The Influence of Mortar Strength on the Mechanical Behavior of Ceramic and Concrete Structural Masonry Blocks

Giovani Jordi Bruschi[1], Gian Marcelo Gaio[2], Gilson Francisco Paz Soares[2]

[1] Department of Civil Engineering, Federal University of Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, 90035-190 – Porto Alegre – RS – Brazil.

[2]Department of Civil Engineering, Regional Integrated University of Alto Uruguai and the Missions (URI – Campus Erechim – RS), Brazil.

giovani.bruschi@ufrgs.br, giangaio@hotmail.com, gilsonfps@uricer.edu.br

Abstract. *This paper analyses the influence of mortar strength on the mechanical behavior of ceramic and concrete structural masonry blocks. Experimental tests of uniaxial compression were carried out on blocks as well as prisms, with mortar strengths lower, higher and within the limits of the Brazilian standard recommendation. The characteristic strength of prisms (f_{pk}) was lower than the blocks (f_{bk}) in all combinations. The lowest decreases in strength occurred for both materials in the prisms with mortar strength within the limits indicated by the Brazilian standard. In addition, the ceramic materials were more sensitive to the variation on the mortar strength when compared to the concrete blocks.*

1. Introduction

Structural masonry is a long-established technique and has been utilized since the first man-made constructions such as pyramids, coliseums, and cathedrals (Mojsilovic and Stewart, 2015). Initially, low strength materials and empirical calculation methodologies were applied, which resulted in more robust structures. The construction techniques were improved with the use of more resistant materials alongside new alternatives methodologies (Barros et al., 2019).

The structural masonry walls constructed in Brazil, are generally compounded by concrete, ceramic or sand-lime blocks. However, in accordance with Prudêncio Jr. et al. (2003), there is a preferable option for concrete blocks due to technical reasons, since they present the highest efficiency factor, an elasticity modulus similar to the mortar joint and can be produced with variable strengths, shapes, colors, and textures. Nonetheless, the ceramic materials are still largely applied due to the lower prices.

The non-reinforced structural masonry of concrete blocks is composed of mortar-laid blocks, that may contain reinforcements for constructive or binding purposes. This type of masonry consists of structural elements that have various functions, but collectively provide structural stability (Rizzatti et al., 2012; Barros et al., 2019). This technique can rationalize all construction stages, optimizing time, materials and human resources (Juste, 2001). In virtue of these advantages, the utilization of structural masonry in the civil construction market has been intensified in recent years. Normally, in this type of structure, the blocks must have minimal strength. To achieve this value, the blocks must have high compactness and low porosity, which may hinder their adherence to the mortar joint (Paes et al., 2003; Rezende et al., 2013).

The property that governs the mechanical behavior of structural masonry is the compressive strength. It should be noted that this parameter is considerably higher than the tensile strength of the material. Thus, the projects should minimize tensile stresses and/or other stresses that may generate traction as bending moment (Prudêncio Jr. et al., 2003; Parsekian et al., 2016)

In addition, the use of industrialized mortars can considerably reduce the block-joint adhesion, this phenomenon can lead to the appearance of horizontal cracks, especially in external walls. For high strength blocks, these mortars tend to drastically decrease the efficiency factor and modify the rupture mechanism of the structure (Prudêncio Jr. et al., 2003).

The mechanical analysis of structural masonry is extremely complex, due to the different materials on its composition and the stress state acting on the materials (Mohamad et al., 2007; Foraboschi, 2019). Therefore, to improve the performance of this construction technique, it is necessary to fully comprehend the properties of the constituent materials and their influence on the behavior of the structure (Parsekian et al., 2016).

The properties of the structural blocks depend fundamentally on five factors: (i) nature of the constituents; (ii) humidity during production; (iii) dosage, (iv) degree of compaction; and (v) curing type. In addition, the basic elements of structural masonry must present minimum performance characteristics, compliance with standard specifications and properties that enable the fulfillment of these requirements (Parsekian and Soares, 2010).

According to Oliveira et al. (2018), the mortar of structural masonry has four well-defined functions: (i) to bond masonry units, aiding them to withstand lateral efforts; (ii) to distribute the stresses acting on the wall; (iii) to absorb the natural deformations to which the masonry is subjected; and (iv) to seal the joints.

The mortar properties on fresh and hardened state directly influence the characteristics of the structural masonry joints, as well as the performance of the whole ensemble (Casali, 2008; Schankoski et al., 2015; Oliveira et al., 2015). The moment the mortar is placed in contact with the block, the processes of water removal and joint densification begin (Oliveira et al., 2015). The water transfer mechanism can result in two distinctive products, densification with a reduction in porosity and an increase in resistance or desiccation with an increase in porosity and a decrease in resistance (Casali, 2008). This outcome is closely linked to the porosity and absorption rate of the blocks.

The influence of mortar dosage on structural masonry performance is substantial, and the neglecting of its properties can cause pathologies due to misuse of the material. Thus, an experimental analysis of the materials is extremely important to avoid future complications (Hendry 2001; Diamond 2003; Mohamad et al., 2007).

International studies on the water transfer mechanism of structural masonry (Jennings et al., 2000; Forth et al., 2000; Sarangapani et al., 2002) usually analyze ceramic bricks, and sometimes concrete blocks. In Brazil, some studies (Paes et al., 2003) have verified the water transfer processes from the mortar to the substrate. However, there are few studies performed with Brazilian materials involving the comparison of different structural masonry blocks.

To fulfill this gap, the main objective of this research is to analyze the mortar resistance influence on the compressive strength of ceramic and concrete structural blocks, as well as to verify which of the blocks presented the higher sensitivity to these changes.

2. Method

Aiming the verification of the mortar influence on the mechanical strength, a total of 36 prisms (Figure 1) were executed, containing two blocks, a single horizontal joint and capping on both surfaces in contact with the press plates.

(a) (b)

Figure 1. Prisms (a) ceramic (b) concrete

For the concrete blocks, 18 specimens were executed: (i) 6 prisms, utilizing a 2 MPa mortar strength (below the limit of the Brazilian standard); (ii) 6 prisms, utilizing a 4 MPa mortar strength (within the limit of the Brazilian standard); and (iii) 6 prisms, utilizing a 6 MPa mortar strength (above the limit of the Brazilian standard). On the other hand, for the ceramic blocks, 18 specimens were also executed: (i) 6 prisms, utilizing a 4 MPa mortar strength (below the limit of the Brazilian standard); (ii) 6 prisms, utilizing an 8 MPa mortar strength (within the limit of the Brazilian standard); and (iii) 6 prisms, utilizing a 15 MPa mortar strength (above the limit of the Brazilian standard).

The blocks utilized for the experimental analysis follow the subsequent specifications: (i) concrete block, nominal dimensions 140 x 190 x 390 (width W = 140 mm, height H = 190 mm, and length L = 390 mm) with compression strength of 4 MPa;

and (ii) ceramic block, nominal dimensions 140 x 190 x 290 (width W = 140 mm, height H = 190 mm, and length L = 290 mm) with compression strength of 10 MPa.

2.1. Characterization of the blocks

The characterization followed the procedures of ABNT NBR 15270-3 (2005) for the ceramic blocks and ABNT NBR 12118 (2013) for the concrete blocks. The tolerance limits for the dimensional characteristics were ± 5 mm for length, height and width, and ± 3 mm for the surface flatness.

2.2. Net area determination of the blocks

The net area was determined according to Annex "A" of ABNT NBR 12118 (2013) and ABNT NBR 15270-3 (2005).

2.3. Saturation test of the blocks

Posterior the curing process of both capping surfaces, the blocks were immersed in a water tank for six hours. After the established period, they were removed from the tank and the saturation test was executed.

2.4. Compression test of the blocks

The compression test was executed immediately after the removal from the saturation tank. The determination of the compressive strength for both types of block was performed following the test procedures described in Annex "C" of ABNT NBR 15270-3 (2005) and ABNT NBR 12118 (2013). The equipment utilized was a hydraulic press, model PC200CS - EMIC with a maximum capacity of 2000 kN. The applied load had a constant speed of 0.05 MPa/s (tolerance ± 0.01). The characteristic compressive strength (fbk) was calculated according to the ABNT NBR 6136 (2014).

2.5. Compression test of the prisms

The compression test was executed in accordance with the procedures of ABNT NBR 15812-2 (2010) and ABNT NBR 15961-2 (2011). The loading rate was 0.05 ± 0.01 MPa/s.

2.6. Determination of the characteristic compression strength of the prisms

The results for the compressive characteristic strength (f_{pk}) of the prisms were calculated according to ABNT NBR 15812-1 (2010).

3. Results and discussion

3.1. Concrete blocks characterization

The dimensions of the concrete blocks are given in Table 1. The values provided by the manufacturer are L = 140 mm, H = 190 mm, and W = 390 mm. All measurements are within the individual tolerance limit of ± 5 mm for L, H, and W and ± 3 mm for the flatness. The discovered variation coefficient classifies the sample as homogeneous, thus no specimen had to be discarded.

Table 1. Physical characterization of the concrete blocks

Block	Width (W) (mm)	Height (H) (mm)	Length (L) (mm)	Flatness (mm)
1	140.00	188.00	391.00	1.00
2	142.00	190.00	392.00	2.00
3	140.00	192.00	391.00	1.00
4	142.00	187.00	392.00	2.00
5	140.00	191.00	390.00	1.50
6	140.00	189.00	392.00	2.00
7	142.00	190.00	390.00	1.00
8	142.00	189.00	390.00	2.50
9	141.00	190.00	391.00	1.00
10	142.00	192.00	391.00	2.00
11	141.00	192.00	392.00	2.00
12	141.00	188.00	390.00	0.50
13	142.00	190.00	389.00	2.00
14	140.00	190.00	392.00	1.00
15	140.00	188.00	390.00	1.50
Average	141.00	189.73	390.86	1.53
Standard deviation	0.92	1.58	0.99	0.58
V.C.	0.006	0.008	0.002	0.37

The net area values are presented in Table 2. No results had to be discarded since the variation coefficient also classified the sample as homogeneous. It should be noted that the average values obtained are valid and are derived from 15 specimens, making the results more accurate since the Brazilian standard requires the characterization to be carried out with at least 6 specimens.

Table 2. Mass and area of the concrete blocks

Block	Submerged mass (g)	Saturated mass (g)	Gross area (cm²)	Net area (cm²)
1	6500.00	11950.00	547.40	289.89
2	6750.00	12300.00	556.64	292.11
3	6570.00	12300.00	547.40	289.06
4	6400.00	11800.00	556.64	288.77
5	6600.00	12000.00	546.00	282.72
6	6400.00	11750.00	548.80	283.07
7	6700.00	12200.00	553.80	289.47
8	7100.00	12750.00	553.80	298.94
9	6600.00	12050.00	551.31	286.84
10	6900.00	12550.00	555.22	294.27
11	6950.00	12650.00	552.72	296.88
12	6600.00	12050.00	549.90	289.89
13	7000.00	12700.00	552.38	300.00
14	6600.00	12000.00	548.80	284.21
15	6500.00	11850.00	546.00	284.57
Average	6678.00	12193.33	551.12	290.05
Standard deviation	217.88	334.80	3.67	5.52
V.C.	0.03	0.03	0.007	0.02

The results of uniaxial compression strength are presented in Table 3. The data shows that the sample is categorized as medium dispersion, regarding the compressive strength (variation coefficient = 22%) and homogeneous (low dispersion) for the other parameters.

Table 3. Uniaxial compression strength of the concrete blocks

Block	Width (mm)	Height (mm)	Length (mm)	Gross area (cm²)	Net area (cm²)	Uniaxial compression strength (MPa)
1	140.00	188.00	391.00	547.40	289.89	3.43
2	142.00	190.00	392.00	556.64	292.11	4.61
3	140.00	192.00	391.00	547.40	289.06	4.67
4	142.00	187.00	392.00	556.64	288.77	7.59
5	140.00	191.00	390.00	546.00	282.72	6.25
6	140.00	189.00	392.00	548.80	283.07	6.12
7	142.00	190.00	390.00	553.80	289.47	7.91
8	142.00	189.00	390.00	553.80	298.94	6.25
9	141.00	190.00	391.00	551.31	286.84	8.16
10	142.00	192.00	391.00	555.22	294.27	7.13
11	141.00	192.00	392.00	552.72	296.88	5.59
12	141.00	188.00	390.00	549.90	289.89	6.03
13	142.00	190.00	389.00	552.38	300.00	6.21
14	140.00	190.00	392.00	548.80	284.21	8.35
15	140.00	188.00	390.00	546.00	284.57	5.99
Average	141.00	189.73	390.87	551.12	290.05	6.29
Standard deviation	0.92	1.58	0.99	3.67	5.52	1.39
V.C.	0.007	0.008	0.002	0.007	0.02	0.22

The values shown in Table 4 are the seven lowest values of the individual compressive strength, increasingly ordered and derived from Table 3.

Table 4. Values considered for the calculation of the concrete blocks f_{bk}

Block type	f_{b1} (MPa)	f_{b2} (MPa)	f_{b3} (MPa)	f_{b4} (MPa)	f_{b5} (MPa	f_{b6} (MPa)	f_{bi} (MPa)
Concrete	3.43	4.61	4.67	5.59	5.99	6.03	6.12
f_{b1}, f_{b2}, …, f_{bi} = increasingly ordered 7 lowest individual strengths (ABNT NBR 6136, 2014)							

The strength values, as well as the blocks characteristic compressive strength, are presented in Table 5. The values of f_{bk1}, f_{bk2}, f_{bk3} and f_{bk4} are all parameters utilized for the calculation of the characteristic compressive strength (f_{bk}) of the blocks, and they were obtained following the procedures of ABNT NBR 6136 (2014).

The characteristic compressive strength was 4.03 MPa, extremely similar to the data provided by the manufacturer, proving the quality of the utilized materials.

Table 5. f_{bk} values of the concrete blocks

Block	f_{bk1} (MPa)	f_{bk2} (MPa)	f_{bk3} (MPa)	f_{bk4} (MPa)	f_{bk} (MPa)
Concrete	3.99	6.29	4.03	4.03	4.03

3.2. Ceramic blocks characterization

The dimensions of the ceramic blocks are presented in Table 6. The values provided by the manufacturer are L = 140 mm, H = 190 mm, and W = 290 mm.

All dimensions are within the individual tolerance limit of ± 5 mm for L, H, and W and ± 3 mm for the flatness. As a result of the homogeneity of the sample, no specimen had to be discarded.

Table 6. Physical characterization of the ceramic blocks

Block	Width (mm)	Height (mm)	Length (mm)	Flatness (mm)
1	137.00	192.00	287.00	2.0
2	139.00	190.00	287.00	2.0
3	136.00	190.00	287.00	1.0
4	136.00	190.00	287.00	2.0
5	137.00	190.00	287.00	1.5
6	138.00	192.00	287.00	2.5
7	138.00	193.00	287.00	2.5
8	137.00	192.00	288.00	2.5
9	138.00	188.00	287.00	2.0
10	138.00	192.00	286.00	2.5
11	138.00	191.00	287.00	2.0
12	138.00	191.00	288.00	1.0
13	137.00	191.00	287.00	2.0
14	138.00	190.00	287.00	2.0
15	137.00	190.00	287.00	1.0
Average	137.47	190.80	287.07	1.9
Standard deviation	0.83	1.26	0.46	0.54
V.C.	0.006	0.006	0.001	0.28

The results of the net area of the blocks are presented in Table 7. No result had to be discarded since the variation coefficient classifies the sample as homogeneous.

Table 7. Mass and area of the ceramic blocks

Block	Submerged mass (g)	Saturated mass (g)	Gross area (cm²)	Net area (cm²)
1	4100.00	7870.00	393.19	196.35
2	4200.00	7830.00	398.93	191.05
3	4000.00	7840.00	390.32	202.11
4	3850.00	7886.00	390.32	212.42
5	3800.00	7870.00	393.19	214.21
6	3900.00	7938.00	396.06	210.31
7	4230.00	7814.00	396.06	185.70
8	4100.00	7910.00	394.56	198.44
9	4000.00	7950.00	396.06	210.11
10	4200.00	7880.00	394.68	191.67
11	3950.00	7950.00	396.06	209.42
12	4000.00	7920.00	397.44	205.24
13	4400.00	7920.00	393.19	184.29
14	3800.00	7870.00	396.06	214.21
15	3730.00	7830.00	393.19	215.79
Average	4017.33	7885.20	394.62	202.75
Standard deviation	188.28	44.84	2.42	10.82
V.C.	0.05	0.006	0.006	0.05

The uniaxial compression results of the ceramic blocks are shown in Table 8, classifying the sample as homogeneous for all parameters.

Table 8. Uniaxial compression strength of the ceramic blocks

Block	Width (mm)	Height (mm)	Length (mm)	Gross area (cm²)	Net area (cm²)	Uniaxial compression strength (MPa)
1	137.00	192.00	287.00	393.19	196.35	15.26
2	139.00	190.00	287.00	398.93	191.05	14.71
3	136.00	190.00	287.00	390.32	202.11	15.19
4	136.00	190.00	287.00	390.32	212.42	11.08
5	137.00	190.00	287.00	393.19	214.21	10.98
6	138.00	192.00	287.00	396.06	210.31	12.35
7	138.00	193.00	287.00	396.06	185.70	12.39
8	137.00	192.00	288.00	394.56	198.44	12.31
9	138.00	188.00	287.00	396.06	210.11	11.28
10	138.00	192.00	286.00	394.68	191.67	14.34
11	138.00	191.00	287.00	396.06	209.42	14.16
12	138.00	191.00	288.00	397.44	205.24	10.31
13	137.00	191.00	287.00	393.19	184.29	9.81
14	138.00	190.00	287.00	396.06	214.21	13.08
15	137.00	190.00	287.00	393.19	215.79	12.81
Average	137.47	190.80	287.07	394.62	202.75	12.67
Standard deviation	0.83	1.26	0.46	2.42	10.82	1.77
V.C.	0.006	0.006	0.001	0.006	0.05	0.14

Table 9 presents the seven lowest compressive strength values of the specimens. This compilation was arranged in an increasing manner and retrieved from Table 8.

Table 9. Values considered for the calculation of the ceramic blocks

Block	f_{b1} (MPa)	f_{b2} (MPa)	f_{b3} (MPa)	f_{b4} (MPa)	f_{b5} (MPa	f_{b6} (MPa)	f_{bi} (MPa)
Ceramic	9.81	10.31	10.98	11.08	11.28	12.31	12.35
f_{b1}, f_{b2}, …, f_{bi} = increasingly ordered 7 lowest individual strengths (ABNT NBR 6136, 2014)							

The strength values, as well as the blocks characteristic compressive strength, are presented in Table 10.

Table 10. f_{bk} values of the of the ceramic blocks

Block type	f_{bk1} (MPa)	f_{bk2} (MPa)	f_{bk3} (MPa)	f_{bk4} (MPa)	f_{bk} (MPa)
Ceramic	9.57	12.67	9.66	9.66	9.66

Once again, the values of f_{bk1}, f_{bk2}, f_{bk3} and f_{bk4} are all parameters utilized for the calculation of the characteristic compressive strength (f_{bk}) of the blocks, and they were obtained following the procedures of ABNT NBR 6136 (2014). The characteristic compressive strength (f_{bk}) was 9.66 MPa. This result was extremely similar to the value presented by the manufacturer (10 MPa), proving the quality of the materials.

3.3. Concrete prisms strength

The strength results are shown in Table 11. It was possible to notice that, the average compressive strength of the concrete prisms for all combinations was lower than the blocks, which was 6.29 MPa (Table 4). These results validate the theoretical prerogative proposed by Foraboschi (2019), Livitsanos et al. (2019) and Askouni and Papanicolaou (2019), in which the prisms average strength is lower than the characteristic strength of the blocks (f_{bk}). However, the strength values were noticeably similar, especially on the combination 1B.

Table 11. Strength of the concrete prisms

Prism	A*	B*	C*
	Compressive strength (MPa)	Compressive strength (MPa)	Compressive strength (MPa)
1	5.11	6.09	6.63
2	3.92	4.62	3.90
3	4.89	8.43	5.96
4	5.80	4.77	5.16
5	5.75	8.15	7.13
6	5.72	5.48	5.55
Average	5.20	6.26	5.72
Standard deviation	0.73	1.66	1.14
V.C.	0.14	0.26	0.2

** (A) 2 MPa mortar strength; (B) 4 MPa mortar strength; (C) 6 MPa mortar strength*

It was observed that the variation coefficient of the concrete blocks was slightly elevated, classifying the sample as a medium dispersion. Likewise, this occurred in the concrete prisms in combinations 1B and 1C, especially in the case of combination 1B (26.58%). In this case, two specimens differed from the others (3 and 5) which presented elevated strength values.

The results of Table 12 represent the three lowest compressive strength values, increasingly arranged.

Table 12. Values considered for the calculation of the concrete prisms f_{pk}

Mortar	f_{p1} (MPa)	f_{p2} (MPa)	f_{pi} (MPa)
A	3.90	5.16	5.55
B	4.62	4.77	5.48
C	3.92	4.89	5.11

f_{p1}, f_{p2}, …, f_{pi} = increasingly ordered 3 lowest individual strengths (ABNT NBR 15812-1, 2010)

The strength values, as well as the average characteristic compression strength of the concrete prisms, are presented in Table 13. The values of f_{pk1}, f_{pk2}, f_{pk3} and f_{pk4} are all parameters utilized for the calculation of the characteristic compressive strength (f_{pk}) of the prisms, and they were obtained following the procedures of ABNT NBR 15812-1 (2010). The same tendency shown in Table 13 was observed in the f_{pk} values of the concrete prisms. The average characteristic compressive strength of the prisms (f_{pk}) for all combinations was lower than the blocks characteristic strength (f_{bk}), which was 4.03 MPa (Table 5).

Table 13. f_{pk} values of the concrete prisms

Mortar	f_{pk1} (MPa)	f_{pk2} (MPa)	f_{pk3} (MPa)	f_{pk4} (MPa)	f_{pk} (MPa)
A	3.51	3.12	3.51	4.86	3.51
B	3.91	3.47	3.91	5.43	3.91
C	3.71	3.30	3.71	4.41	3.71

Figure 2 illustrates the strength relationship between the blocks and the concrete prisms. The characteristic compressive strength of concrete prisms (f_{pk}) was lower than the blocks (f_{bk}), being this difference approximately 13%, 3%, and 8% in specimens A, B, and C respectively. Since no mortar was utilized on the mechanical characterization of the blocks, the strength value was the constant characteristic compressive strength of the blocks (f_{bk}) in all comparisons.

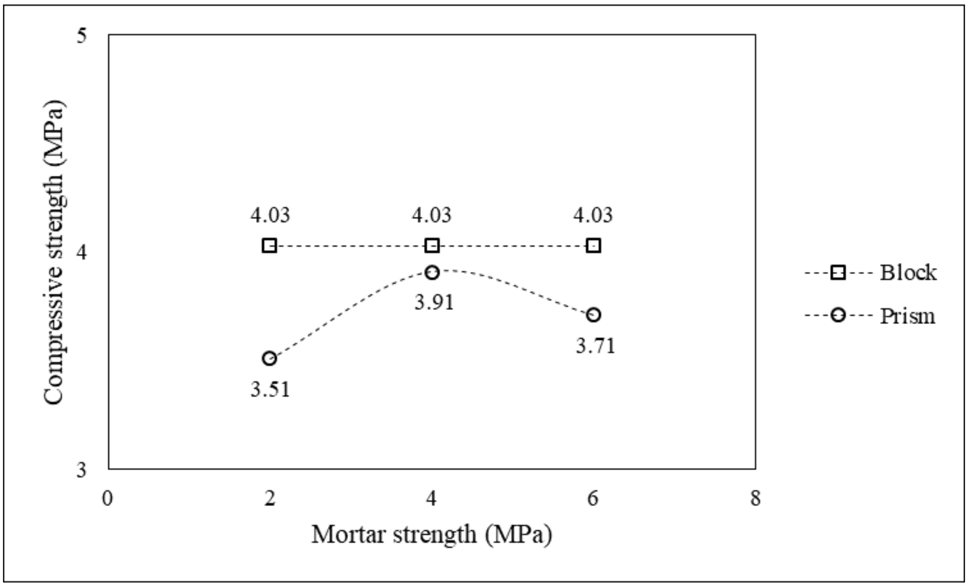

Figure 2. Strength relationship between concrete prisms and blocks

The highest strength results were achieved by using a mortar with strength approximately equal to the strength of the block (specimen B). Alternatively, the lowest strength results were evidenced in specimen A and an intermediate behavior was manifested in specimen C.

The mortar compressive strength plays a secondary role in the compressive strength of walls when compared to the compressive strength of the blocks. Since the mortar occupies a small volume in the wall, a significant increase in the compressive strength of the mortar only affects this limited portion in the overall strength (Hendry, 2001; Casali 2008). In addition, in accordance with Faraboschi (2019), structural masonry mortars should have their strength limited by the dosage, which cannot be excessively rich in cement as it can cause workability problems, excessive shrinkage and cracking.

The presented results corroborate and validate the indications provided by the Brazilian standard, that recommends the utilization of an ensemble as reproduced in specimen B. In addition, when comparing specimens, A and C, it is possible to realize that the lowest mortar strength resulted in the lowest compression strength.

In walls or blocks subjected to compression, the mortar strength should not exceed the strength of the block. If this happens, a highly rigid mortar can be produced, which negatively affects the performance of the masonry (Drougkas et al., 2019). Thus, the mortar must have as minimum strength 70% of the strength of the block and as maximum the block strength itself.

3.4. Ceramic prisms strength

The strength results are described in Table 14. The average compressive strength of the ceramic prisms in all combinations (A, B and C) was lower than the average compressive strength of the blocks, which was 12.67 MPa (Table 8).

Table 14. Strength of the ceramic prisms

Prism	A*	B*	C*
	Compressive strength (MPa)	Compressive strength (MPa)	Compressive strength (MPa)
1	6.13	7.97	9.18
2	3.85	8.52	6.47
3	4,84	8.44	5.42
4	4.52	7.90	6.34
5	5.18	8.50	9.02
6	4.39	8.23	9.40
Average	4.82	8.26	7.64
Standard deviation	0.78	0.27	1.75
V.C.	0.16	0.33	0.23

** (A) 4 MPa mortar strength; (B) 8 MPa mortar strength; (C) 15 MPa mortar strength*

The data of Table 15 represent the three lowest values of individual compression strength, increasingly ordered and extracted from Table 14.

Table 15. Values considered for the calculation of the ceramic prisms f_{pk}

Mortar strength (MPa)	f_{p1} (MPa)	f_{p2} (MPa)	f_{pi} (MPa)
A	3.85	4.39	4.52
B	7.90	7.97	8.23
C	5.42	6.34	6.47

f_{p1}, f_{p2}, …, f_{pi} = increasingly ordered 3 lowest individual strengths (ABNT NBR 15812-1, 2010)

The strength values found for each condition as well as the characteristic strength are presented in Table 16. On again f_{pk1}, f_{pk2}, f_{pk3} and f_{pk4} are all parameters utilized for the calculation of the characteristic compressive strength (f_{pk}) of the prisms, and they were obtained following the procedures of ABNT NBR 15812-1 (2010). The f_{pk} values for all mortar strengths were lower than the f_{bk} of the ceramic blocks, reassuring the theoretical assumption previously presented.

Table 16. f_{pk} values of the ceramic prisms

Mortar	f_{pk1} (MPa)	f_{pk2} (MPa)	f_{pk3} (MPa)	f_{pk4} (MPa)	f_{pk} (MPa)
A	3.72	3.31	3.72	4.09	3.72
B	7.64	6.79	7.64	7.02	7.02
C	5.29	4.71	5.29	6.49	5.29

Figure 3 graphically illustrates the relationship between the strength of the blocks and the ceramic prisms. Once again, since no mortar was utilized on the mechanical characterization of the blocks, the strength value was the constant characteristic compressive strength of the blocks (f_{bk}) in all comparisons.

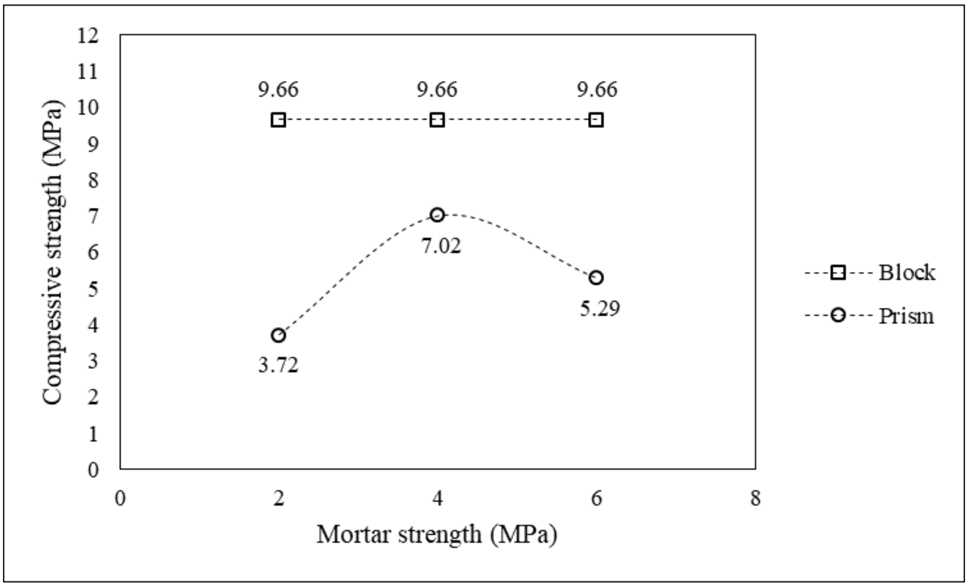

Figure 3. Strength relationship between ceramic prisms and blocks

The characteristic compressive strength of the concrete prisms (f_{pk}) was lower than the blocks of the same material (f_{bk}), being this difference approximately 61.5%, 27.3%, and 45% in specimens A, B, and C respectively. The same behavior evidenced in the concrete materials was manifested in the ceramic blocks, in which the highest strengths were achieved in specimen B, followed by the specimens' C and A.

As the main demand on masonry walls, in accordance with Drougkas et al. (2019), is compression stress, the mortar must have sufficient strength to properly distribute the acting loads throughout the masonry unit area. Thus, the compressive strength of the mortar must be compatible with the blocks. Once again the results corroborate the prerogative that the mortar strength must be contained in the interval of 0.7 to 1 times the strength of the block.

The nature of the substrate proved to be of great influence on the strength of the analyzed prisms. It was also evident the influence of water transport from fresh mortar to the interior of the block (mechanical interlocking). The fact that the ceramic block presents a more compact and smoother surface can hinder the water transportation since the fluid is more restricted in a saturated pore system (Ren et al., 2019; Hatungimana et al., 2019). This characteristic may result in a more porous interface of the mortar and, consequently, reduce the mechanical strength of the structure (Darakchiev et al., 2016; Hála et al., 2018).

4. Concluding remarks

The results of the mechanical characterization, on both blocks, showed characteristic strength values practically equal to the provided by the manufacturers, with a difference of only 0.75% for the concrete blocks and 3.4% for the ceramic blocks. These results contributed to the greater reliability of the data obtained on the prisms.

The characteristic resistance of prisms (f_{pk}) was lower than the blocks (f_{bk}) for both materials. This indicates that the prism can be influenced by its composing elements (e.g. block, mortar, geometry, measurements, modulus of elasticity) on the compressive strength. Thus, the behavior of an isolated block completely differs from the behavior of an entire wall, and the quantification of this relationship is of fundamental importance on the security of any structural masonry project.

The lowest decreases in strength occurred for both materials in the prisms of model B, corroborating the minimum and maximum thresholds of the mortar strength, indicated in the Brazilian standard. The lower limit consists of 70% of the strength of the block and, on the other hand, the upper limit is defined by the strength of the block itself.

The ceramic prisms were more sensitive to the changes in the mortar strength since they presented the largest decreases in strength. The fact that the ceramic blocks have a more compact and smoother surface can result in a more porous interface, reducing the mechanical strength of the material. This reveals the importance of not empirically applying the same strength ratio for different materials.

The results of this research are very specific for local conditions of equipment, climate, labor force and materials (blocks and industrialized mortar). However, a clear theoretical tendency on the theme could be identified, collaborating for future researches as well as for the state-of-the-art on structural masonry blocks.

References

ABNT. Associação Brasileira de Normas Técnicas. NBR 15270-3 (2005). Blocos cerâmicos para alvenaria estrutural e de vedação – Métodos de ensaio. Rio de Janeiro.

ABNT. Associação Brasileira de Normas Técnicas. NBR 12118 (2013). Blocos vazados de concreto simples para alvenaria — Métodos de ensaio. Rio de Janeiro.

ABNT. Associação Brasileira de Normas Técnicas. NBR 15812-1 (2010). Alvenaria estrutural – Blocos cerâmicos – Projetos. Rio de Janeiro.

ABNT. Associação Brasileira de Normas Técnicas. NBR 15961-2 (2011). Alvenaria estrutural – Blocos de concreto – Execução e controle de obras. Rio de Janeiro.

ABNT. Associação Brasileira de Normas Técnicas. NBR 6136 (2014). Blocos vazados de concreto simples para alvenaria – Requisitos. Rio de Janeiro.

Askouni, D. P. and Papanicolaou, G. C. (2019). Textile Reinforced Mortar-to-masonry bond: Experimental investigation of bond-critical parameters. *Construction and Building Materials*, v. 207, p. 535-547. https://doi.org/10.1016/j.conbuildmat.2019.02.102, Março.

Barros, M., Cavaco, E., Neves, L. and Júlio, E. (2019). Effect of non-structural masonry brick infill walls on the robustness of a RC framed building severely damaged due to a landslide. *Engineering Structures*, v. 180, p. 274-283. https://doi.org/10.17632/fjdtrry9zs, Abril.

Casali, J. M. (2008). Estudo da interação entre argamassa de assentamento e bloco de concreto para alvenaria estrutural: transporte de água e aderência. Ph. D. Thesis, Universidade Federal de Santa Catarina, Florianópolis, pp 30-39.

Darakchiev, R., Darakchiev, S., Dahonova-Atanasova, D. and Nakov, S. (2016). Ceramic block packing of Honeycomb type for absorption processes and direct heat transfer, *Chemical Engineering Science*, v. 155, p. 127-140. 10.1016/j.ces.2016.07.028, Abril.

Diamond, S. (2003). Percolation due to overlapping ITZs in laboratory mortars? A microstructural evaluation. *Cement and Concrete Research*, v. 33, p. 949-955. https://doi.org/10.1016/S0008-8846(02)00996-1, Abril.

Drougkas, A., Verstrynge, E., Hayen, R. and Van Bale, K. (2019). The confinement of mortar in masonry under compression: Experimental data and micro-mechanical analysis. *International Journal of Solids and Structures*, v. 162, p. 105-120. 10.1016/j.ijsolstr.2018.12.006, Abril.

Foraboschi, F. (2019). Masonry does not limit itself to only one structural material: Interlocked masonry versus cohesive masonry. *Journal of Building Engineering*, v. 26, p. 100831. https://doi.org/10.1016/j.jobe.2019.100831, Abril.

Forth, J. P., Brooks, J. J. and Tapsir, S. H. (2000). The effect of unit water absorption on long-term movements of masonry. *Cement and Concrete Composites*, v. 20, p. 273-280. https://doi.org/10.1016/S0958-9465(00)00027-5, Março.

Hála, P., Sovják, R., Micunek, T., Frydýn, M. and Nouzovský, L. (2018). Fracture behavior of ceramic blocks with thin-walled cellular structures under dynamic loadings. *Thin-Walled Structures*, v. 122, p. 597-605. 10.1016/j.tws.2017.10.050, Abril.

Hatungimana, D., Taskopru, C., Içhedef, M., Saç, M. M. and Yazici, S. (2019). Compressive strength, water absorption, water sorptivity and surface radon exhalation rate of silica fume and fly ash based mortar. *Journal of Building Engineering*, v. 23, p. 369-376. https://doi.org/10.1016/j.jobe.2019.01.011, Abril.

Hendry, A. W. (2001). Masonry walls: materials and construction *Construction and Building materials*, v. 14, p. 323-330. 10.1016/S0950-0618(01)00019-8, Abril.

Jennings, V. A., Werner, A. M., Park, C. and Lange, D. A. (2000). Water transport phenomena between brick and mortar. *The Masonry Society Journal*, v. 18, p. 61-74. 10.1007/978-94-007-4635-0_26, Março.

Juste, A. E. (2001). Estudo da resistência e da deformabilidade da alvenaria de blocos de concreto submetida a esforços de compressão. Ph. D. Thesis, Universidade de São Paulo, São Carlos, pp 23-30, Abril.

Livitsanos. G., Shetty, N., Verstrynge, E., Wevers, M. and Aggelis, D. G. (2019). Shear failure characterization in masonry components made with different mortars based on combined NDT methods. *Construction and Building Materials*, v. 220, p. 690-700. https://doi.org/10.1016/j.conbuildmat.2019.06.058, Abril.

Mohamad, G., Roman, H. R., Rizzatti, E. and Romagna, R. (2007). Alvenaria Estrutural. Ipsis Gráfica e Editora.

Mojsilovic, N. and Stewart, M. G. (2015). Probability and structural reliability assessment of mortar joint thickness in load-bearing masonry walls. *Structural Safety*, v. 52, p. 209-218. 10.1016/j.strusafe.2014.02.005, Março.

Oliveira, A. L., Corrêa, B. P., Ribeiro, I. F. R., Souza, R. A. and Calçada, L. M. L. (2015). Influência do uso de aditivo retentor de água à base de éter de celulose nas propriedades das argamassas de assentamento em alvenaria estrutural de blocos de concreto. *Ambiente Construído*, v. 15, p. 57-59. https://doi.org/10.1590/s1678-86212015000300026, Abril.

Oliveira, F. A., Nogueira Silva, F. A., Pires Sobrinho, C. W. A., Azevedo, A. C., Delgado, J. M. P. Q. and Guimarães, A. S. (2018). Structural performance of unreinforced masonry elements made with concrete and horizontally perforated ceramic blocks – Laboratory tests. *Construction and Building Materials*, v. 182, p. 20-34. 10.1016/j.conbuildmat.2018.06.092, Abril.

Paes, I. L., Bauer, E. and Carasek, H. (2003). Revestimento em argamassa: influência do substrato no transporte e fixação de água, nos momentos iniciais pós-aplicados. *V Simpósio Brasileiro de Tecnologia das Argamassas*, 5, p. 533-544.

Parsekian, G. A., Corrêa, M. R. S., Lopes, G. M. and Cavichiolli, I. (2016). Estudo teórico e experimental de paredes esbeltas de alvenaria estrutural. *Ambiente Construído*, v. 16, p. 197-213. https://doi.org/10.1590/s1678-86212016000400114, Abril.

Parsekian, G. A. and Soares, M. M. (2010). Alvenaria estrutural em blocos cerâmicos: projeto, execução e controle. Editora O Nome da Rosa.

Prudêncio Jr, L. R., Oliveira, A. L. and Bedin, C. A. (2003). Alvenaria estrutural de blocos de concreto. Editora Gráfica Palloti.

Ren, F., Zhou, C., Zeng, Q., Ding, Z., Zing, F. and Wang, W. (2019). The dependence of capillary sorptivity and gas permeability on initial water content for unsaturated cement mortars. *Cement and Concrete Composites*, v. 104, p. 103356. https://doi.org/10.1016/j.cemconcomp.2019.103356, Abril.

Rezende, F. M., Mohamad, G., Parsekian, G. A., Rizzatti, E. and Sánchez, E. S. F. (2013). Análise do emprego de armaduras treliçadas planas como alternativa tecnológica para a execução de vergas em alvenaria estrutural. *Ambiente Construído*, v. 13, p. 51-73. https://doi.org/10.1590/S1678-86212013000100005, Abril.

Rizzatti, E., Roman, H. R., Mohamad, G. and Nakanishi, E. Y. (2012). Mechanical Behavior Analysis of Small Scale Modeling of Ceramic Block Masonry Structures: geometries effects. *Revista do IBRACON de Estruturas e Materiais*, v. 5, p. 702-736. https://doi.org/10.1590/S1983-41952012000500007, Abril.

Sarangapani, G., Reddy, B. V. V. and Groot, C. J. P. (2002). Water loss from fresh mortars and bond strength development in low strength masonry. *Masonry*

International, v. 15, p. 42-47. https://doi.org/10.1590/S1983-41952015000200002, Abril.

Schankoski, R. A., Prudêncio Jr, L. R. and Pilar, R. (2015). Influência do tipo de argamassa e suas propriedades do estado fresco nas propriedades mecânicas de alvenarias estruturais de blocos de concretos para edifícios altos. *Revista Matéria*, v. 20, p. 1008-1023. https://doi.org/10.1590/S1517-707620150004.0104, Abril.