IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Influence of the relationships between compressive strengths of mixed and industrialized mortars and concrete blocks on the behavior of masonry prisms

Influência das relações entre resistências à compressão de argamassas mistas e industrializadas e blocos de concreto no comportamento de prismas de alvenaria

Rafaella Salvador Paulino[a]
Berenice Martins Toralles[a]

[a]Universidade Estadual de Londrina - UEL, Departamento de Construção Civil, Londrina, PR, Brasil

Received 22 June 2023
Revised 26 August 2023
Accepted 26 September 2023
Corrected 27 March 2024

Abstract: The performance of masonry structures depends not only on the quality of blocks and mortars but also on their interactions. This study aims to evaluate the influence of unit and mortar characteristics on the compressive strength of masonry. Prisms were produced using concrete blocks with nominal strengths of 8 and 10 MPa, combined with mixed and industrialized mortars with lower, similar, and higher strengths compared to the blocks. Response surfaces and contour plots were generated to visualize the effects of unit and mortar properties on prism strength. Estimations were performed, and the failure mechanisms of prisms for various combinations of blocks and mortars were analyzed. The failure modes of the prisms were characterized by ductile failure (in weaker mortars), cohesive rupture of the assembly (in intermediate-strength mortars), and brittle failure (in stronger mortars), primarily due to lateral tensile forces acting on the blocks. The findings of this research contribute to the existing knowledge database in the field and can assist in the appropriate selection of blocks and mortars for structural masonry applications.

Keywords: mixed mortar, industrialized mortar, concrete block prisms, masonry, failure modes.

Resumo: O bom desempenho da alvenaria depende não somente da qualidade dos blocos e argamassas, mas também das interações que se processam entre eles. Este trabalho teve como objetivo avaliar a influência das unidades e das argamassas na resistência à compressão da alvenaria. Prismas foram produzidos com blocos de concreto de resistências nominais de 8 e 10 MPa e argamassas mistas e industrializadas com resistências inferior, aproximada e superior à do bloco. Superfícies de resposta e gráficos de contorno foram desenvolvidos para mostrar o efeito das unidades e das propriedades das argamassas na resistência dos prismas. Estimativas foram realizadas e os mecanismos de ruptura dos prismas para diferentes combinações de bloco e argamassa foram analisados. Os prismas romperam de forma dúctil (argamassas mais fracas), pela ruptura do conjunto (argamassas intermediárias) e de forma frágil (argamassa mais fortes), principalmente pela tração nos blocos. Os resultados complementam as pesquisas da área já existentes e pode ser usado para selecionar corretamente blocos e argamassas para alvenaria estrutural.

Palavras-chave: argamassa mista, argamassa industrializada, prismas de bloco de concreto, alvenaria, modo de ruptura.

How to cite: R. S. Paulino, and B. M. Toralles, "Influence of the relationships between compressive strengths of mixed and industrialized mortars and concrete blocks on the behavior of masonry prisms," *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 5, e17503, 2024, https://doi.org/10.1590/S1983-41952024000500003

Corresponding author: Rafaella Salvador Paulino. E-mail: rafaellaspaulino@gmail.com
Financial support: None.
Conflict of interest: Nothing to declare.
Data Availability: The data that support the findings of this study are openly available in [[Biblioteca Digital da Produção Científica, Tecnológica, Artística e Cultural, Universidade Estadual de Londrina], at [http://www.bibliotecadigital.uel.br/document/?code=vtls000224952].
This document has an erratum: https://doi.org/10.1590/S1983-41952024000500011

1 INTRODUCTION

Compressive strength of masonry is a fundamental consideration in structural design [1]. It is influenced by various factors, including the strength of the mortar and units, the height-to-thickness ratio of the units, the orientation of the units concerning the direction of applied load, and the thickness of mortar joints [2], [3], [4]. Gaining a comprehensive understanding of the behavior of the unit/mortar assembly is crucial [5]. While units are primarily responsible for resisting compressive loads, it is the mortar that ensures load transmission, provides adhesion between the units, accommodates deformations, and ensures durability and waterproofing of the wall [6], [7], [8], [9]. The selection of blocks should not be based solely on their compressive strength; special attention should be given to their compatibility with the mortar [10]. Generally, higher unit compressive strength leads to higher masonry compressive strength, although not necessarily in a proportional manner [11], [12]. Research [13], [14], [15] indicates that using a mortar with higher rigidity and strength than the block increases the portion of load absorbed by the masonry due to the increased modulus of elasticity of the block/mortar assembly. Using a mortar weaker than the block can result in the detachment of the outer layer of walls constructed with concrete blocks. Traditionally, masonry has been constructed using stiffer units and relatively low-strength mortar, typically ranging from 0.4 to 0.7 times the strength of the blocks [8], [16], [17]. However, there are specific situations where more deformable units are utilized, particularly in the construction of affordable housing in developing nations, such as in Brazil and India [18], [19], [20], [21], [22]. On the other hand, there are instances where units significantly stronger than the mortar are employed, especially with recent advancements in high-strength masonry block technologies [2], [23], [24], [25], [26]. Masonry prisms serve as a means to analyze the interaction among different masonry components [5], [27]. The failure mechanisms of a prism are a series of effects directly influenced by the relative strength of the mortar and the block [28], [29], [30]. In general, compressive failure can occur in three distinct ways [2]: I) when the mortar is weaker than the block, the masonry strength is constrained by the strength of the mortar, which typically fails through crushing; II) when the mortar possesses moderate strength, the masonry strength is determined by the combination of compressive and tensile strengths of the block, with failure often occurring due to lateral tension; III) when the mortar is stronger than the block, the masonry strength is limited by the compressive strength of the block. It is generally preferred that failure occurs in mode "II", which represents a balanced compromise between adequate masonry compressive strength and reduced likelihood of explosive behavior (mode "III"), while also minimizing the potential for cracking in the mortar joint (mode "I"). For conventional masonry, it is recommended [14], [31] that the mortar strength should range from 70% to 100% of the block's compressive strength in gross area to ensure compatibility between the components. There are also guidelines [8] specifying that the mortar strength should be between 70% and 150% of the block's strength in gross area. According to ABNT NBR 16868-1:2020 [32], it is recommended to specify the compressive strength of the mortar limited to 1.5 times the specified characteristic strength of the block. Several studies [33], [34], [35] have examined the compressive strength of masonry prisms with various configurations and compared the findings with international masonry codes and other experimental research. The failure mode of prisms has also been investigated in several studies [18], [36], [37], [38] wherein specimens of different sizes and materials were analyzed to establish a correlation between the failure mode and parameters such as material properties and dimensions. Mohamad et al. [36] studied how mortar strengths affect block masonry strength and concluded different types of mortars induce different failure modes in the masonry prisms and there is clear evidence that the failure of hollow concrete masonry starts after onset of mortar crushing. They emphasized that prisms bonded with lower-strength mortar experienced joint failure due to mortar crushing. Similar findings were reported by Zahra et al. [39] and Barbosa et al. [38], through their experimental exploration of hollow block prisms, varying blocks and mortar strengths. However, the authors [36] noted that altering mortar types did not significantly impact masonry efficiency. This study aimed to analyze the impact of unit and mortar properties on the behavior of concrete block prisms under compressive loads. The investigation considered both the recommended ratios provided in the literature and technical standards, as well as designs falling outside of these ranges. By examining the strength and failure mechanisms of the prisms, the results are expected to complement existing research in the field and provide valuable data on masonry behavior. The ultimate goal is to prevent or mitigate undesired consequences resulting from the lack of compatibility between the constituent elements, eliminate undesirable failure modes, and promote the appropriate selection of blocks and mortars for structural masonry.

2 MATERIALS AND EXPERIMENTAL PROGRAM

Masonry prisms were constructed using two types of blocks, BL1 and BL2, in conjunction with six types of mortars: mixed (MA, MB and MC) and industrialized (IA, IB and IC). The selection of mortars and blocks was based on their compressive strength, aiming to produce prisms within the recommended range for practical use, as indicated in the literature [8], [14], [31]. Apart from the recommended combinations (type B), weaker (type A) and stronger (type C) mortars were also used to construct the prisms. This allowed for the creation of block/mortar resistance combinations that fell below and exceeded the recommended values. The prisms were subjected to compressive strength testing to analyze the efficiency ratio, fracture modes, and material compatibility. Additionally, estimates of compressive strength for masonry walls were conducted.

2.1 Blocks

Hollow concrete blocks with nominal strengths of 8.0 MPa (BL1) and 10.0 MPa (BL2), and dimensions of (14 x 19 x 39) cm (length x thickness x height), were selected for constructing the prisms due to their representation of practical usage in Brazil. The blocks were subjected to geometric (effective dimensions, wall thickness), physical (water absorption and net area), and mechanical characterizations, including characteristic compressive strength (f_{bk}) and average compressive strength (f_{bm}), as specified by ABNT NBR 12118:2014 [40] (Figure 1).

Figure 1. Concrete blocks: a and b) capping c) compressive strength

2.2 Mortars

For the experimental program, mortars from two categories, mixed and industrialized, were utilized. The mortar mix proportions for prisms construction were selected with the aim of utilizing weaker mortars (type A), intermediate-strength mortars (type B), and stronger mortars (type C), in relation to the compressive strength of the blocks. The mixed mortars were prepared using Portland cement CP II F-32, with a unit weight of 1.069 g/cm^3 [41] and density of 3.11 g/cm^3 [42]; hydrated lime CH III, with a unit weight of 0.599 g/cm^3 [41] and density of 2.66 g/cm^3 [42]; and natural sand of quartzous origin sourced from the Paraná River, Brazil. The granulometric composition and physical characteristics of the sand are presented in Table 1, and the CP II-F-32 specifications, as provided by the manufacturer, are outlined in Table 2.

Table 1. Grains retained percentage in the sieves and physical characteristics of the sand.

Sieve (mm)	Retained massa (g)	% retained	% retained accumulated
4.8	0.0	0.0	0.0
2.4	5.0	1.0	1.0
1.2	12.5	2.5	3.5
0.6	50.0	10.0	13.5
0.3	252.5	50.5	64.0
0.15	180.0	36.0	100.0
Fineness modulus (-)		1.82	NBR NM 248 [43]
Maximum size (mm)		1.18	
Classification (-)		Fine	
Unit mass (g/cm^3)		1.49	NBR NM 45 [41]
Specific mass (g/cm^3)		2.62	NBR NM 52 [44]
Fineness (Sieve nº 30) (%)		0.3	NBR 9289 [45]
Fineness (Sieve nº 200) (%)		10.8	NBR 9289 [45]

Table 2. Cement chemical and physical properties.

CP II-F-32		Limit - NBR 16697 [46]
Physical properties		
Initial curing period (min.)	195	≥ 60
Initial curing period (min.)	255	≤ 600
Specific surface area (cm^2/g)	3290	≥ 2600
Insoluble residue (%)	1.08	≤ 7.5
Compressive strength – 1 day (MPa)	15.0	N/A
Compressive strength – 3 days (MPa)	28.4	≥ 10
Compressive strength – 7 days (MPa)	34.9	≥ 20
Compressive strength – 28 days (MPa)	41.4	≥ 32
Chemical compositions		
Al_2O_3 (%)	4.18	-
SiO_2 (%)	18.56	-
Fe_2O_3 (%)	2.65	-
CaO (%)	60.11	-
MgO (%)	3.69	N/A
SO_3 (%)	2.57	≤ 4.5
Loss on ignition (%)	6.41	≤ 12.5
Free calcium oxide (%)	1.15	-

The industrialized mortars used were of the structural type, specifically formulated for the construction of concrete blocks. These mortars consisted of limestone sand, Portland cement CP II-Z-32, and hydrated lime CH II. They had a unit weight ranging from 1.60 to 1.65 kg/dm^3 and nominal strengths of 4, 6, and 8 MPa. The water/dry materials ratio (w/dm) for the mixed mortars was adjusted, while the water content in the industrialized mortars was determined in accordance with the manufacturer's recommendation. Both types of mortars met the flow requirement of (260 ± 10) mm, as determined by the flow table test [47]. On the day of prism molding, the mortars were prepared following the guidelines outlined in [48]. The fresh-state characterization of the mortars included measurements of bulk density, air content [49], and water retentivity [50]. Test specimens were then molded to evaluate the hardened-state properties of the mortars after 28 days. The following tests were conducted: water absorption [51], flexural strength, compressive strength [52], and dynamic modulus of elasticity [53] (Figure 2).

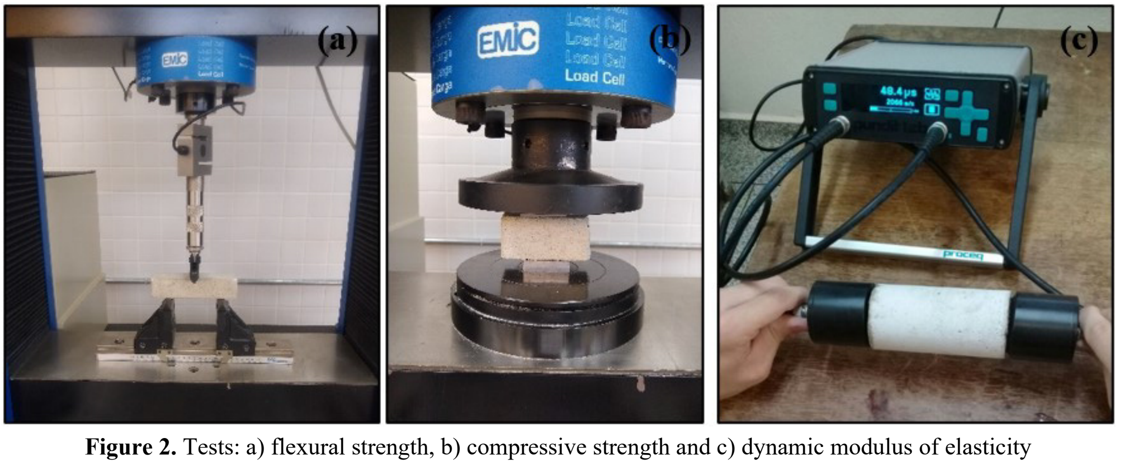

Figure 2. Tests: a) flexural strength, b) compressive strength and c) dynamic modulus of elasticity

2.3 Prisms

Prisms were constructed by placing two hollow concrete blocks in a plumb orientation, with a height/thickness ratio of 2.8, following the specifications of C-1314-22 [54]. The type of mortar and block varied, as indicated in Table 3.

Full mortar bedding was used, and the thickness of the mortar joint was maintained at (10 ± 3) mm [55]. The prisms were molded by a qualified professional to ensure standardization of execution, and the curing process took place in a laboratory environment for a duration of 28 days. To cap the prisms, cement paste [40] was applied, and thereafter, they were subjected to compressive strength testing. The compression load was applied at a rate of 0.15 MPa/s and directly measured by the load cells of the EMIC press, which had a load capacity of up to 2000 kN.

Table 3. Identification and characterization of prisms and test conditions.

Prism	Block	Mortar	Condition*	Number of specimens
PBL1MA	BL1	MA	$f_m \leq 0.7\, f_b$	3
PBL1MB		MB	$0.7\, f_b \leq f_m \leq 1.5 f_b$	3
PBL1MC		MC	$f_m \geq 1.5\, f_b$	3
PBL1IA	BL1	IA	$f_m \leq 0.7\, f_b$	3
PBL1IB		IB	$0.7\, f_b \leq f_m \leq 1.5 f_b$	3
PBL1IC		IC	$f_m \geq 1.5\, f_b$	3
PBL2MA	BL2	MA	$f_m \leq 0.7\, f_b$	3
PBL2MB		MB	$0.7\, f_b \leq f_m \leq 1.5 f_b$	3
PBL2MC		MC	$f_m \geq 1.5\, f_b$	3
PBL2IA	BL2	IA	$f_m \leq 0.7\, f_b$	3
PBL2IB		IB	$0.7\, f_b \leq f_m \leq 1.5 f_b$	3
PBL2IC		IC	$f_m \geq 1.5\, f_b$	3

Nota: f_m = mortar compressive strength (MPa). f_b = block gross area compressive strength (MPa). *according to Parsekian et al. [8].

3 RESULTS AND DISCUSSIONS

3.1 Blocks

Table 4 presents the physical and mechanical properties of the concrete blocks.

Table 4. Average values of different properties of the concrete blocks.

Property	Block	
	BL1	BL2
Length (cm)	39.13 (0.18)	39.22 (0.14)
Width (cm)	13.98 (0.29)	14.00 (0.00)
Height (cm)	19.02 (0.40)	19.27 (0.42)
Average thickness of longitudinal shells (mm)	35.01 (0.32)	35.12 (0.17)
Average thickness of transverse webs (mm)	32.03 (0.31)	32.04 (0.21)
Water absorption (%)	7.86 (20.49)	8.60 (16.42)
Gross area (cm^2)	547.04	549.08
Net area (cm^2)	326.64	328.98
Net area / gross area ratio	1.675	1.669
Gross area compressive strength (MPa)	8.33 (6.39)	11.98 (6.20)
Net area compressive strength (MPa)	13.95 (3.82)	19.99 (3.72)
Characteristic compressive strength (MPa)	7.18 (7.41)	10.77 (6.90)

Note: coefficients of variation (%) in parentheses.

3.2 Mortars

Table 5 presents the amount of constituent materials and the properties in the fresh state of mixed and industrialized mortars.

Table 5. Mix proportions and average values of different properties of fresh mortars.

Mortar	Mix proportion (by mass)	Materials						Fresh state			
		Cement (g)	Lime (g)	Sand (g)	Water (ml)	w/c ratio	w/dm ratio	Flow (mm)	Bulk density (g/cm^3)	Air content (%)	Water retentivity (%)
MA	1:1.25:6.75	0.389	0.486	2.625	0.731	1.880	0.209	260^{a}	2.06^{A}	3.97^{a}	97.20^{A}
								(0.38)	(0.25)	(6.01)	(0.16)
MB	1:0.75:5.25	0.500	0.375	2.625	0.665	1.330	0.190	257^{a}	2.09^{A}	3.45^{a}	95.90^{A}
								(0.45)	(1.26)	(8.13)	(0.70)
MC	1:0.50:4.50	0.583	0.292	2.625	0.624	1.070	0.178	261^{a}	2.13^{A}	3.10^{a}	95.63^{A}
								(0.38)	(0.86)	(9.68)	(0.16)
IA	-	-	-	-	0.665	-	0.190*	258^{a}	2.31^{a}	9.88^{b}	97.92^{B}
								(0.97)	(1.55)	(9.98)	(0.28)
IB	-	-	-	-	0.665	-	0.190*	261^{a}	2.30^{a}	10.85^{b}	98.09^{B}
								(0.77)	(0.27)	(2.71)	(0.19)
IC	-	-	-	-	0.665	-	0.190*	256^{a}	2.31^{a}	10.40^{b}	96.67^{B}
								(0.45)	(0.22)	(2.35)	(0.16)
Statistical analysis								$\rho = 0.191$	$\rho = 0.003$	$\rho = 0.531$	$\rho = 0.015$
									$\rho = 0.423$	$\rho = 0.054$	$\rho = 0.0003$

Note: *manufacturer's recommended water content in relation to dry materials: 17.6% - 20.4%. Coefficients of variation (%) in parentheses. Analysis of variance (ANOVA) was performed with a confidence level of 95%: ^{a,b} not statistically significant; ^{A,B} statistically significant. Column 9: analysis between all mortars. Columns 10, 11 and 12: analysis between mortars of the same classes (M and I). The recommended water content by the manufacturer in relation to the dry materials is 17.6 - 20.4 (%).

The consistency index of the mortars fell within the specified range of (260 ± 10) mm. The air content values for the mixed mortars ranged from 3% to 4%, which is consistent with previous studies [56], [57]. The increase in lime content in these mortars likely contributed to greater air incorporation and a decrease in bulk density due to the mechanical mixing process [58]. On the other hand, the industrialized mortars exhibited an air content of approximately 10%. The mortars in this research demonstrated a high-water retention value, ranging from 95.63% to 98.09%, as recommended [59]. While current Brazilian standards do not set specific limits for this property, C-270 [60] specifies that water retentivity in laying mortars should exceed 75%. Although there is no maximum value specified, water retention is considered a crucial parameter. The lime present in the mixed mortars possesses favorable water retention characteristics due to its high specific surface area (SSA) and the significant adsorptive capacity of its crystals [61]. An increased lime content indicates improved workability of the material and a longer open time for handling the mortar during block laying [62]. Table 6 presents the properties of the mortars in the hardened state.

Table 6. Average values of the different properties of hardened mortars.

Mortar	Water absorption (%)		Flexural strength (MPa)		Compressive strength (MPa)		Dynamic modulus of elasticity (GPa)	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
MA	14.06 (2.03)	12.90^{A} (0.69)	1.85 (2.48)	1.65^{a} (3.22)	4.60 (8.91)	5.17^{a} (6.38)	6.52 (6.39)	7.12^{a} (4.79)
MB	13.30 (4.00)	12.82^{A} (1.90)	3.35 (4.75)	2.96^{A} (3.71)	7.95 (13.46)	8.98^{A} (5.01)	10.17 (4.63)	12.18^{A} (4.79)
MC	12.58 (2.05)	12.40^{A} (1.62)	4.76 (3.21)	4.22^{B} (5.81)	11.15 (7.71)	13.61^{B} (5.81)	12.59 (4.39)	14.66^{b} (5.72)
IA	17.68 (6.93)	14.64^{a} (9.41)	2.01 (2.22)	1.82^{a} (7.40)	2.00 (13.00)	5.68^{a} (10.74)	7.17 (3.82)	7.48^{a} (7.44)
IB	14.96 (4.80)	14.25^{a} (0.40)	4.03 (3.54)	3.56^{A} (4.21)	6.26 (10.86)	10.75^{A} (7.91)	12.62 (11.65)	13.85^{A} (5.75)
IC	13.94 (4.66)	13.25^{a} (1.79)	5.33 (2.58)	4.74^{B} (2.59)	10.90 (11.93)	14.48^{B} (3.25)	13.83 (5.17)	15.89^{b} (5.53)
Statistical analysis	-	^{A} $\rho = 0.010$	-	^{a} $\rho = 0.172$	-	^{a} $\rho = 0.161$	-	^{a} $\rho = 0.313$
	-	^{a} $\rho = 0.091$	-	^{A} $\rho = 0.009$	-	^{A} $\rho = 0.010$	-	^{A} $\rho = 0.015$
	-	-	-	^{B} $\rho = 0.021$	-	^{B} $\rho = 0.016$	-	^{b} $\rho = 0.089$

Note: coefficients of variation (%) in parentheses. Analysis of variance (ANOVA) was performed with a confidence level of 95%: ^{a,b} not statistically significant; ^{A,B} statistically significant. Columns 3: analysis between mortars of the same class (M and I). Columns 5, 7, 9: analysis between mortars of different classes, but the same type (A, B and C).

Mixed mortars showed increased water absorption with a higher lime content. On the other hand, industrialized mortars exhibited higher values for both properties compared to mixed mortars, which can be attributed to their composition. As the curing process progressed and voids closed, these values decreased from 7 to 28 days. Regarding the mechanical properties, the increase in lime content affected the compressive strength and flexural strength of the mixed mortars. The industrialized mortars demonstrated higher compressive strength than the nominal values, potentially due to the range of water content used. At 28 days, the dynamic modulus of elasticity of the mortars ranged from 7.12 GPa to 15.89 GPa. The IC and MC mortars exhibited the highest modulus of elasticity, indicating a lower deformation absorption capacity among the studied mortars. However, it is important to note that a high modulus of elasticity is not advisable for structural masonry, as the mortar should be able to absorb deformations and allow for small movements in the wall without cracking [63], [64].

3.3 Prisms

Table 7 presents the average compressive strength results and analysis of the prisms.

Table 7. Average compressive strength, efficiency ratio and failure mode of prisms.

Prism	f_b (MPa)	f_m (MPa)	f_p (MPa)	f_p^* (MPa)	f_p/f_b	f_m/f_b	Respected condition	Failure mode
PBL1MA	8.33	5.17	5.35 (5.42)	5.78	0.64	0.62	$f_m \leq 0.7\, f_b$	Crushing of the mortar
PBL1MB	8.33	8.98	6.95 (2.07)	6.82	0.83	1.08	$0.7\, f_b \leq f_m \leq 1.5 f_b$	Lateral traction
PBL1MC	8.33	13.61	6.74 (7.09)	7.72	0.81	1.63	$f_m \geq 1.5\, f_b$	Compression of the block
PBL1IA	8.33	5.68	5.16 (6.65)	5.94	0.62	0.68	$f_m \leq 0.7\, f_b$	Crushing of the mortar
PBL1IB	8.33	10.75	6.70 (7.44)	7.19	0.80	1.29	$0.7\, f_b \leq f_m \leq 1.5 f_b$	Lateral traction
PBL1IC	8.33	14.48	6.61 (9.24)	7.87	0.79	1.74	$f_m \geq 1.5\, f_b$	Compression of the block
PBL2MA	11.98	5.17	6.46 (4.81)	7.45	0.54	0.43	$f_m \leq 0.7\, f_b$	Crushing of the mortar
PBL2MB	11.98	8.98	7.42 (4.73)	8.79	0.62	0.75	$0.7\, f_b \leq f_m \leq 1.5 f_b$	Lateral traction
PBL2MC	11.98	13.61	7.21 (3.55)	9.96	0.60	1.14	$f_m \geq f_b$ **	Compression of the block
PBL2IA	11.98	5.68	6.32 (3.47)	7.66	0.53	0.47	$f_m \leq 0.7\, f_b$	Crushing of the mortar
PBL2IB	11.98	10.75	7.21 (10.19)	9.28	0.60	0.90	$0.7\, f_b \leq f_m \leq 1.5 f_b$	Lateral traction
PBL2IC	11.98	14.48	6.75 (6.96)	10.14	0.56	1.21	$f_m \geq f_b$ **	Compression of the block

Notes: f_p = prism compressive strength (MPa); $f_p^* = K \cdot f_b^{0,7} \cdot f_m^{0,3}$, where K is a factor to account for the type and perforation in units, f_b is the compressive strength of units, f_m is the compressive strength of mortar, according to BS EN 1996-1-1 [65]; **according to Mohamad et al. [29] and Gomes [31]; coefficients of variation (%) in parentheses.

The prisms PBL2MB, PBL2MC, and PBL2IB demonstrated the highest compressive strengths. For these cases, the mortar strengths were 0.75, 1.14, and 0.90 times the block strengths, falling within the recommended range. Both for blocks BL1 and BL2, the weaker mortars (MA and IA) resulted in the lowest compressive strengths in the prisms. The values were 62% and 68% of the block strength for PBL1MA and PBL1IA, and 43% and 47% for PBL2MA and PBL2IA. Industrialized mortars performed similarly to mixed mortars when compared within the same strength range (MA and IA; MB and IB; MC and IC). Mortar MC is about 51% stronger than MB, but this higher strength led to a reduction of 3% to 2% in the strengths of the prisms cast with BL1 and BL2, respectively. Compared to mortar MA, MC is 163% stronger, resulting in increases of 26% and 12% in the strengths of the BL1 and BL2 prisms, respectively. In the industrialized mortars, IC is 35% stronger than IB, but this led to reductions of 1.3% and 6.4% in the strengths of the BL1 and BL2 prisms. Compared to IA, IC is 154% stronger, resulting in increases of 28% and 6% in the strengths of the BL1 and BL2 prisms, respectively.

In terms of failure modes, the prisms demonstrated varying behaviors, attributable to the compatibility between the unit (block) and the mortar. In cases where the compressive strength of the mortar was lower than that of the block, localized crushing in the mortar often occurred, accompanied by the concentration of tensile stresses and the propagation of vertical cracks through the units (Figure 3). Similar behaviors have been observed in other studies [39], [23].

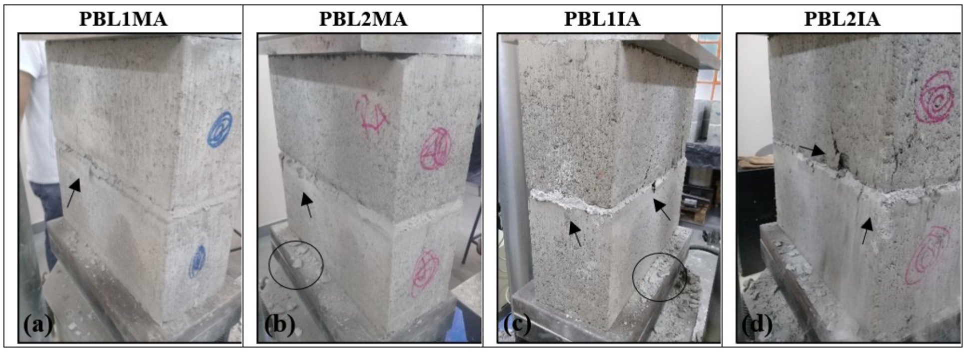

Figure 3. Failure modes of prisms produced with type A mortar

The most desirable failure mode, known as rupture of the set, is characterized by the appearance of a vertical crack in the block, preceded by signs of joint rupture in the mortar through its cracking [66], [67]. In this research, this failure mode was observed when the ratios between the compressive strength of the mortar and the concrete block fell within the recommended parameters for practical use [8] (Figure 4).

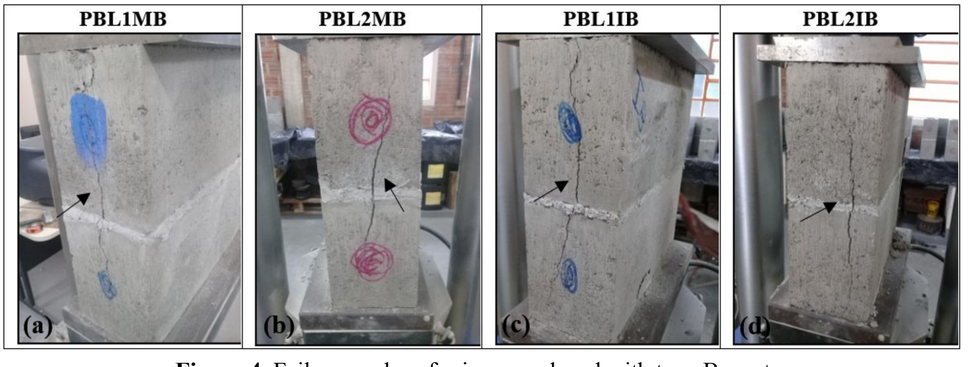

Figure 4. Failure modes of prisms produced with type B mortar

Recent studies suggest that the best mechanical performance of prisms is generally observed when the compressive strength of the mortar is reasonably close to the net area compressive strength of the blocks, except for prisms constructed with high-strength blocks [27]. In such cases, the compressive strength of the unit has an impact on the efficiency factor. When the mortar joints have higher compressive strength than the blocks, the failure mode is characterized by the appearance of vertical cracks in the blocks (Figure 5) [29], [39].

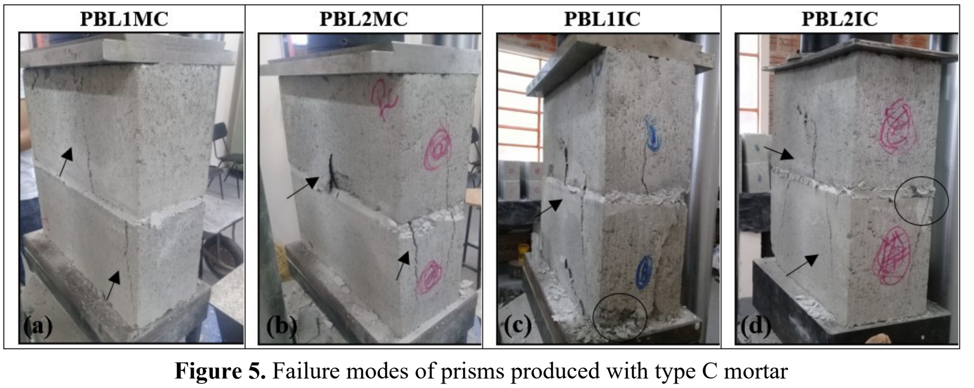

Figure 5. Failure modes of prisms produced with type C mortar

Strong mortars tend to crack suddenly due to their lower ability to absorb deformations, lacking the necessary ductility to accommodate the deformations of the entire structure under the applied loads [31]. This phenomenon may also be attributed to the incompatibility between the deformation properties of the units and the mortar [59], [68], [69],[70]. It is not advisable to use mortars with high modulus of elasticity in structural masonry [14], [63], [64]. Moreover, using a mortar with higher compressive strength than the blocks can contribute to a brittle failure of the structure [71]. Prisms constructed with industrialized mortars demonstrated similar performance to those constructed with mixed mortars, when compared within the same compressive strength range. This highlights the potential suitability of industrialized mortars as a viable alternative, capable of achieving similar results as traditional mixed mortars.

Response surfaces and contour graphs show the influence of the compressive strength of blocks and mortars (Figure 6) and the modulus of elasticity of mortars (Figure 7) on the compressive strength of masonry prisms.

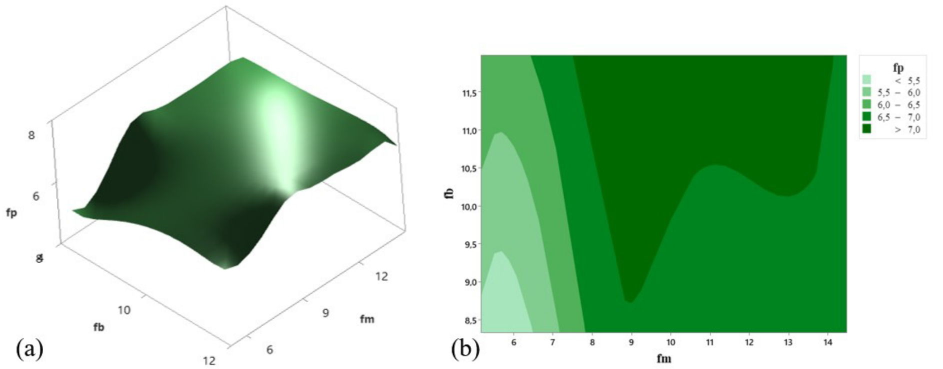

Figure 6. Response surface (a) and contour graph (b) for the effect of mortar and blocks' compressive strength (f_m and f_b) on the compressive strength of masonry prisms (f_p) (in MPa).

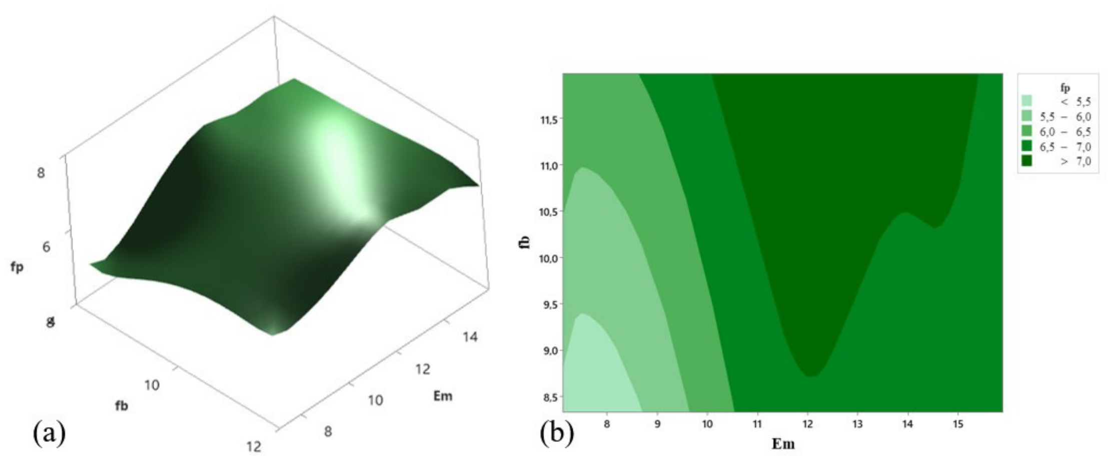

Figure 7. Response surface (a) and contour graph (b) for the effect of compressive strength of blocks (f_b) (in MPa) and modulus of elasticity of mortars (E_m) (in GPa) on the compressive strength of masonry prisms (f_p) (in MPa)

The prisms with the lowest compressive strength were observed in the ones constructed with mortars and blocks of the lowest compressive strength. However, an increase in mortar compressive strength did not necessarily result in improved prism performance. This finding is consistent with previous studies [11], [16], [61], and [72], which also reported a lack of linear proportionality between mortar compressive strength and prism compressive strength. The high modulus of elasticity of the mortars had a negative impact on the compressive strength of the prisms. This is attributed to the confinement effect when mortar is placed in the joint between units, leading to a stress concentration in that specific region, subsequently causing premature cracking of the units, particularly when the mortar exhibits excessive rigidity. It was observed that the variation in prism compressive strength is more sensitive for weaker mortars compared to others. Studies [73], [74] indicate that the primary factor influencing prism compressive strength is the strength of the unit, which means it is not a linear relationship. This is evident in the response graph. For blocks with higher compressive strength, the increase in prism compressive strength becomes smaller with an increase in mortar compressive strength [74]. When the same mortars were used, the BL2 block provided higher compressive strength for the prisms compared to the BL1 block. The efficiency ratio (f_p/f_b), which represents the proportion of the unit's compressive strength "used" in the wall's compressive strength [31], is also presented in Table 7. The efficiency ratio was higher when the block with the lowest compressive strength (BL1) was used, ranging from 0.64 to 0.83. For the BL2 block, the efficiency ratios ranged from 0.53 to 0.62. The lowest efficiency ratios were observed when the mortar with the lowest compressive strength (IA) was used, while the highest ratios occurred when there was a smaller difference between the compressive strength of the unit and the mortar for both blocks. The estimation of prisms compressive strength was conducted according to the European standard BS EN 1996-1-1 [65], and the results obtained from the proposed equation closely matched the experimentally obtained values, which supports the findings of Zahra et al. [39]. Although other standards such as AS3700 [75], CSA S304.1 [76], and MSJC [77] also provide estimates for wall compressive strength, it was found that these standards are inconsistent and not conservative in their predictions [29], [23]. The results obtained for Zahra et al. [39] revealed that the compressive strength predictions of BS EN 1996-1-1 [65] exhibit closer proximity to experimental masonry strengths. Conversely, a significant portion of the outcomes were overestimated when utilizing AS3700 [75] and MSJC [77]. Regarding CSA S304.1 [76], the analyzed data series displayed an alternating pattern, at times underestimating and at other times overestimating the results.

4 CONCLUSIONS

This research presents a study on the compressive behavior of masonry made of hollow concrete blocks laid with mixed and industrialized mortars, and blocks with different nominal strengths. The materials complied with the recommended ranges for use according to the literature and the Brazilian technical standard, based on the compressive strength of the units and mortars. Prisms were produced using mortars with strengths lower and higher than the recommended values. The prisms constructed with mortars having compressive strengths approximately 75%, 114%, and 90% of the block's compressive strength exhibited the best results. It is recommended to adhere to the recommended ranges for mortar and block strengths to ensure adequate compressive behavior of masonry structures. An increase in mortar strength does not necessarily imply better prism performance, as the elastic modulus of the mortar does not increase in the same proportion as its compressive strength. As the compressive strength of the concrete block increases, there is an increase in the compressive strength of the prisms; however, it is not proportional. The failure mode of masonry depends on whether the mortar joint is weak or strong compared to the masonry units. The use of weak or excessively rigid mortars can compromise the structural strength and lead to either ductile or brittle failure, respectively. Although industrialized mortars have shown good performance, it is suggested that future studies be conducted to analyze their long-term durability, considering the different formulations of these types of mortars available in the market. The obtained data and explanations of failure mechanisms can be utilized by designers to appropriately select properties of blocks and mortars for their structural masonry projects, especially in the absence of guidelines for structural design that consider the failure mode of masonry elements.

REFERENCES FORMATS

[1] M. Dhanasekar, J. A. Thamboo, and S. Nazir, "On the in-plane shear response of the high bond strength concrete masonry walls," *Mater. Struct.*, vol. 50, pp. 214, 2017, http://dx.doi.org/10.1617/s11527-017-1078-7.

[2] E. S. Fortes, G. A. Parsekian, J. S. Camacho, and F. S. Fonseca, "Compressive strength of masonry constructed with high strength concrete blocks," *Rev. IBRACON Estrut. Mater.*, vol. 10, no. 6, pp. 1273–1319, 2017, http://dx.doi.org/10.1590/S1983-41952017000600008.

[3] M. B. Ravula and K. V. L. Subramaniam, "Experimental investigation of compressive failure in masonry brick assemblages made with soft brick," *Mater. Struct.*, vol. 50, pp. 19, 2017, http://dx.doi.org/10.1617/s11527-016-0926-1.

[4] J. Garzón-Roca, C. O. Marco, and J. M. Adam, "Compressive strength of masonry made of clay bricks and cement mortar: estimation based on neural networks and fuzzy logic," *Eng. Struct.*, vol. 48, pp. 21–27, 2013, http://dx.doi.org/10.1016/j.engstruct.2012.09.029.

[5] A. Abasi, R. Hassanli, T. Vincent, and A. Manalo, "Influence of prism geometry on the compressive strength of concrete masonry," *Constr. Build. Mater.*, vol. 264, pp. 120182, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2020.120182.

[6] J. Álvarez-Pérez et al., "Multifactorial behavior of the elastic modulus and compressive strength in masonry prisms of hollow concrete blocks," *Constr. Build. Mater.*, vol. 241, pp. 118002, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2020.118002.

[7] C. E. S. Tango, "Structural masonry control tests of concrete blocks", *in Seminar on Concr. Inspection*, Brazilian Institute of Concrete, 1981. pp. x-x. Publication I.11.

[8] G. Parsekian et al., *Behavior and Dimensioning of Structural Masonry*, São Paulo: EdUFSCar, 2012.

[9] M. A. Ramalho and M. R. S. Corrêa, *Design of Structural Masonry Buildings*, São Paulo: Pini, 2003.

[10] R. O. Steil and L. R. Prudêncio, "Influência da geometria dos blocos no fator de eficiência das alvenarias estruturais de blocos de concreto," in *Int. Seminar on Struct. Masonry for Developing Countries*, Belo Horizonte, 2002. pp. 35-42.

[11] L. R. Prudêncio Jr., et al., 2003. *Concrete Block Structural Masonry,* Florianópolis: Palloti, 2003.

[12] A. W. HEndry *Structural Brickwork*, London: The Macmillan Press, 1981.

[13] R. J. K. Mendes, "Resistência à compressão de alvenarias de blocos cerâmicos estruturais," M.S. thesis, Univ. Fed. Sta. Catarina, Florianópolis, 1998.

[14] G. Mohamad, "Comportamento mecânico na ruptura de prismas de blocos de concreto," M.S. thesis, Univ. Fed. Sta. Catarina, Florianópolis, 1998.

[15] P. D. Garcia, "Contribuições ao estudo da resistência à compressão de paredes de alvenaria de blocos cerâmicas," M.S. thesis, Univ. São Paulo, São Carlos, 2000.

[16] G. H. Nalon et al., "Strength and failure mechanisms of masonry prisms under compression, flexure and shear: components' mechanical properties as design constraints," *J. Build. Eng.*, vol. 28, pp. 101038, 2020, http://dx.doi.org/10.1016/j.jobe.2019.101038.

[17] T. Shi, X. Zhang, H. Hao, and C. Chen, "Experimental and numerical investigation on the compressive properties of interlocking blocks," *Eng. Struct.*, vol. 228, pp. 111561, 2021, http://dx.doi.org/10.1016/j.engstruct.2020.111561.

[18] N. N. Thaickavil and J. Thomas, "Behaviour and strength assessment of masonry prisms," *Case Stud. Constr. Mater.*, vol. 8, pp. 23–38, 2018, http://dx.doi.org/10.1016/j.cscm.2017.12.007.

[19] J. A. Thamboo, "Material characterization of thin layer mortared clay masonry," *Constr. Build. Mater.*, vol. 230, no. pp. 116932, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2019.116932.

[20] K. H. Yang, Y. Lee, and Y. H. Hwang, "A stress-strain model for brick prism under uniaxial compression," *Adv. Civ. Eng.*, vol. 2019, pp. 7682575, 2019, http://dx.doi.org/10.1155/2019/7682575.

[21] J. A. Thamboo and M. Dhanasekar, "Correlation between the performance of solid masonry prisms and wallettes under compression," *J. Build. Eng.*, vol. 22, pp. 429–438, 2019, http://dx.doi.org/10.1016/j.jobe.2019.01.007.

[22] N. Sathiparan and U. Rumeshkumar, "Effect of moisture condition on mechanical behavior of low strength brick masonry," *J. Build. Eng.*, vol. 17, pp. 23–31, 2018, http://dx.doi.org/10.1016/j.jobe.2018.01.015.

[23] F. E. Caldeira et al., "Influence of joint thickness and strength of mortars on the compressive behavior of prisms made of normal and high-strength concrete blocks," *Constr. Build. Mater.*, vol. 234, pp. 117419, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2019.117419.

[24] E. S. Fortes, G. A. Parsekian, F. S. Fonseca, and J. S. Camacho, "High-strength concrete masonry walls under concentric and eccentric loadings," *J. Struct. Eng.*, vol. 144, no. 6, pp. 04018055, 2018, https://doi.org/10.1061/(ASCE)ST.1943-541X.0001978.

[25] L. O. Castro, R. C. S. S. Alvarenga, R. M. Silva, and J. C. L. Ribeiro, "Experimental evaluation of the interaction between strength concrete block walls under vertical loads," *Rev. IBRACON Estrut. Mater.*, vol. 9, no. 5, pp. 643–681, 2016, http://dx.doi.org/10.1590/S1983-41952016000500002.

[26] F. S. Fonseca, E. S. Fortes, G. A. Parsekian, and J. S. Camacho, "Compressive strength of high-strength concrete masonry grouted prisms," *Constr. Build. Mater.*, vol. 202, pp. 861–876, 2019, http://dx.doi.org/10.1016/j.conbuildmat.2019.01.037.

[27] G. H. Nalon et al., "Review of recent progress on the compressive behavior of masonry prisms," *Constr. Build. Mater.*, vol. 320, pp. 126181, 2021, http://dx.doi.org/10.1016/j.conbuildmat.2021.126181.

[28] A. Drougkas, E. Verstrynge, R. Hayen, and K. van Balen, "The confinement of mortar in masonry under compression: experimental data and micro-mechanical analysis," *Int. J. Solids Struct.*, vol. 162, pp. 105–120, 2019, http://dx.doi.org/10.1016/j.ijsolstr.2018.12.006.

[29] G. Mohamad, S. Fonseca, T. Vermeltfoort, and A. Lubeck, "Stiffness plasticity degradation of masonry mortar under compression: preliminar results," *Rev. IBRACON Estrut. Mater.*, vol. 11, no. 2, pp. 279–295, 2018, http://dx.doi.org/10.1590/S1983-4195201800020004.

[30] J. Llorens et al., "Experimental study on the vertical interface of thin-tile masonry," *Constr. Build. Mater.*, vol. 261, pp. 119976, 2020, http://dx.doi.org/10.1016/j.conbuildmat.2020.119976.

[31] N. G. Gomes, "The strength of masonry walls," M.S. thesis, Univ. São Paulo, São Paulo, 1983.

[32] Associação Brasileira de Normas Técnicas, *Structural Masonry – Part 1: Design*, NBR 16868-1, 2020.

[33] S. R. Sarhat and E. G. Sherwood, "The prediction of compressive strength of ungrouted hollow concrete block masonry," *Constr. Build. Mater.*, vol. 58, pp. 111–121, 2014, http://dx.doi.org/10.1016/j.conbuildmat.2014.01.025.

[34] S. R. Balasubramanian et al., "Experimental determination of statistical parameters associated with uniaxial compression behavior of brick masonry," *Curr. Sci.*, vol. 109, no. 11, pp. 2094–2102, 2015.

[35] S. Das, J. Liu, M. El-Sayed, and G. Sturgeon, *The Effect of Height-to-thickness Ratio on Compressive Strength of Hollow Concrete Masonry*, Windsor: CMS, 2013.

[36] G. Mohamad, P. B. Lourenço, and H. R. Roman, "Mechanics of hollow concrete block masonry prisms under compression: review and prospects," *Cement Concr. Compos.*, vol. 29, no. 3, pp. 181–192, 2007, http://dx.doi.org/10.1016/j.cemconcomp.2006.11.003.

[37] L. Berto, A. Saetta, R. Scotta, and R. Vitaliani, "Failure mechanism of masonry prism loaded in axial compression: computational aspects," *Mater. Struct.*, vol. 38, no. 2, pp. 249–256, 2005, http://dx.doi.org/10.1007/BF02479350.

[38] C. S. Barbosa, P. B. Lourenço, and J. B. Hanai, "On the compressive strength prediction for concrete masonry prisms," *Mater. Struct.*, vol. 43, no. 3, pp. 331–344, 2010, http://dx.doi.org/10.1617/s11527-009-9492-0.

[39] T. Zahra, J. Thamboo, and M. Asad, "Compressive strength and deformation characteristics of concrete block masonry made with different mortars, blocks and mortar beddings types," *J. Build. Eng.*, vol. 38, pp. 102213, 2021, http://dx.doi.org/10.1016/j.jobe.2021.102213.

[40] Associação Brasileira de Normas Técnicas, *Hollow Concrete Blocks for Concrete Masonry – Test Methods*, NBR 12118, 2013.

[41] Associação Brasileira de Normas Técnicas, *Aggregates – Determination of the unit weight and air-void contents*, NBR NM 45, 2006.

[42] Associação Brasileira de Normas Técnicas, *Portland cement and other powdered material – Determination of density*, NBR NM 23, 2000.

[43] Associação Brasileira de Normas Técnicas, *Aggregates – Sieve analysis of fine and coarse aggregates*, NBR NM 248, 2003.

[44] Associação Brasileira de Normas Técnicas, *Fine Aggregate – Determination of the Bulk Specific Gravity and Apparent Specific Gravity*, NBR NM 52, 2002.

[45] Associação Brasileira de Normas Técnicas, *Hydrated Lime for Mortars: Determination of Fineness*, NBR 9289, 2000.

[46] Associação Brasileira de Normas Técnicas, *Portland Cement: Requirements*, NBR 16697, 2018.

[47] Associação Brasileira de Normas Técnicas, *Mortars Applied on Walls and Ceilings – Determination of the Consistence Index*, NBR 13276, 2016.

[48] Associação Brasileira de Normas Técnicas, *Mortar for Laying and Coating Walls and Ceilings: Preparation of the Mixture for Carrying Out Tests*, NBR 16541, 2016.

[49] Associação Brasileira de Normas Técnicas, *Mortar for Laying and Coating Walls and Ceilings — Determination of Mass Density and Air Content*, NBR 13278, 2005.

[50] Associação Brasileira de Normas Técnicas, *Mortar for Laying and Coating Walls and Ceilings: Determination of Water Retention*, NBR 13277, 2005.

[51] Associação Brasileira de Normas Técnicas, *Hardened Mortar and Concrete: Determination of Water Absorption, Void Ratio and Specific Mass*, NBR 9778, 2005.

[52] Associação Brasileira de Normas Técnicas, *Mortar – Determination of the Flexural and the Compressive Strength in the Hardened Stage – Method of Test*, NBR 13279, 2005.

[53] Associação Brasileira de Normas Técnicas, *Mortar for Laying and Coating Walls and Ceilings: Determination of the Dynamic Modulus of Elasticity Through Ultrasonic Wave Propagation, NBR 15630*, 2008.

[54] American Society for Testing and Materials. *Standard Test Method for Compressive Strength of Masonry Prisms, C-1314*, 2022.

[55] Associação Brasileira de Normas Técnicas, *Structural Masonry: Part 2: Execution and Control of Works*, NBR 16868-2, 2020.

[56] E. H. Nakakura, *Analysis of Classification Requirements for Laying and Coating Mortars* (Technical Bulletin). São Paulo: Escola Politécnica, USP, 2004.

[57] J. M. Casali, "Estudo comparativo do comportamento de diferentes tipos de argamassas de assentamento para alvenaria estrutural de blocos de concreto", M.S. thesis, Univ. Fed. Sta. Catarina, Florianópolis, 2003.

[58] A. A. P. Mansur and H. S. Mansur, "Evaluation of the air content in mortars modified with poly (vinyl alcohol)," in *Brazilian Cong. Mater. Eng. Science,* Foz do Iguaçu, 2006, pp. 3788-3799.

[59] G. Parsekian and M. Soares, *Structural Masonry in Ceramic Blocks: Design, Execution and Control*, São Carlos: Nome da Rosa, 2010.

[60] American Society for Testing and Materials, *Standard specification for mortar for unit masonry*, C-270, 2019.

[61] F. H. Sabbatini, *Laying Mortars for Resistant Masonry Walls* (Technical Bulletin). São Paulo: Escola Politécnica, USP, 1986.

[62] L. Casali and L. R. Prudêncio Jr., "New test method for the evaluation of the workability of concrete block masonry bedding mortars," *in Int. Brick and Block Masonry Conf.,* Sidney, 2008.p. 1-10.

[63] F. H. Sabbatini, "O processo construtivo de edifícios de alvenaria estrutural sílico-calcária," M.S. thesis, Univ. São Paulo, São Paulo, 1984.

[64] F. M. Khalaf et al., "Mechanical properties of material used in concrete blockwork construction," *Mag. Concr. Res.*, vol. 44, no. 158, pp. 1–14, 1992, http://dx.doi.org/10.1680/macr.1992.44.158.1.

[65] British Standards Institution, *Design of Masonry Structures - Part 1–1: General Rules for Reinforced and Unreinforced Masonry Structures*, EN 1996-1-1: Eurocode 6, 2005.

[66] J. S. Passos et al., "Requirements and trends for quality control of structural masonry," in *Brazilian Concrete Congress,* Curitiba, 2009, pp. x-x.

[67] T. S. Cheema and R. E. Klingner, "Compressive strength of concrete masonry prisms," *J. Am. Concr. Inst.*, vol. 83, pp. 88–97, Jan/Feb. 1986.

[68] H. Hernoune et al., "Strengthening of masonry walls with CFRP composite: experiments and numerical modeling," *J. Silic. Based Comp. Mater.*, vol. 72, pp. 2–11, 2020, http://dx.doi.org/10.14382/epitoanyag-jsbcm.2020.1.

[69] A. Kaczmarek, "Technical evaluation of construction mortars with various lime quantity additions," in *World Multidis. Civil Eng., Archit., Urban Planning Symp.*, Prague, 2019, pp. 1–6.

[70] S. Pavia Brennan, "Portland cement-lime mortars for conservation. historic mortars", in *Historic Mortars: Advances in Research and Practical Conservation,* J. J. Hughes, J. Válek and C. J. W. P. Groot, Ed., USA: Springer, 2019, pp. 129–142.

[71] R. H. Atkinson and J. L. Noland, "A proposed failure theory for brick masonry in compression," in *Canadian Masonry Symp.*, Edmonton, 1983. pp. 1-7.

[72] R. O. G. Martins et al., "Influence of blocks and grout on compressive strength and stiffness of concrete masonry prisms," *Constr. Build. Mater.*, vol. 182, pp. 233–241, 2018, http://dx.doi.org/10.1016/j.conbuildmat.2018.06.091.

[73] S. H. Prado, "Resistência à compressão de tijolos e blocos cerâmicos de diferentes formas e dimensões", M.S. thesis, Univ. Fed. Sta. Catarina, Florianópolis, 1995.

[74] M. J. Oliveira, "Materiais descartados pelas obras de construção civil: estudo dos resíduos de concreto para reciclagem", Ph.D. thesis, Univ. Estad. Paul., Rio Claro, 2002.

[75] Australian Standards for Masonry Structures, *Masonry structures*, AS3700, 2018.

[76] CSA Standards, *Design of Masonry Structures*, S304.1-04, 2010.

[77] Masonry Standards Joint Committee, *Building Code Requirements for Masonry Structures*, TMS 402/ASCE 5/ACI 530, 2011.

Author contributions: RSP: formal analysis, investigation, methodology, validation, visualization, writing - original draft, writing - review and editing; BMT: conceptualization, methodology, project administration, supervision, validation.

Editors: Vladimir Haach, Guilherme Aris Parsekian.