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COMPRESSIVE STRENGTH AND FAILURE MODE OF AXIALLY LOADED HOLLOW CONCRETE BLOCK MASONRY

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ABSTRACT

The study presented herein evaluated the influence of the mortar strength on the prism-block strength ratio and on the failure mode of axially loaded hollow concrete block masonry. The literature indicates that mortar strength has little influence on the masonry strength; however, it lacks information on the influence of the mortar strength on the failure mode of the masonry. To address this lack of information, two sets of prisms, two-blocks high, were constructed using one type of block and two different types of mortar: one with high strength (mortar-block strength ratio of approximately 1.0) and another with low strength (mortar-block strength ratio of approximately 0.15). In addition to measuring applied loads and deformations, the tests were monitored with a high definition camera, capable to shot 24-frames-per-second images, to observe the rupture sequence of the prisms. The net area average strength for the prisms with high-strength mortar was approximately 15.0 MPa and the prism-block strength ratio was 0.72. For the prisms with low-strength mortar, the average strength was approximately 14.0 MPa and the prism-block strength ratio was 0.67. These results agree with those of other researchers -mortar has little influence on masonry prism strength. However, the failure mode was very different. The prisms assembled with low-strength mortar failed due to mortar crushing, followed by generalized cracking and spalling of the blocks at the joint. The failure occurred at stress/strength levels of approximately 50%. Post-rupture evaluation showed a complete breakdown of the adhesion between the block and the mortar and destruction of the porous structure of the mortar. In contrast, the prisms assembled with high-strength mortar experienced typical conical breaks. The results of the research presented herein indicate that evaluating masonry strength regardless of its failure mode can result in strength overestimation and uncertain level of safety.

KEYWORDS: *hollow concrete block masonry, assemblage mortar, failure mode.*

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INTRODUCTION

Modern masonry, a composite material with structural capacity, is formed from the combination of, at least, two materials, blocks and mortar. These materials have different physical properties and mechanical properties that are associated to the multiaxial stresses developed during loading. The behavior of masonry is, thus, complex, making difficult the establishment of models capable to reproduce its failure [1].

According to Mohamad et al. [2], mortars are responsible for the monolithic behavior and stability of a masonry wall, and their main function is the transmission of loads, in addition to absorbing deformations and compensating eventual dimensional irregularities in the blocks. Traditionally, the mortar importance and its properties were left in the background, and the mortar was considered the weaker link in the system, for it was believed that increments in the mortar strength would not cause expressive strength increases to the system. Only in the 1970's, from Khoo and Hendry's [3] studies, a new understanding of the mortar importance was obtained when evaluating the mortar triaxial behavior and the masonry failure mode under compression.

In Brazil there are two standards for masonry: NBR 15812 [4] and NBR 15961 [5]. Related specifically for mortar, the standards recommend only that mortar compressive strength be at least 1.5 MPa and be limited to 0.7 of the compressive characteristic strength of the block (f_{bk}) calculated using net area. In contrast, in the American [6], British [7] and European [8] codes, there are some additional considerations, such as masonry strength prediction from block and mortar properties, so that it is possible to make predictions about the masonry after construction.

Mohamad [1] and Schankoski et al. [9] have concluded that, for certain blocks and mortar combinations, mainly when the mortar has much lower compressive strength than that of the block, the failure load may result in uncertain safety levels which may not be acceptable. That is because there might be situations in which the masonry experiences mortar joint degradation, i.e., joint crushing, at loads lower than the failure load, even though the standards prescriptive requirements are meet.

While idealizing the masonry system and deciding what materials to used, the performance of each material cannot be evaluated separately, given the physical and mechanical interaction that occurs between them. In this context, it is necessary to evaluate the mortar strength influence on the masonry failure mode and to determine in what circumstances mortar joint crushing occurs. Thereby, a research was conducted that evaluated the mortar strength influence on the prism strength/block strength efficiency ratio and on the failure mode of hollow concrete block masonry under axial compression. The results of the research are presented in this article.

BRIEF LITERATURE REVIEW

For masonry full performance, the bond between blocks and mortar is essential to ensure that strengths and strains are homogeneous on the interface between the materials. The adherence and the strains equality make complex stress conditions act on the components. When mortar is more deformable than the block, it is subjected to a triaxial compressive condition called confinement. Several studies [10-17] mention and recognize the importance of mortar confining. Restrained from free expansion, mortar exhibits different behavior from that of mortar subjected to simple uniaxial compression, and its mechanical properties, such as compressive strength and modulus of elasticity, are altered. Therefore, the confining modifies the masonry system performance.

Masonry can fail due to tensile stress in the block or due to crushing of the mortar joint and crushing occurs when mortar reaches its confining strength limit [13]. Thus, the necessity of equality between mortar mix proportions and block to ensure that failure occurs by tensile stress in the block [2]. The importance and role of such equality is highlighted by Mohamad [1] and Schankoski et al. [9]. These authors have concluded that, when failure occurs due to joint crushing, the mortar has a strong influence on the masonry behavior, without causing reduction in the failure load.

Mohamad [1] tested prisms assembled with concrete block with compressive strength of approximately 23 MPa and two types of mortar, one with uniaxial compressive strength of approximately 20 MPa and the other with approximately 7 MPa, to evaluate the failure modes and the stress-strains behavior. The author concluded that the mortar determines the masonry failure mode, and, although the average strength for the prisms, regardless of the mortar type used, was about 14 MPa, the stress-strain behavior was significantly different. For prisms constructed with the stronger mortar, the stress-strain behavior was linear until about 60% of failure load and, from then on, nonlinear behavior was observed and failure was sudden and due to vertical cracks on the blocks. For prisms constructed with the weak mortar, nonlinear behavior started approximately at 30% of the compressive strength, with lateral strains increasing significantly at approximately 60% of the strength; localized mortar crushing was observed at approximately 50% of the strength. For these prisms, the onset of failure was caused by mortar crushing, which was followed by crack propagation in the blocks.

Schankoski et al. [9] also studied the failure mode of prisms constructed with concrete blocks having an average compressive strength of approximately 18.7 MPa and different types of mortar. For prisms assembled with mortar of significantly lower strength than that of the block, approximately 6 MPa, the authors observed mortar crushing at loads approximately equal to 70% of failure load. According to these authors, before reaching the failure load, the masonry stopped acting as a homogenous material due to the degradation of mortar joint.

These authors emphasized the importance of knowing when mortar crushing occurs for correct prediction of masonry capacity and correct understanding of masonry behavior, aiming to design safe structures that complies with code requirements.

METODOLOGY

In order to evaluate the influence of the mortar strength influence on the prism strength/block strength efficiency ratio and on the masonry failure mode, two-blocks high prisms were constructed with two types of mortar having different strength.

Block properties

The blocks were characterized physically and mechanically. The blocks average dimensions and compressive strengths using gross area ($f_{bc,gross}$) and net area ($f_{bc,liq}$) were determined according to NBR 12118 [18]; in addition, indirect tensile strength was determined according to ASTM C 1006 [19]. For the testing, the blocks were capped with high strength Portland cement and sand mortar. The average physical and mechanical properties of the blocks are summarized in Table 1.

Table 1: Average physical and mechanical properties of concrete blocks

Property	Value
Width	139.8 mm
Height	189.6 mm
Length	395.0 mm
External walls thickness	25.9 mm
Internal walls thickness	26.9 mm
Mass	12,960 g
Absorption rate	6.%
Gross area – A_{gross}	552.3 cm2
Net area – A_{net}	323.3 cm2
A_{net}/A_{gross}	0.59
Bulk area compressive strenght - $f_{bc,gross}$	12.3 MPa (13%)[1]
Net area compressive strenght - $f_{bc,net}$	21.0 MPa (13%)[1]
Bulk area Indirect tensile strength - f_{bt}	1.65 MPa (22%)[1]

[1] Value in parentheses are the coefficients of variation.

MORTAR PROPERTIES

Mortars were bagged, with average compressive strengths, at 28 days, of 2.94 MPa and 20.6 MPa, here denominated, respectively, as weaker (W) and stronger mortar (S). The mortars used in the characterization tests were mixed at the same time that the prisms were assembled. The amount of water added was that recommended by the manufacturer, and little adjustment was needed to obtain the required consistence of 230 ±10mm. The compressive and bending tensile strengths were determined using prismatic samples of 4 x 4 x 16cm according to NBR 13279 [20], and indirect tensile strength was obtained using cylindrical samples of 5 cm x 10 cm (diameter x height), according to NBR 7222 [21]. The strengths were obtained at 28 days of age. Table 2 summarizes the mechanical properties of the tested mortars.

Table 2: Mechanical properties of mortars

Mortar Type	Compressive strenght[1] - f_m (MPa)	Bending strength - $f_{mt,f}$ (MPa)	Tensile strength [1] - $f_{mt,d}$ (MPa)	$f_{mt,d}/f_m$
Strong (S)	20.63 (9,5%)	5.55 (5.1%)	3.72 (18.2%)	0.18
Weak (W)	2.94 (10,9%)	1.32 (8.9%)	0.52 (8.4%)	0.18

[1] Value in parentheses are the coefficients of variation.

Using the results shown in Tables 1 and 2, the relationship between mortar strength and block strength were calculated as 0.14 for the weaker mortar and 0.98 for the stronger mortar.

Construction of the prisms

For each prism group six samples were constructed. All prisms were constructed by the same mason in order to minimize construction variability, and the thickness of the mortar joints was 1±0.3 cm. The prisms were tested at 28 days following the recommendations of the Brazilian standard NBR 15961-2 [5].

A servo-controlled test machine was used for the tests and a load-controlled protocol was used. A high rigidity loading plate was used to insure uniform loading of the prism. Applied load and prism deformation were recorded.

A high-speed camera, capable of shooting 24-frames-per-second, was used to record the test. The camera was fixed on a tripod and kept in the same position for all tests. A software was then used to examine the pictures.

ANALYSIS AND DISCUSSION OF RESULTS

The following results are presented in Table 3: the stress at the onset of failure using net area ($\sigma_{pi,net}$), which is the stress when either joint crushing or the first crack in blocks was observed; the strength and corresponding stress using net ($f_{p,net}$) and gross ($f_{p,gross}$) areas; the ratio between the stresses at the onset of failure and that corresponding to the strength (σ_{pi}/f_p); the average stresses ($f_{p,liq}$ e $f_{p,gross}$) corresponding to the strength; the standard deviations; the coefficients of variation; and the average prism strength/block strength ratio (f_p/f_b). In some cases, the stress at the onset of failure could not be determined because failure was abrupt. The (σ_{pi}/f_p) ratio can be used as a measure of prism ductility. The lower this ratio, the more ductile is the failure, which means that there was gap between the rising of located fails in blocks or mortar joints and the increasing of those fails until failure. The ratio prism strength/block strength is a measure of the efficiency of the block.

Table 3: Test results and mechanical properties of prisms

Prism	Block A_{liq} (cm²)	Block A_{gross} (cm²)	$\sigma_{pi,liq}$ (MPa)	*Final Load (KN)*	Strength $f_{p,liq}$ (MPa)	Strength $f_{p,gross}$ (MPa)	$\frac{\sigma_{pi}}{f_p}$	$f_{p,liq}$ average (MPa)	$f_{p,gross}$ average (MPa)	DP (MPa)	CV. (%)	$\frac{f_p}{f_b}$
W1	323,29	552,34	2,81	344,65	10,66	6,24	0,26	14,08	8,24	2,48	17,60	0,67
W2			4,43	476,90	14,75	8,63	0,30					
W3			4,37	564,50	17,46	10,22	0,25					
W4			-	461,48	14,27	8,35	-					
W5			3,25	501,33	15,51	9,08	0,21					
W6			2,75	381,58	11,80	6,91	0,23					
S1			-	429,52	13,29	7,78	-	15,18	8,89	2,22	14,60	0,72
S2			-	451,81	13,98	8,18	-					
S3			-	419,06	12,96	7,59	-					
S4			-	488,76	15,12	8,85	-					
S5			-	572,55	17,71	10,37	-					
S6			-	583,79	18,06	10,57	-					

The stress *versus* strain curves of the prisms are shown in Figure 1. The shaded areas intend to show the range of individual results while the lines within the shaded areas are the average result. Typical failure for each type of prism are also shown.

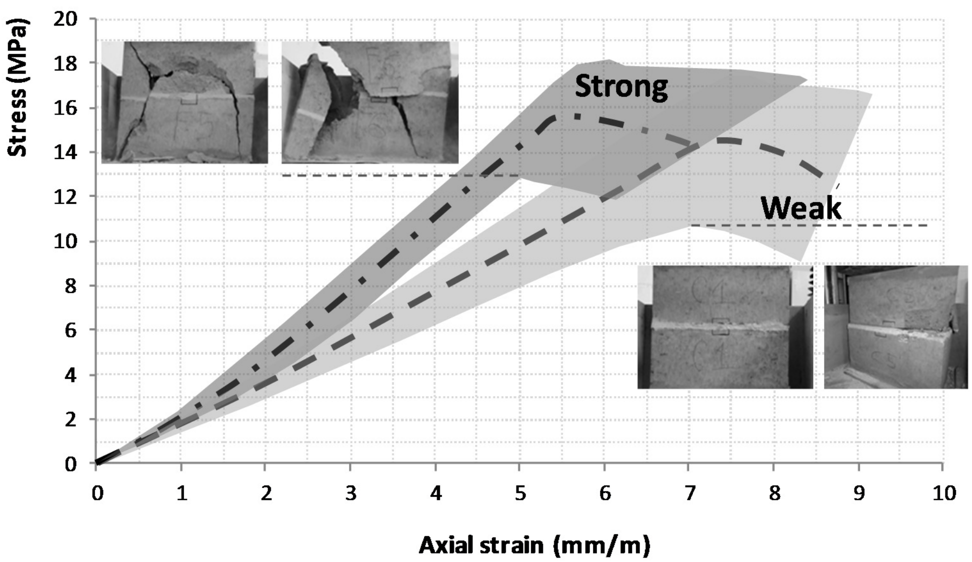


Figure 1: Axial stress versus strain curve for the prisms.

The behavior of both prisms groups was similar until approximately 2 MPa, from then on, for the same stress, the prisms constructed with weaker mortar experienced larger deformation than that of the prisms with stronger mortar. In general, the prisms constructed with the weaker mortar are more ductile than those constructed with the stronger mortar.

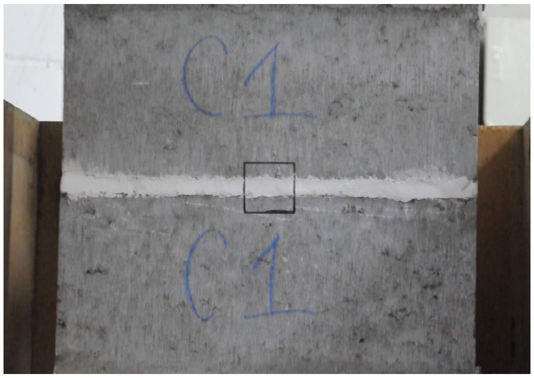
For the prisms constructed with the stronger mortar, the average strength calculated using the net area was 15.2 MPa, with a coefficient of variation of 14.6% and an efficiency ratio 0.72. In turn, prisms constructed with the weaker mortar presented an average strength calculated using the net area of 14.0 MPa, with coefficient of variation of 17.6% and an efficiency factor of 0.67. The little influence of the mortar strength on concrete blocks masonry strength has already been pointed out by other researchers [22-24]. However, despite the strengths between the prisms with stronger mortar and those with weaker mortar were similar, the failure mode was completely different. The mortar influence on the failure mode and mechanic of the prisms has been highlighted by Steil et al. [25], Mohamad et al. [26], Barbosa and Hanai [27], and Haach et al. [24]. The prisms constructed with stronger mortar failed similar to monolithic and homogeneous materials, with a conical-break post-failure cracking. In turn, the prisms constructed with weaker mortar experienced joint crushing at stress levels between 30 and 50% of the prism strength. The crushing was noticed by the initiation of cracks in the mortar surface and by the detachment of mortar in contact with the blocks. For stress levels of the order of 70% of the prism strength, the mortar joint cracking was significant and there was detachment of parts of its external surface. Nevertheless, the joint crushing did not result in significant load degradation. Failure occurred after the formation of vertical cracks in the blocks.

Figure 2 shows prisms S5 and S6 after failure. These prisms are representatives of the behavior of the prism group constructed with the stronger mortar. The failures of the prisms constructed with the strong mortar were brittle, sudden, and explosive.

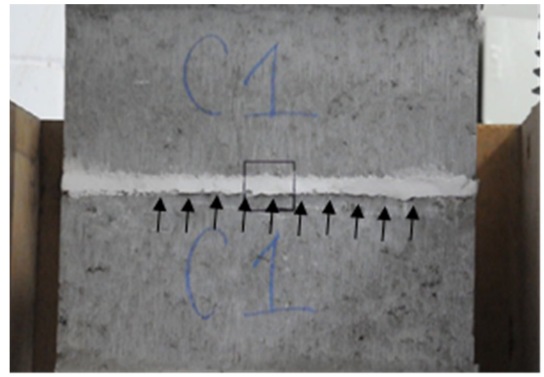
(a) prism S5 (b) prism S6

Figure 2: Cracking pattern of prisms S5 and S6.

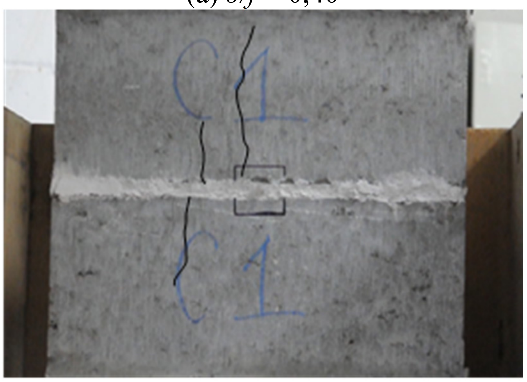
The prisms constructed with the weaker mortar had the behavior represented by prisms W1 and W6, as shown in Figures 3 and 4, respectively. There were regions, highlighted and shown with arrows in Figures 3 and 4, where detachment between the mortar and the block, indicating mortar crushing, were observed. Soon after mortar crushing was observed, vertical cracks appeared on the blocks. A possible explanation for the formation of the cracks is as follows: the mortar detachment and crushing caused the detached region of the block to be unsupported. As load continued to be applied, the gap between the top surface of the bottom block and the bottom surface of the top block at the detached region tended to close generating tensile stresses on the surfaces of the block. The tensile stresses caused the block to eventually crack vertically (as shown in Figure 3).



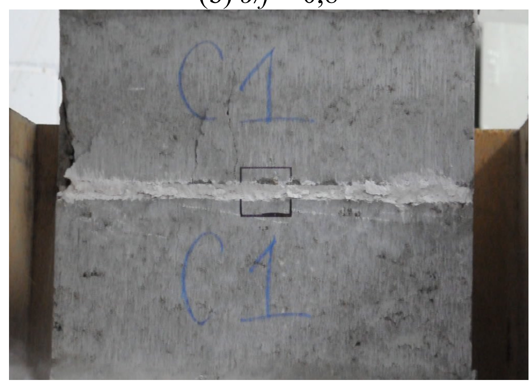
(a) $\sigma/f = 0{,}40$



(b) $\sigma/f = 0{,}8$

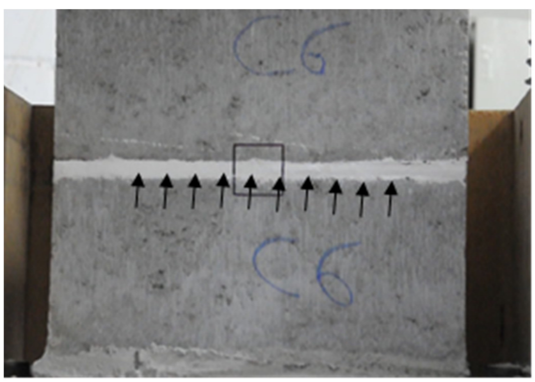


(c) $\sigma/f = 1{,}0$

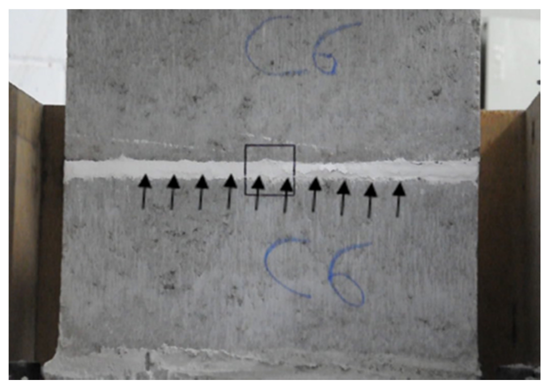


(d) post rupture

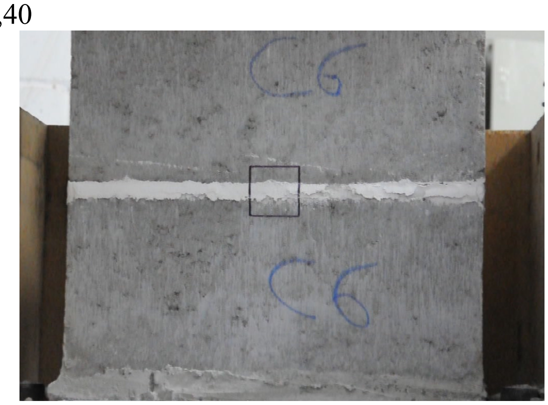
Figure 3: Failure sequence of the prism W1.



(a) $\sigma/f = 0{,}40$



(b) $\sigma/f = 0{,}7$



(c) $\sigma/f = 1{,}0$

Figure 4: Failure sequence of the prism W6.

The post-failure autopsy of the prisms with weaker mortar shows that the block-mortar bond was completely broken and the mortar porous structure completely destroyed; the mortar as essentially like a compacted powder. Figure 5 shows the complete detachment between the mortar and the blocks and the compacted powder appearance of the mortar after the failure of prism W6.

(a) (b)

Figure 5: Aspect of the mortar joint of prism W6 after the failure

The bond between the blocks and the mortar was influenced by the mortar low compressive strength, the presence of water retainers in the manufactured mortar, and the low water absorption capacity of the concrete blocks, which was approximately 6%. Thus, the connection between mortar and blocks was weak, and as the mortar crushing started at a stress level between approximately 2.7 and 4.5 MPa, there was the break of the bond between the components. A similar behavior was observed by Steil et al. [25].

CONCLUSIONS

This study evaluated the mortar influence on the failure mode and the prism/block efficiency factor of concrete blocks masonry prisms and the conclusions are:

- The mortar strength has little influence on the prisms strength and on the prism strength/block strength efficiency ratio. The difference between the strength of prisms constructed with the stronger mortar and that of the prisms constructed with the weaker mortar prisms was less than 8%.

- Mortar controls the prisms failure mode. Prisms with stronger mortar behaved as a homogeneous material, with a conical-break cracking pattern. In contrast, prisms with weaker mortar experienced mortar crushing and complete degradation of the bond between the mortar and blocks. This behavior was observed at stresses close to 50% of the strength.

- The measurement of the compressive strength of prism is not a reliable parameter without analysis of the failure mode; the compressive strength of prisms built with strong and weak mortars were similar. However, the failure mode of the prisms with weak mortar start by crushing at the half of the final strength observed at machine test.

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