of grout by general purpose mortar used for the bed joints can bring economical advantages, as it can simplify the workmanship and save time of construction. According to Biggs (2005), in some regions of the United States contractors commonly substitute grout by mortar in reinforced masonry construction. The use of mortar instead of grout leads to the reduction of the installation costs with low-lift applications when the masonry is to be partially grouted and reduce the number of materials. On the other hand, this means that the mortar has to present a workability that enables the laying of the concrete units and fills appropriately the reinforced hollow cells. The workability may be considered one of the most important properties of mortar because it influences directly the bricklayer's work according to Sabatini (1984) it is important to mention that the quality of the workmanship can influence considerably the mechanical properties of masonry. According to Panarese et al. (1991), the workability is an assembly of several properties such as, consistency, plasticity and cohesion. Given the fact that plasticity and cohesion are difficult to measure in situ, consistency is frequently used as the measure of the workability.

In the scope of the proposal of a constructive system in reinforced concrete block masonry, Haach *et al.* (2007 and 2011a) studied the performance of a general purpose mortar to be used for filling vertical internal cells of concrete masonry units in substitution of grout. For this purpose, the performance of different mortars was assessed, using distinct levels of consistency, in terms of workability and mechanical properties. The idea was to evaluate the performance of mortars that combine the best workability and flowability with reasonable mechanical properties.

The study presented here related to the evaluation of the compressive behavior of concrete block masonry having the central cells filled with different types of mortars in order to assess its influence on the strength and deformable characteristics. Different levels of consistency by varying the water/binder ratios are considered. The mortars used for the filling are also used for laying the concrete units. The results of the uniaxial compressive tests are analyzed in terms of crack patterns and failure modes, complete stress *vs.* strain diagrams and mechanical properties. Correlations between mechanical properties characterizing the complete stress vs. strain diagrams are derived aiming at defining an analytical model to describe the complete behavior of masonry prisms under compression.

Brief overview of the constructive system

The proposed solution for reinforced structural masonry is based on three cell concrete blocks (Fig. 1a) and a modified general purpose mortar to be used for laying masonry units and for filling the vertical hollow cells (if reinforcement is placed here). The three cell concrete blocks present frogged ends with a dimension that enables to form vertical cells in which vertical reinforcement can be placed. The masonry units have the following geometry: 400mm length x 200mm thickness x 190mm height. The concrete masonry units belong to group 2, Eurocode 6 (Eurocode 2005), with an average percentage of vertical perforation of 46%. The average thickness of shells and webs for the concrete units is about 30mm.

The reinforced masonry solution uses a pre-fabricated truss type steel reinforcement consisting of two parallel wires welded to a continuous zigzag wire for both head and bed joints, see Fig. 1b. The dimensions of this reinforcement depend on the design requirements and the geometry of the units. Reinforced vertical cells should be filled with mortar and the vertical reinforcement should be adequately anchored to the concrete beams or concrete slabs. This means that partially filled joints should be used in case of reinforced concrete block masonry.

Different possibilities for masonry bond can be adopted, namely traditional masonry bond in which vertical reinforcements can be placed simultaneously in internal vertical cells and cells formed by the frogged ends, Fig.1c, or an alternative masonry bond composed of continuous vertical joints formed by the frogged ends of the blocks, see Fig.1d. The latter masonry bond makes the construction technology easier, and is preferably as good performance is found in masonry shear wall tests (Haach et al., 2010). For unreinforced masonry solutions, it is planned that dry joints are used for head joints as the construction is much faster this way.

Experimental Program

In case of structural masonry, it is mandatory that compressive strength is studied as this mechanical property has a major role on the structural behavior of the system. In the particular case of the constructive system presented before, it is important to evaluate the compressive strength of concrete block masonry partially filled by the same mortar used as embedding, which involves economic advantages and can simplify considerably the constructive process of reinforced masonry. To evaluate the adequate filling of the central cells of the concrete units it was needed to evaluate the type of mortar that better filled the unit cells without reducing significantly the compressive strength of masonry. For this effect, an experimental program based on uniaxial compressive tests on masonry prisms was designed. **The masonry specimens were built at reduced scale as 1:2 reduced blocks were considered. In fact, in the scope of the validation of the in-plane cyclic behavior of the solution for the concrete block masonry walls, it was needed to consider reduced scale units (1:2) due to the limitations of the laboratory facilities in terms of actuators capacity (Haach et al. 2010). In addition, for the experimental tests on the validation of the dynamic behavior of masonry buildings based on shaking table tests (Lourenço et al., 2013), reduced scale for the masonry units was also mandatory. Based on the similitude laws that were followed for the construction of the buildings models, similar strength properties should be considered for the units and mortar, aiming at obtaining representativeness at the level of the compressive strength of masonry. Thus, it is believed that the differences between the full and reduced scale masonry under compression studied in the scope of the present paper should be considered negligible.**

Test specimens

In order to access the influence of the mortar filling of the internal cells of the concrete units on the masonry compressive strength, masonry prisms with and without infill mortar were built with 12 different mortars mixes with variable lime proportion and water/cement ratios. Three proportions of mortar were prepared keeping the same binder/aggregate ratio: 1:3 (Portland cement:sand), 1:0.5:4.5 (Portland cement:lime:sand) and 1:1:6. A pre-mixed mortar type M10 (10 MPa of compressive strength), was also used to compare the results. The pre-mixed mortar is composed of Portland cement, lime, lime aggregates and chemical additives. According to the information given by the producer, the mortar follows the requirements of European standard EN 998-2 (2003). For each mix, three different water/cement ratios (w/c) were considered in order to evaluate the filling properties of the central core of the concrete units. **Water/cement ratios were chosen in order to define three levels of flow table value and keeping it rather constant for all mortar mixes.** Given that it is not possible to define the w/c ratio for the dry pre-mixed mortar, the water/dry material (w/dm) was also considered for all types of mortar, see Table 1. The aggregates used in the mortar needed to be scaled **as the** concrete units used in the experimental research were 1:2 **reduced** scale units. With this respect, special care was also taken with the granulometry of materials used in production of the units since the shells and webs of these units had a small thickness. Three hollow cell concrete units of 201 mm (length) x 93 mm(height) x 100 mm(thickness) were considered in the experimental program. These units have two cells with 60 mm x 70 mm and one small cell in the middle of unit with 15 mm x 70 mm. The percentage of holes in the block is about 46%, which, according to the classification given by Eurocode 6 (2005), indicates that the units belong to group 2. The production of the concrete unit blocks was carried out according to European normalization (EN 771-3), namely with respect to dimension tolerances (EN 772-16) and water absorption (EN 772-11).The proportion of raw materials were defined in order to have concrete units with a compressive strength of 10MPa in average. Notice that according of EC8 (2004), the masonry units to be used in construction on seismic prone regions should have a minimum compressive strength of 10MPa.

The tested masonry prisms have a length of one block (201 mm) and a height corresponding to three courses (295 mm). Masonry prisms with a vertical joint in the central course were used in this study, similarly to the specimens tested by Cavaleri et al. (2005) and Mohamad (2007). The influence of the vertical joint and the partial infill of the prism were investigated. Masonry prisms were built with the thickness of horizontal joints equal to 8mm and dry vertical joint. **All specimens were capped with a high-strength cement mortar in order to improve the contact between steel plates and masonry prisms during the compression tests and to avoid any deviation of the load axis from the axis of the specimen**. **It should be noticed that as the strength of the capping is considerably higher than the strength of mortar joints, no influence of the mortar capping on the uniaxial compressive behavior of the masonry prismis is expected. Three** specimens were built for each mortar mix and filling configuration making a total of 72 concrete block masonry prisms.

All masonry prisms were built by the same mason and were cured in laboratory environmental conditions. In order to ensure similar curing conditions, the tests were carried out at an age of 28 days.

Test setup, instrumentation and procedure

The uniaxial compressive tests on concrete masonry prisms were carried out in a stiff steel frame by using a servo-controled equipment and under displacement control through a vertical external LVDT connected to the actuator. The loading was applied with a velocity equal to 3 μm/s intending to follow the requirements of the EN 1052-1 (1999), which recommend that the failure of the specimen should be reached between 15 min and 30 min from the beginning of loading. Two equal plates, one on the top and another one at the base the specimens, were used to provide similar boundary conditions. On the top a spherical roller was used to correct any deviation in position of axes loading.

Seven LVDTs **were** used to measure the vertical and horizontal displacements: four in vertical position (base length = 167.5 mm) and three in horizontal position (base length = 60 mm), according to the configuration indicated in Fig. 2. The vertical LVDTs intended **to** measure the vertical displacements and corresponding vertical strains, and the horizontal LVDTs **aimed at evaluating** the lateral strains along the height of the specimens.

Material Properties

The mechanical properties of the materials, namely units and mortar, were obtained through a set of experimental tests. The normalized compressive strength of the three cell concrete blocks was obtained according to EN772-1 (2000) being the average value of 27.4 MPa in gross area. The elastic modulus of the concrete blocks was derived from the compressive stress-strain diagrams, being the average value of 14.8 GPa. Failure mode of all tested units was pyramidal-trunk. In blocks and ½ blocks, the first cracks appear vertically in corners of the units. Bands of some specimens were completely burst, see Fig. 3. With the increase of the loading, there was a tendency for the connection of vertical cracks by a horizontal crack in the superior region of the unit. This horizontal crack occurs due to the sliding of the upper part of the units over the pyramidal-trunk surface of rupture. In some specimens near the collapse, a vertical crack also appeared in central region of the unit. This typical failure mode is very similar to the one obtained in similar full scale concrete blocks tested under the same loading conditions by Mohamad (2007).

The fresh properties of mortars were obtained based on consistency evaluated through flow table tests according to EN 1015-3. These tests enabled to evaluate the workability of mortars and relate them to the more adequate filling of the internal cells of the concrete units. Besides, hardened properties of the mortars were obtained based on compressive tests of cylindrical specimens (50mm diameter and 100mm height) from which it was possible to obtain the compressive strength and elastic modulus according to standard NBR 13279 (1995). Additionally, flexural and cubic compressive strength and consistency were experimentally evaluated through the standards, EN 1015-11. More details about the attainment of these properties are described in Haach et al. (2011a). It should be stressed that the same mortar was applied for the filling of small cell of masonry prisms and for the laying of masonry units. Table 1 indicates the mixes considered in this study with respective hardened and fresh properties.

Results of uniaxial compressive tests on masonry prisms

Analysis of the Failure modes

From the analysis of crack patterns of the masonry prims it is seen that filled and unfilled prisms exhibited similar behaviour. In spite of the material of filling (embedding mortar) presents significant lower stiffness than units, prisms presented a satisfactory behaviour without significant decrease of strength or increase of cracking due to the expansion of filling material. The reduced size of the filled cell of units leads to be negligible differences on the stiffness of masonry prisms with filling mortar.

In general, in all prisms visual cracking starts near to the ultimate load in the middle of the superior unit as a continuation of the vertical joint, see Fig. 4a. In some specimens this crack also symmetrically appeared in the bottom unit. This crack occurs due to the horizontal high tensile stresses in the middle of upper and bottom units. These tensile stresses are **also** the result of additional lateral strains, besides the tensile strains induced by uniaxial compressive loading, induced by the mortar joints having a considerable lower elastic modulus. **A**ccording to several past researches (Hamid and Drysdale, 1979; McNary and Abrams, 1985), the distinct elastic properties between mortar and concrete units lead to lateral tensile strains resulting in vertical cracking of the units. **In fact,** t**he tensile lateral deformation of the masonry due to the compressive loading results in the lateral deformation of the masonry specimens. Even if the mortar and concrete blocks are solidary, as the mortar has a considerable lower value of the elastic modulus, it exhibits the tendency to deform more than the concrete units. Taking into account that cohesion at the unit-mortar interface exists, the trend for the expansion of the mortar results in additional tensile stresses of the masonry units.**

Th**e** vertical cracks extended to horizontal joints and to extremities of the upper units growing up through the half-units in the middle course. Near the collapse of the masonry prisms some vertical cracks appeared through the thickness starting from the half-units, see Fig. 4b. Spalling of units occurred in some specimens in a brittle manner, see Fig. 4c. Internal cracks cut webs and shells both in filled and unfilled prisms, see Fig. 4d and 4e.

Masonry prisms filled with mortar with a proportion of 1:1:6 revealed to have a higher deterioration of the horizontal joint as the result of a higher squeeze, given that mortar had a smaller compressive strength, see Fig. 5. According to Mohamad (2007), the low compressive strength of mortar can be related to a high porosity due to physical phenomenon of exudation. This possibly led also to the reduction on the unit-mortar interface adherence, resulting in the detachment of the mortar at the horizontal joint and horizontal cracking at the unit-mortar interface.

From the results of LVDTs positioned in horizontal direction it can be observed that cracks not visible probably started around to 30% of the ultimate, which have associated a significant reduction of stiffness, see Fig. 6. With this respect, two different stages of deformation in horizontal behaviour of the prisms can be considered: (1) the first is a stage corresponding to the linear elastic behaviour with a high stiffness before the cracking onset; (2) the second stage initiates after cracking onset at approximately 30% of the strength. This stage is characterized by important increase on the lateral strains, as expected. By comparing the lateral strains measured by the different LVDTs attached to the specimen, it is observed that the horizontal strains in upper and bottom units (LVDTs 5 and 7) were very different in spite of the symmetry of the specimen. The horizontal strain measured at the bottom unit (LVDT 7) was smaller than the strain measured at the upper unit (LVDT 5). The difference on the lateral strains can be the result of non uniformity of the thickness of the webs and shells of the concrete units. In fact, the cells of hollow units are conic in order to facilitate stripping the moulds during the manufacture of units. So, the thickness of webs and shells of upper unit in the region of the contact to the middle course is lower than the thickness of webs and shells of bottom unit in the same region. Consequently, horizontal strains are higher in upper unit due to the lateral expansion of the masonry prisms. It should be noticed that lateral strain at the upper part is close to the strain recorded at the mid height of the specimens at the level of the vertical joint, particularly in case of specimen filled with mortar and during the elastic regime.

The lateral displacements are higher in case of specimens with mortar filling, especially after cracking of the specimens, as can be seen by comparing the lateral strain in Fig. 6a and Fig. 6b.This can be attributed to higher stiffness of the filled concrete block masonry.

Behaviour of masonry in terms of strength and vertical deformations

In order to better understand the behaviour of tested masonry prisms secant elastic modulus and compressive fracture energy were calculated for all specimens. In Table 2 a summary of the mechanical properties measured from the stress-strain diagrams obtained in masonry prims under uniaxial compression is provided, namely compressive strength, secant elastic modulus and the compressive fracture energy. In general, it should be noticed that coefficient of variation, indicated inside brackets, ranges from low to medium values, which demonstrates the feasibility of the experimental results found from the experimental campaign. Here, secant elastic modulus, E_p, was calculated through the relation between the maximum stress and the respective strain. Compressive fracture energy, G_c, was calculated by the integral of the stress *vs.* vertical displacement **complete diagram. According to Lourenço (1996), the consideration of the same energy-based approach to describe tensile and compressive softening is plausible, because the underlying failure mechanisms are identical, since continuous crack grow at micro-level. As previously commented, spalling of shells occurred in a brittle way in some specimens. This failure mode**

strongly influenced the vertical displacements and could be clearly observed by discontinuities in LVDTs. Thus, for the calculation of ultimate elastic strains and compressive fracture energy, the softening branches of the stress *vs.* vertical displacement **diagrams were considered up to the spalling of the specimens.**

Similarly to results available in literature (Page and Shrive, 1988; Cunha et al., 2001, Steil et al., 2001, Köksal et al., 2005), it is seen that the mortar had a small influence in the compressive strength of the masonry prisms, even if it is seen that a trend for the decrease of the compressive strength of mortar result in decrease on the compressive strength of masonry prisms. However, the increase of about 250% on the compressive strength of mortar leads to an increase on compressive strength of about 35% for both unfilled and filled masonry prisms. On the other hand, the increase of compressive strength of mortar leads to an equivalent increase in the elastic modulus for unfilled and filled masonry prisms. Besides, results indicated that a linear relation exist between the secant elastic modulus of masonry prisms (E_p) and the compressive strength of mortar (f_{cm}), see Fig. 7. A small difference **in** this relation could be observed comparing unfilled and filled prisms. **The slightly higher values on the coefficient of correlation for the filled masonry prisms can be attributed to the improved homogeneity of the filled masonry.** Besides, the filling of small cell of prisms, which reduced the percentage of voids from 46% to 42%, in general leads to an increase in the compressive strength of masonry prisms not higher than 24%. Secant elastic modulus of filled masonry prisms also exhibited an increase reaching values up to 40% higher then unfilled masonry prisms. On the other hand, the filling of prisms seemed to reduce the compressive fracture energy. Filled masonry prisms exhibited a reduction on compressive fracture energy at maximum of 19%. The increase of about 250% on the compressive strength of mortar led to **a** decrease on compressive fracture energy around to 45% for filled and unfilled masonry prisms.

The average complete stress *vs.* strain diagrams of specimens **found for specimens built with distinct mortar mixes are presented in Fig. 8. The average curves were defined based on automatic procedure existing in software Microcal (TM) Origin® . From these results, it** can be concluded that mortar mix had a great influence in the deformation capacity of masonry prisms, see also Table 3. It can be noted that the use of lime in mortar mix lead to a much more deformable and lower compressive strength masonry. The strain corresponding to the peak stress, ε_{yp}, and the ultimate strain, ε_{up}, increased with the addition of lime in mortar mix. Specimens built with pre-mixed mortar exhibited compressive strengths similar to general mortar 1:3 but with a more ductile behaviour. Ultimate and peak strains seem to be very dependent on the mortar properties.

The reduction of the compressive strength of mortar led to the increase of both peak and ultimate strains as shown in Fig. 9. In fact, linear trends were attained between the compressive strength of mortar and the peak and ultimate strains recorded in the masonry prisms.

The increase of the peak strain is followed by the increase on the ultimate strain of the masonry specimens and linear relation can be observed between ultimate and peak strains, as seen in Fig. 10. It should be noticed that the increase in the peak strain is associated to the considerable non-linear behaviour in the pre-peak regime. By comparing the stress-strain diagrams of Fig. 8, it is clear the pre-peak nonlinearity is considerably higher in case of specimens built with 1:1:6 mortar mix. It is also interesting to notice that the use of higher strength mortar (1:3) results in more differences in terms of deformation if filled and non-filled masonry specimens are considered. This means that the higher strength and stiffer mortar contribute to a higher increase on the stiffness of the filled masonry. According to what was already found is past research, the filling of vertical joints contributes also for the increase on the shear strength of concrete block masonry (Haach et al., 2011; Vasconcelos et al., 2012).

From Fig. 11, it is also possible to observe that a linear correlation was found between compressive fracture energy and ultimate strain. The compressive fracture energy increases as the total strain increases. In spite of some scatter it is interesting to see that a very reasonable estimation of the compressive fracture energy under compression can be made if the total strain is known. This can be an advantage in case of this mechanical property is needed in numerical simulations. The linear correlation is valid both for filled and unfilled masonry prisms.

Notice that it is believed that the correlations found between the parameters characterizing the compressive behaviour of concrete block masonry should be applied in other types of masonry. However, the generalization of the correlations to other masonry typologies should be based on further experimental campaigns.

Analytical model for stress *vs.* strain diagram of masonry prisms

Based on the analysis previously presented carried out on the relation between the distinct parameters characterizing the stress-strain diagrams, namely strains, elastic modulus and compressive fracture energy, an analytical model is proposed aiming at defining the stress *vs.* strain diagrams of masonry prisms under uniaxial compressive loading. The key parameters characterizing the complete stress *vs.* strain diagrams are the peak compressive strength (f_p), the strain corresponding to the compressive strength

(ε_{yp}), the ultimate strain (ε_{up}) and the stress corresponding to the ultimate strain ($\sigma_{\varepsilon up}$), see Fig. 12.

According to what was suggested by Kaushik *et al.* (2007), the stress *vs.* strain diagram characterizing the uniaxial compressive behaviour of masonry prisms follows a parabolic rising curve until the maximum stress and can be represented by Eq. 1.

$$\sigma = f_p \left[1 - \left(1 - \frac{\varepsilon}{\varepsilon_{yp}} \right)^2 \right] \quad (1)$$

where, (σ, ε) is the pair stress and strain to define the masonry prism compressive behaviour. This model was inspired in the model proposed by Priestley and Elder (1983) for unconfined and confined concrete masonry.

As mentioned before, from Fig. 7 it can be observed that the secant elastic modulus of masonry prisms was proportional to compressive strength of mortar. Thus, the value of peak strain of masonry prisms, ε_{yp}, can be obtained by Eq. 2:

$$E_p = \frac{f_p}{\varepsilon_{yp}} = k_1 f_m \rightarrow \varepsilon_{yp} = \frac{f_p}{k_1 f_m} \quad (2)$$

where, E_p is the secant elastic modulus of the masonry prism, f_m is the compressive strength of mortar and k_1 is a coefficient of proportionality between the secant elastic modulus and the compressive strength of mortar.

The post-peak descending branch can be approximated to a linear stretch between the peak stress (ε_{yp}, f_p) and the point corresponding to the ultimate strain (ε_{up}, $\sigma_{\varepsilon up}$), see Fig. 11. Given that the ultimate strain (ε_{up}) can be estimated from the strain at peak stress (ε_{yp}) and that it is also correlated with the compressive fracture energy (G_c), it is possible to conclude that the ultimate strain, ε_{up}, can be obtained by Eq. 3, and the compressive fracture energy, G_c, can be obtained by Eq. 4:

$$\varepsilon_{up} = k_2 \varepsilon_{yp} \tag{3}$$

$$G_c = k_3 \varepsilon_{up} \tag{4}$$

where, k_2 and k_3 are coefficients of proportionality already obtained. In fact, in Fig. 10 it can be observed that the ultimate strain was proportional to peak strain and in Fig. 11 could be observed that the compressive fracture energy was proportional to ultimate strain. These relations enable to obtain the stress corresponding to the ultimate strain, $\sigma_{\varepsilon up}$, through Eq. 5 considering Eq.1, 2, 3 and 4 and a linear post-peak branch:

$$\sigma_{\varepsilon up} = \left[\frac{2k_2 k_3}{f_p \delta (k_2 - 1)} - \frac{4}{3(k_2 - 1)} - 1 \right] f_p \tag{5}$$

where, δ is the initial length used to calculate the strains. In this study, δ is the initial distance between the measurement points of vertical LVDTs. Here the values of the constants k_1, k_2 and k_3 assumes the values of 451, 2.17 and 1.11 for filled masonry prisms respectively and 407, 2.27 and 1.13 for unfilled masonry prisms respectively.

The complete **average** stress vs. strain diagrams obtained in the experimental campaign were compared to the stress vs. strain obtained analytically from the equations presented before, see Fig.13 and Fig. 14, in which it is presented one masonry prism of each mortar mix. It is seen that good agreement was found between experimental and analytical stress vs. strain diagrams, both in the pre-peak and post peak regime.

Experiments with a larger variation of compressive strength of mortar and units should be carried out in order to confirm the relations proposed in this study.

Conclusions and final remarks

The study presented here dealt with the experimental evaluation of the uniaxial compressive behavior of concrete block masonry prisms taking into account the filling of an internal cell of the concrete blocks with distinct types of mortar, which was used and embedded mortar. The filling of the internal cells of the units should be made when vertical reinforcements are needed. For the mortar distinct types of binder to sand ratio were considered and different water/cement ratios were also taken into account in the design of the experimental campaign.

From the experimental analysis, the main following conclusion can be drawn:

(a) The mortar exhibited a small influence in the compressive strength of the masonry prisms but revealed to have significant influence in their deformability. This means that the secant elastic modulus and deformations of masonry prisms are variable with the compressive strength of mortar. Besides the compressive fracture energy in compression can be also related with the compressive strength of mortar as the compressive fracture energy is well correlated to the ultimate strain.

(b) In spite of the material used to infill the prisms have distinct deformability, the expansion observed is negligible. Thus, filled masonry prisms exhibited a satisfactory behavior under uniaxial compression.

(c) The use of lime allows the achievement of deformable masonry even if with slightly lower compressive strength.

(d) In this study, stress *vs.* strain diagrams characterizing the uniaxial compressive strength of masonry prisms could be obtained from compressive strength of mortar and compressive strength of masonry prisms.

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Fig. 1 - Details of the constructive systems based on concrete block masonry: (a) block and half concrete block; (b) steel truss type reinforcement; (c) traditional masonry bond with truss type reinforcement; (d) alternative masonry bond composed of continuous vertical joints formed by the frogged ends of the concrete blocks (Haach 2009).

Fig. 2 – Geometry and instrumentation of the masonry prisms.

Fig. 3 – Cracking pattern of masonry units: (a) frontal view and (b) lateral view.

Fig. 4 – Cracking of prisms: (a) Cracking in frontal face, (b) cracking in lateral face, (c) spalling of units, (d) internal cracks in unfilled prisms and (e) internal cracks in filled prisms.

Fig. 5 – Deterioration of the horizontal joint for prisms built with mortar 1:1:6.

Fig. 6 – Horizontal strains (mortar mix 1:3, w/c = 0.9): (a) unfilled and (b) filled.

Fig. 7 – Relation between average values of secant elastic modulus of masonry prisms and compressive strength of mortar.

Fig. 8 – Average diagrams stress *vs.* strain: (a) mix 1:3, (b) mix 1:0.5:4.5, (c) mix 1:1:6 and (d) pre-mixed.

Fig. 9 – Relation between average values of strains in masonry prisms and compressive strength of mortar: (a) strain at maximum load and (b) ultimate strain.

Fig. 10 – Relation between average values of ultimate strain and peak strain.

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Fig. 12 – Proposed analytical stress vs. strain diagram of masonry prisms.

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