EXPERIMENTAL AND ANALYTICAL MODEL FOR COMPRESSION BEHAVIOUR IN HOLLOW CONCRETE BLOCK

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ABSTRACT
The structural behavior of concrete masonry is influenced by the mechanical properties of the constituent materials. The compressive strength of masonry is the most important parameter in the design of masonry structures and it primarily depends on the strength of the individual block units. Mathematical modeling of structures with masonry walls requires the material properties (compressive strength and modulus of elasticity) and constitutive relationships of masonry and its constituents. Code for design masonry structures gives the formulas for calculating the average axial compressive strength of concrete masonry. In these formulas, there are many unknown parameters to predict real compression behavior in the masonry, because the parameters of these formulas are related to the type of block materials.

An experimental investigation was performed to generate the complete stress-strain curves of hollow concrete blocks in uniaxial compression with nominal strength (10 MPa) made of local materials. A number of empirical and analytical models available in the literature of the complete stress-strain curve for concrete under uniaxial compression are reviewed and discussed using the published experimental data.

Based on experimental data, a new model with emphasis on compressive strength is proposed to generate the complete stress-strain relationships for hollow concrete block. The proposed model fit the experimental data with excellent agreement and it is capable of predicting the behavior of normal and high strength hollow concrete block. The proposed empirical model can be employed in the non-linear finite element analysis and design procedures of concrete masonry structures.

KEYWORDS: stress-strain curve, compressive strength, elastic modulus, hollow concrete block, masonry

INTRODUCTION
Concrete and masonry share some characteristics, including, good compressive strength, low tensile strength, fragility, among others. This makes it valid to think that the accumulated knowledge of several investigations performed in concrete can be extrapolated to the masonry

by, for example, the use of analytical and similar empirical expressions. Obviously this is something that should be validated by experimental evidence.

A fundamental step in the investigation of the mechanical performance of structural masonry is adequate knowledge of the strength variables of masonry unit (Jaafar et al., 2006). There are very few studies on this subject and most of them have focused on the behavior of the whole set (units + mortar), without paying attention to happens to each of the parties independently (Haach et al., 2010). Although the behavior of the masonry unit is different than the behavior of the prism or wall, the strength parameters of the unit are directly related to the performance of different geometric system organizations (Jaafar et al., 2006). The compressive strength is possibly the most important parameter to determine masonry units, since it is the predominant type of action in this structural system. Also, the stress-strain determines the most important design parameters of the masonry, and it is used to predict the structural behavior of the system and to identify different states of mechanical performance limits.

MECHANICAL BEHAVIOR MODELS

There are many parameters involved in the constitutive laws of hollow concrete blocks, few experimental tests which are made to these materials showed the variation of these parameters because of the diversity in the mechanical properties of the raw material in the locations where the system is built (Kaushik et al., 2007). Although a few surveys focused on establishing the mechanical behavior of the masonry unit, several studies about prismatic elements and small walls, including the research made by Jaafar et al. (2006), agree that the strength of the masonry is primarily limited by the strength of their unit and furthermore, the variations in the strength of the mortar and concrete filler are less importance in the maximum strength of the structural system (Navas, 2007). This implies that the most efficient way to increase performance in masonry structural strength is optimizing their units.

The first analytical model was proposed by Hognestag (1951), who proposed a parabolic expression for the stress-strain curve in concrete (Equation 1), and which was later used in masonry by Paulay and Priestley (1992) with very good results in correlation to experimental values for normal strength concrete.

$$\frac{f_c}{f'_c} = \frac{2\varepsilon}{\varepsilon_c} - \left(\frac{\varepsilon}{\varepsilon_c}\right)^2 \qquad (1)$$

Popovics (1973) proposed a stress-strain curve involving two behavioral parameters (Equation 2). The first one, "n", establishes a correlation between the initial elastic moduli and concrete breakout and the second, "k", establishes the different behavior of the curve in its section downward.

$$\frac{f_c}{f'_c} = \frac{\frac{n}{n-1}\left(\frac{\varepsilon}{\varepsilon_c}\right)}{\frac{1}{n-1}+\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{n}{n-1}k}} \qquad (2)$$

where,

$$n = \frac{E_i}{E_c}$$

$$k = 1, for\ \varepsilon < \varepsilon_c\ and\ \ k = 0.67 + \frac{f'_{c(MPa)}}{62} > 1, for\ \varepsilon > \varepsilon_c$$

The equation of Popovics (1973), was confronted with several experimental results, showing appropriate behavior for concrete with f'_c <55 MPa (Murugesan, 2009).

Although these equations have been proposed for conventional concrete, because of its similarity to the mortar which is used to produce concrete blocks, they will be taken as basis of comparison for the performance of this type of prefabricated material and then, to propose an equation that best suits of structural behavior of this material of construction.

MATERIALS

The tested blocks are prefabricated concrete masonry units by means of a vibro-compaction system in an industrialized production plant. The tested blocks in this study can be classified into these subgroups: according to weight (moderate weight blocks [1680-2000 kg/m^3]), by strength (low resistance [8-13 MPa]).

The concrete block which was studied is prism shaped with two vertical cores and symmetry in two main directions. Its nominal size is 150 * 200 * 400 mm and its approximate actual size is (140±1)*(190±2)*(390±1) mm (Figure 1).

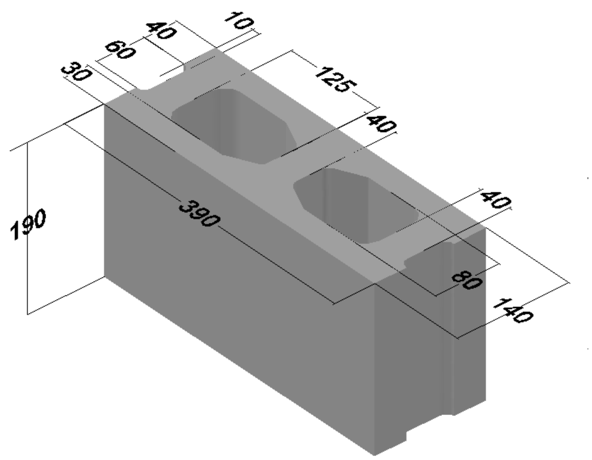


Figure 1. Geometry of the tested concrete block (units: mm).

The cross section of the block has a gross area of 54,600 mm^2 and an average net area of 32,800 mm^2, which represents approximately 60% of the total area of the section. Areas were calculated by dividing the cross section of the concrete block into multiple simple geometric areas.
The raw materials of the tested concrete blocks and their respective amount by weight are: fine sand (5.5%), medium sand (30.1%), coarse sand (46.5%), cement (6.9%), fly ash (5.5%) and water (5.5%).

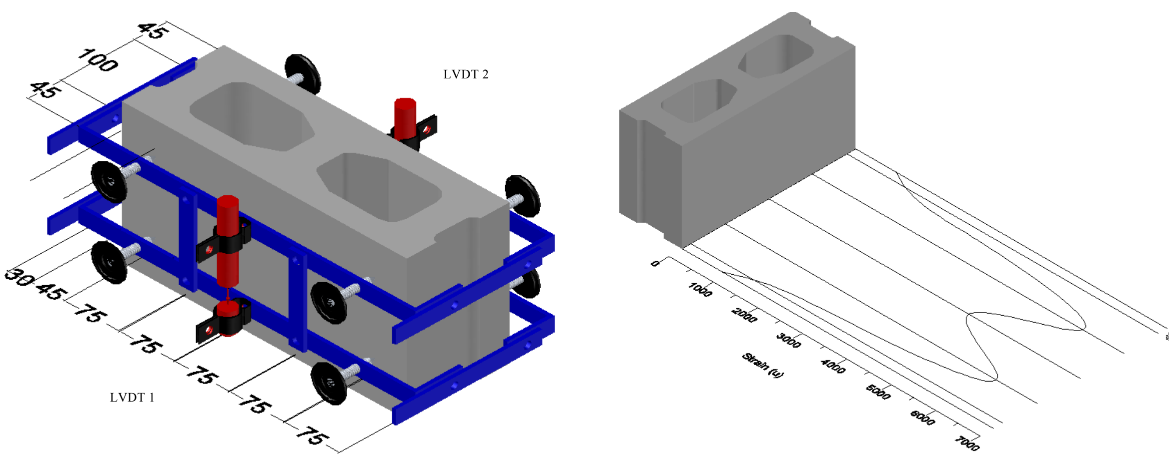
EXPERIMENTAL PROGRAM

Each concrete block was monotonically loaded with controlled speed of 1 kN/s in a steadily way until the failure, following established requirements of Icontec Standard NTC 4024 (NTC 4024, 2001). Specimens were tested in a servo-hydraulic compression machine with a capacity of 2500 kN and a precision of ± 1 kN, which was controlled by an acquisition system of digital data (Figure 2).

a) Concrete block test set-up b) Servo-hydraulic compression machine

Figure 2. Test set-up

To monitor the displacement in the direction of the applied axial load, two LVDT (Linear Voltage Differential Transducer) were placed on each side of the block in the mid-length (Figure 3a).



a) Coupling frame to the block (mm). b) Expected displacement curve

Figure 3. Displacement measuring device.

The ends of concrete blocks were capping with sulfur mortar caps to ensure a smooth, parallel, uniform bearing surfaces that are perpendicular to the applied axial load during compressive strength testing.

TEST RESULT

Figure 4 shows that 93% of the blocks have a stress-strain behavior relatively linear until 30% of its maximum strength point, from which some fissures start appearing inside the block unit, gradually increasing its inelastic behavior. Reaching a close load level to 90% of its maximum load, it shows a greater increase of cracking and causing failure with wedge detachment in a diagonal shear crack.

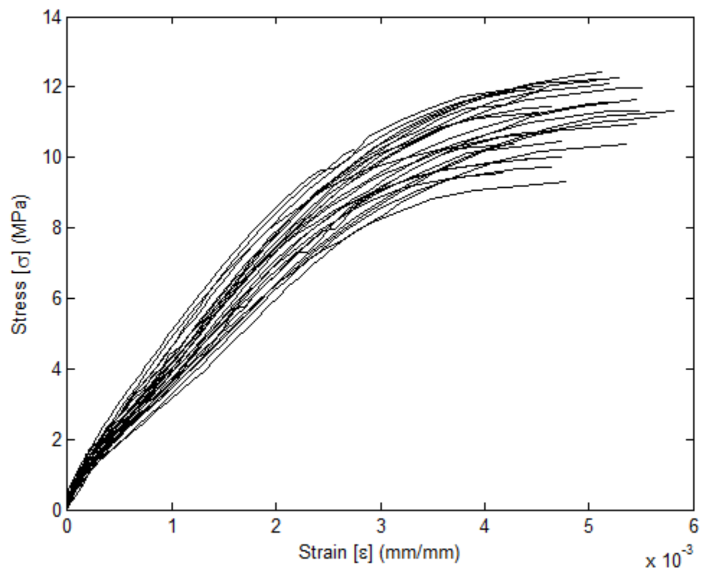


Figure 4. Stress-strain curves of the blocks tested.

Stress value was calculated divided the compressive force registered for servo-hydraulic compression machine by net area of the concrete block (Equation 3). Strain value was calculated divided the displacement registered for LVDT by initial length in the coupling frame of the block (Equation 4).

$$\sigma = \frac{P}{A} \quad (3)$$

$$\varepsilon = \frac{\delta}{l_0} \quad (4)$$

Hognestag (1951) and Smith and Young (1955) established a mathematical correlation between the stress-strain curve for concrete, they defined the parameters of the curve regardless of the compression strength of the concrete mix. After that, Sargin et al. (1971) and Popovics (1973) found that curves in the concrete mix under different levels of resistance showed variations and proposed some additional parameters in their formulations to incorporate the effects of concrete strength level and the descending shape curve, until reached the maximum compressive strength.

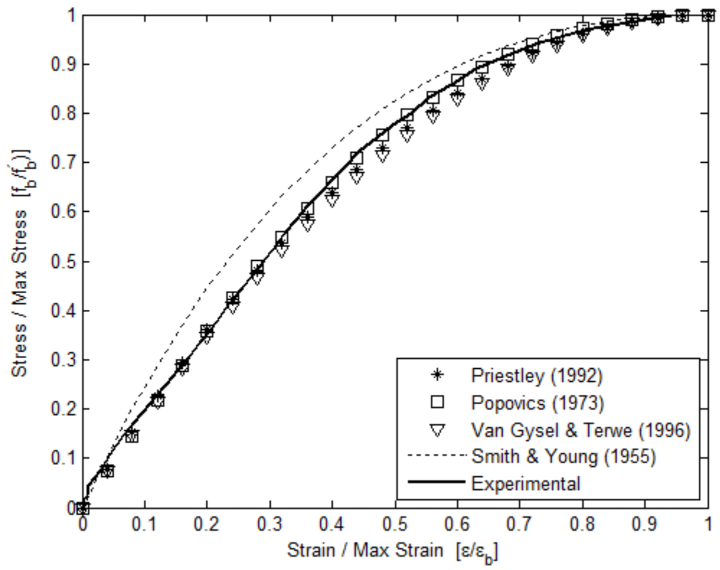


Figure 5 Experimental data blocks vs. analytical models of commercial resistance (f_b'=10MPa).

The experimental results in concrete blocks are not different from what was observed by these authors in particular (Figure 5), however, a similar behavior is observed between prefabricated concrete blocks and conventional concrete when they are submitted to uniaxial compressive stress.

According to analytical model proposed by Popovics (1973), it is required the behavior characteristic parameter of the stress-strain curve for the relationship between the initial tangent modulus (E_i) and the secant modulus of elasticity (E_c) (Figure 6). The relationship between these two modules of elasticity obtained in the tested concrete blocks showed that the tendency in the concrete block is similar to the tendency observed in the conventional concrete.

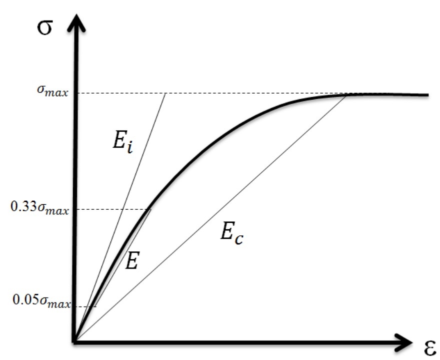


Figure 6. Method of determine modulus of elasticity.

The experimental results can be approximated the relationship between the initial tangent modulus (E_i) and the secant modulus of elasticity (E_c) through by the following expression (Equation 5):

$$\frac{E_i}{E_c} = 1.7404 - 0.01208 f_b' \tag{5}$$

FAILURE MODES

The failure of the compression blocks is characterized through a diagonal shear crack. Such cracks are produced by a combination of the stresses generated by a low slenderness ratio of the block and the upper confinement generated by the test plates (Barbosa & Hanai, 2006). This type of failure is typically generated by the lateral confinement which is produced by the friction force during the contact block-test plates (Figure 7).

Figure 7. Failure diagonal cutting blocks typical of low and medium resistance.

Barbosa and Hanai (2009) observed in their experimental test that the cracking of the concrete blocks were approximately generated at 80% of its maximum load, where the stress-strain curve shows a significant decline compared to the initial part of the elastic area. Later, these cracks produce the failure of the block through a combined effect between compressive stress and shear stress in the unit, creating a diagonal shear wedge that comes from the low slenderness ratio of the block and the lateral confinement provided by the test plates (Figure 7).

Among the results observed in the present research, none of the test specimens with commercial strength (f_b' = 10MPa) presented an explosive failure, all failures were accompanied by the diagonal cracks prolongation usually presented in the block endings, which is similar to observed by Barbosa and Hanai (2009) in their experiments.

ANALYTICAL MODEL PROPOSED

Observing the good correlation between the experimental and analytical curves given in the literature, is proposed a mathematical equation to express the stress-strain curve of the concrete blocks that takes the best experiences from the analytical models proposed for the conventional concrete. This new equation presents a curve, whose parameters have been calibrated by the experimental results obtained in sixty concrete blocks tested.

After reviewing the analytical models found in literature, and comparing them with the experimental results obtained in the failure of the concrete blocks to uniaxial compression, it was observed that the equations better match to the laboratory tests are those which involve within its parameters the change the shape of the stress-strain curve according to the maximum compressive strength of the concrete (Equation 4). Thus, the decision has been made of working with the expression proposed by Popovics (1973), due to its better correlation with experimental results and simplicity in the mathematical formulation, when they are compared with other expressions.

$$\frac{f_b}{f_b'} = \frac{\frac{n_b}{n_b - 1}\left(\frac{\varepsilon}{\varepsilon_b}\right)}{\frac{1}{n_b - 1} + \left(\frac{\varepsilon}{\varepsilon_b}\right)^{\frac{n_b}{n_b - 1}k_b}} \tag{4}$$

where, $n_b = \frac{E_i}{E_c} = 1.7404 - 0.01208 f_b'$

The proposed empirical correlation is formulated based on the experimental results of uniaxial compression tests on tested specimens.

The comparison between the experimental results obtained and the proposal curve can be observed in Figure 8.

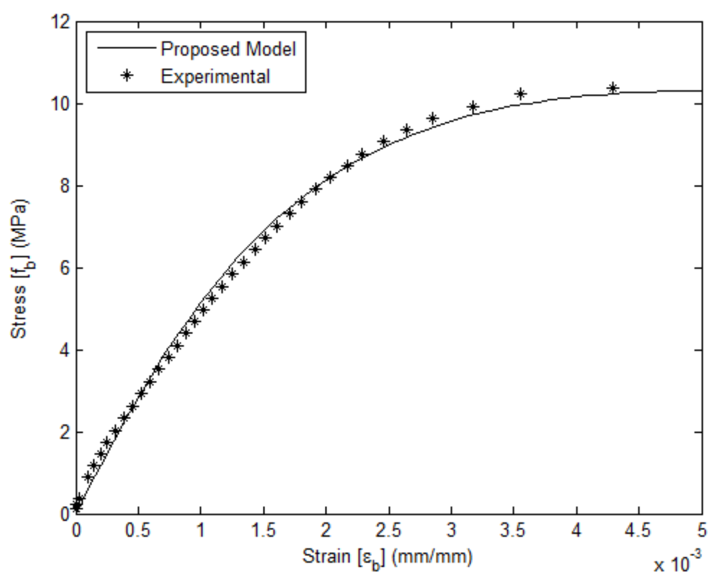


Figure 8. Analytical Model versus experimental results

As shown in Figure 7, there is a good correlation between the experimental values and the analytical model proposed for commercial resistance blocks. It is observed that both, the conventional concrete and precast concrete blocks, the stress-strain curve is depending on the magnitude of the uniaxial compressive strength, and although the constructive process of both materials differs, its structural performance under uniaxial compression loads is similar.

CONCLUSIONS AND ANALYSIS OF RESULTS

It has been experimentally evaluated that the mechanical behavior of concrete prefabricated blocks to compressive loads, obtaining the stress-strain history and the main parameters controlling the behavior of masonry units such as high compression strength and their corresponding strain and modulus of elasticity. From the results obtained and considering the similarity in the experimental results, the expression proposed by Popovics (1973) has been adapted in order to evaluate the compressive behavior of concrete, in the case of precast concrete blocks. To do this, new empirical correlations were set to obtain the parameters according to the observed structural performance of concrete blocks. This is an essential tool for the design of masonry structures under criteria based on structural performance.

The results show that although the construction process differs in both the conventional concrete and the precast concrete blocks, the stress-strain curves proposed in the literature and structural performance under compressive uniaxial loads are similar.

ACKNOWLEDGEMENTS

The development of this research would not have been possible without the support of the companies: Adoquin-Ar prefabricated and Ingeconcreto, thanking especially their managers, Mr. Juan P. Arbelaez and Mr. Jesus H. Arango. We also thanks to the students Luis Fernando Moreno and Juan Manuel Maya, for their unconditional help in every test, and a very big thanks to the University of Medellín, supporting the PhD work of Professor John Mario Garcia.

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NOTATION

f_c: Concrete compressive stress
f_b: Compressive stress of the concrete block
σ: Stress
ε: Strain
P: Load applied by servo-hydraulic compression machine
A: Net area of the concrete block
δ: Displacement registered for LVDT
l_0: Initial length in the coupling frame of the block
f_c': Maximum compressive strength of concrete
f_b': Maximum compressive strength of the concrete block
ε_c: Strain in concrete corresponding tof_c'
ε_b: Strain in the concrete block corresponding to f_b'
n: Correlation between the initial tangent modulus of elasticity and maximum drying in concrete
n_b: Correlation between initial tangent modulus of elasticity and maximum drying in concrete block
k: Parameter for the descending stress-strain curve in concrete, for ascending curve $k = 1$
k_b: Parameter for the descending stress-strain curve in concrete, for ascending curve $k_b = 1$
E_i: Initial tangent modulus corresponding to $\varepsilon = 0$.
E_c: Secant modulus maximum resistance $E_c = \frac{f_c'}{\varepsilon_c}$
E: Modulus of elasticity secant line with the proposal of the MSJC