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ORIGINAL ARTICLE

Estimate models of compression strength of prisms from structural masonry components

Modelos de estimativas de resistência à compressão de prismas a partir de componentes da alvenaria estrutural

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Abstract: This work proposes models to estimate the resistance of hollow and grouted concrete blocks prisms based on the compressive strength of their components. A database composed of 27,426 tests results on hollow and grouted prisms, mortar, grout and concrete blocks was assessed, grouped into 875 samples. Different statistical analysis models were proposed, and the best model was selected for each predetermined block resistance range. The blocks strength r ranges are Range 1 (up to 8 MPa), Range 2 (from 8 to 18 MPa) and Range 3 (above of 18 MPa). An adjustment factor of 95% confidence was calculated for each model. When comparing the results of the models with the results estimated by the design codes, it was observed that, in general, the estimates of the models of hollow and grouted prisms were similar to those of prism resistance of ABNT NBR 16868-1 (2020), except for the Range 3 resistance, in which the code is more conservative, and the proposed model with the intrinsic adjustment factor estimated values lower than those proposed by the norm. Regarding the international standards, AS-3700 (2017), TMS 602 (2021) and CSA S304 (2014) presented more conservative estimates, while Eurocode 6 (2020) adapted better to the results of the proposed models. Models considered as safe are proposed, based on the hundreds of analyzed samples, allowing estimating the hollow and grouted prism strength from their components strengths for concrete blocks structural masonry.

Keywords: structural masonry, structural concrete block, compressive strength, prisms.

Resumo: Este trabalho propõe modelos para estimar a resistência de prismas ocos e grauteados de blocos de concreto com base na resistência à compressão de seus componentes. Um banco de dados composto por 27.426 resultados de ensaios a compressão de prismas ocos e grauteados, argamassas, grautes e blocos de concreto, agrupados em. Foram propostos diferentes modelos de análise estatística, o melhor modelo foi selecionado para cada faixa de resistência de bloco pré-determinada. As faixas de resistência a compressão do bloco consideradas são Faixa 1 (até 8 MPa), Faixa 2 (de 8 a 18 MPa) e Faixa 3 (acima de 18 MPa). Um fator de ajuste de confiança de 95% foi calculado para cada modelo. Ao comparar os resultados dos modelos com os resultados estimados pelos códigos de projeto, observou-se que, em geral, as estimativas dos modelos de prismas ocos e preenchidos foram semelhantes às da resistência de prismas da ABNT NBR 16868-1 (2020), exceto para a resistência da Faixa 3, na qual a recomendação da norma é mais conservadora, e o modelo proposto com o fator de ajuste intrínseco estimou valores mais baixos do que os propostos pela norma. Em relação às normas internacionais, AS-3700 (2017), TMS 602 (2021) e CSA S304 (2014) apresentaram estimativas mais conservadoras, enquanto o Eurocode 6 (2020) se adaptou melhor aos resultados dos modelos propostos. São propostos modelos de cálculo considerados seguros, com base nas centenas de amostras analisadas, que permitem estimar a resistência de prisma oco e grauteado a partir da resistência de seus componentes para alvenaria estrutural em blocos de concreto.

Palavras-chave: alvenaria estrutural, bloco de concreto estrutural, resistência à compressão, prismas.

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1 INTRODUCTION

Structural masonry is defined as masonry admitted as part of the structure. Prisms are simplified samples of masonry and are widely used in quality control of this type of structural system. They are particularly important because they allow evaluating the compressive strength of the masonry used in the construction and, thus, guarantee that the project is executed according to the designer's specifications [1]–[3]. In Brazil, the monitoring of these parameters is carried out through tests specified in ABNT NBR 16868-3 [4], which indicates that the characteristic compressive strength obtained through tests must be equal to or greater than that specified by the designer. Prisms and the quality control performance tests are essential to guarantee the safety and effectiveness of constructions [5].

The relationships between the compressive strength of hollow and grouted prisms and blocks are important data for structural masonry design. These relationships depend on the influence of variables, such as the geometry of the components, the average compressive strength of the mortar and the characteristic compressive strength of the grout when the prism is filled with grout. The components, block, mortar and grout, have different behavior and composition, thus they influence such relationships [6], [7].

The Brazilian standard ABNT NBR 16868-2 [8] specifies the control of masonry resistance from testing of its components (prisms, blocks, mortars and grouts). This quality control is necessary and also specified in other international standards. Examples are: American standard TMS 602 [9], Australian standard AS 3700 [10], European standard Eurocode 6 [11] and Canadian standard CSA S304 [12].

Some existing standards, such as TMS 602 [9] and CSA S304 [12], are limited by not presenting compressive strength values for prisms made with high-strength blocks. Fortes et al. [13] tested prisms built with concrete blocks, with a resistance range from moderate to high. The concrete block strength considering are 21.6, 27.0, 37.8, 38.9, 41.1, 55.4, 69.0, 74.7 MPa (net area), combined with mortar and grout of variable resistance. Each prism was assembled with two blocks measuring 14 cm x 19 cm x 39 cm. Hollow and grouted prisms were tested, and, subsequently, relations to estimate the resistance of prisms from the resistance value of the block were obtained. The authors report prism (hollow and grouted) to block strength ratio for blocks strengths from 6 MPa to 70 MPa (net area), or from 3 to 35 MPa (gross area).

Álvarez-Pérez et al. [14] proposed an analytical expression to estimate the compressive strength of prisms made with hollow concrete blocks. The multifactorial technique was used to develop statistical models, analyzing the variables associated with the models and investigating their main influence on the interaction between the studied factors. Micro modeling was adopted to simulate the hollow concrete block prism strength in the ABAQUS software, calibrated by the experimental tests results on the following materials: blocks, mortar and interfaces of blocks. The tested prisms had dimensions of 39,3 cm x 59,9 cm x 14,4 cm, with a mortar joint of 10 mm. The authors concluded that the most influential parameters for estimating masonry strength are the compressive and tensile strength of the block, as well as the thickness of the mortar joint.

Several factors influence the structural performance of masonry prisms, such as the quality of the workmanship, environmental conditions, material properties and characteristics of the blocks. To better understand these aspects, many experimental tests and complementary research are needed [15]. Technological control is essential and requires the number of tests demanded in Brazilian technical standards for the job site quality control is greater than those demanded in international standards, which may represent an additional cost for smaller construction projects with a significant amount of testing samples demands.

This work reports models to estimate the compressive strength of hollow and grouted prisms, based on the results of tests on prisms, structural blocks of concrete, mortar and grout supplied by Brazilian companies that produce blocks and construction companies. This approach may offer a more cost-effective and viable alternative for the quality control of structural masonry works, without compromising construction safety and effectiveness.

2 TECHNICAL STANDARDS RECOMMENDATIONS

In the context of the design of structural masonry buildings, NBR 16868-1 [1] suggest the use of Table 1 to specify the resistance of materials (block, mortar and grout) taking into account the resistance of the hollow or grouted prism. Table 1 presents reference values that are valid for the indicated geometries (14 cm x 39 cm) and for mortars and grouts composed of cement, lime and coarse aggregate, without additives or additives.

Walls with grout built with mortar on both faces of the block; 14 cm thick blocks; f_{bk} = characteristic compressive strength of the masonry block; f_a = compressive strength of the mortar; f_{pk} = characteristic compressive strength of hollow prism; $f_{pk}*$ = characteristic compressive strength of the grouted prism.

To determine the compressive strength of structural concrete masonry based on knowing the compressive strength of the structural blocks and the type of mortar, TMS 602 standard [9] specifies in the use of Table 2. The mortar joint thickness cannot exceed 15.9 mm.

Table 1. Suggested values for block, mortar and grout strength specification, from hollow or grouted prism strength (Adapted from NBR 16868-1 [1]).

Characteristic compressive strength (MPa)					f_{pk}/f_{bk}	f_{pk}^*/f_{bk}
f_{bk}	f_a	f_{gk}	f_{pk}	f_{pk}^*		
3	4	15	2.4	4.8	0.8	2.0
4	4	15	3.2	6.4	0.8	2.0
6	6	15	4.5	7.9	0.75	1.75
8	6	20	6	10.5	0.75	1.75
10	8	20	7.0	12.3	0.7	1.75
12	8	25	8.4	13.4	0.7	1.6
14	12	25	9.8	15.7	0.7	1.6
16	12	30	10.4	16.6	0.65	1.6
18	14	30	11.7	18.7	0.65	1.6
20	14	35	12.0	19.2	0.6	1.6
22	18	35	12.1	19.4	0.55	1.6
24	18	40	13.2	21.1	0.55	1.6

Table 2. Compression strength of masonry based on the compression strength of concrete masonry units and type of mortar used (Adapted from TMS 602 [9]).

Concrete block compressive strength - net area (MPa) [1]	Concrete masonry compression strength - net area ASTM C90 (MPa)	
	Mortar type M or S	Mortar type N
12.07	-	13.79
13.79	13.79	18.27
15.51	17.93	23.44
17.24	22.41	28.96
18.96	26.89	-
20.96	31.03	-

[1]For units with less than 102 mm nominal height, use 85% of the listed values.

The Australian standard AS-3700 [10] establishes that the determination of the characteristic resistance value of the masonry used in the structural design must be based on test results with materials of the same properties from those used in the construction project. For structural masonry constructed from clay, concrete or calcium silicate units, the hollow prism characteristic resistance shall be obtained from Equation 1 that is based in a factor from the block strength obtained from Equation 2, the value compression factor strength for concrete masonry units (f'_{uc}) and the compressive strength factor (k_m) given by Table 3 and the value of mortar joint thickness factor (k_h) given by Table 4.

$$f'_m = k_h \times f'_{mb} \tag{1}$$

$$f'_{mb} = k_m \times \sqrt{f'_{uc}} \tag{2}$$

Table 3. Value compression factor strength for concrete masonry units (Adapted from AS-3700 [10]).

Masonry unit	Type of joint	Mortar class	f'_{uc} (MPa)								k_m
			5	10	15	20	25	30	40	≥ 50	
Concrete	Total[1]	M3	3.10	4.4	5.4	6.3	7.0	7.7	8.8	9.9	1.4
	Lateral[2]	M3	3.60	5.1	6.2	7.2	8.0	8.8	10.1	11.3	1.6

Linear interpolation can be used; f'_{uc} is characteristic compression strength of the unit; k_m is the compression strength factor. [1] Mortar is applied to both vertical and horizontal joints. [2] Mortar is applied only vertical joints.

Table 4 - Value of mortar joint thickness factor (Adapted from AS-3700 [10]).

Ratio between masonry unit height and mortar joint thickness	0.0	3.3	7.6	9.0	11.9	16.2	19.0
k_h	0.00	0.78	1.00	1.05	1.14	1.24	1.30

To estimate the compressive strength of grouted prisms, the procedure is different from the one for hollow prisms. The procedure, when there are no tests, is based on Equation 3.

$$F_0 = \varphi\left[f'_m \times A_b \times + k_c \times A_g \times \left(\frac{f'_{cg}}{1.3}\right)^{(0.55+0.005\times f'_{cg})}\right] \quad (3)$$

Like TMS 602 [9], the CSA S304 [12] standard allow estimating the prism strength from the compressive strength of the mortar and of the, as shown in Table 5.

Table 5. Compression strength of masonry based on the compression strength of concrete masonry units and type of mortar used (Adapted from CSA S304 [12]).

Concrete block compressive strength – net area (MPa)	**Mortar type S**		**Mortar type N**	
	Hollow prism unit strength (MPa)	**Grouted prism unit strength (MPa)**	**Hollow prism unit strength (MPa)**	**Grouted prism unit strength (MPa)**
≥ 30	17.5	13.5	12.0	9.0
20	13.0	10.0	10.0	7.5
15	10.0	7.5	8.0	6.0
10	6.5	5.0	6.0	4.5

To determine the characteristic compressive strength of plain masonry, Eurocode 6 [11] proposes equations that are based on the compressive strength of the block, the average compressive strength of the mortar and the thickness of the mortar joint. There is the *K* factor, which is a constant that depends on the type of block and mortar, when test results are not available.

Equation 4 is used for masonry of general purpose mortar. This should not be applied to dimensioned natural stone masonry, for which Equation 5 is used. All of these are made with 10 mm mortar joints.

$$f_k = K \times f_b^{0.7} \times f_m^{0.3} \quad (4)$$

$$f_k = K \times f_b^{0.7} \times f_m^{0.15} \quad (5)$$

For masonry with thin layer mortar (thickness greater than 0.3 mm and less than or equal to 5 mm) and clay from Groups 1 and 4, Equation 6 applies. For masonry with joints of the same thickness, but clay from Groups 2 and 3, Equation 7 is used. The parameter *K* is a constant, whose value is acquired in Table 6.

$$f_k = K \times f_b^{0.85} \quad (6)$$

$$f_k = K \times f_b^{0.7} \quad (7)$$

It should be noted that, for grouted prisms, the same equations shown above are used. However, for concrete block masonry built with general-purpose mortar, filled with grout, f_k should be the average compressive strength between the strength of the structural block and the resistance of the material that fills the holes, and the parameters of Group 1 must be used.

Table 6. Value of *K* for general purpose, thin layer, and lightweight mortars (adapted from Eurocode 6 [11]).

Masonry unit		General purpose mortar	Thin layer mortar	Lightweight mortar	
				$600 \le \rho d \le 800$ (kg/m^2)	$800 \le \rho d \le 1300$ (kg/m^2)
Aggregate concrete	Group 1	0.55	0.8	0.45	0.45
	Group 2	0.45	0.65	0.45	0.45
	Group 3	0.40	0.50	-	-
	Group 4	0.35	-	-	-

Combination mortar/unit not typically used, therefore no value provided.

Considering that the height/thickness ratio (*h*/*t*) of most prisms used in the research is 2.79 (*t* = 14 cm and *h* = 39 cm), the compressive strength, presented in subsequent comparisons, was adjusted using the height/thickness factors from the standard specimen in the ASTM standards [16], CSA S304 [12], Eurocode 6 [11] and AS-3700 [10]. The factors are shown in Figure 1.

Figure 1. Correction factor for masonry prism with 2 blocks (*h* = 390 mm and *t* = 140 mm).

3 MATERIALS AND METHODS

To achieve satisfactory levels of confidence in a statistical analysis, a large amount of data is needed. A database was prepared (complete data is available at Leite [17]) with test values for compressive strength of blocks, compressive strength of hollow prisms, compressive strength of grouted prisms, grout and mortar strength. It is noteworthy that the blocks and materials considered for the study meet the Brazilian standards specifications.

All the information contained in the database was obtained from test reports requested by construction companies from actual structural concrete blocks masonry building construction quality control results. The following test results were provided for the study:

- Block resistance, hollow prism, solid prism, mortar and grout (f_b, f_p, f_p*, f_a and f_g, respectively);
- Number of specimens of each sample;
- Individual results of specimens;
- Standard block dimension: 14 cm x 29 cm, 14 cm x 39 cm or 19 cm x 39 cm.

The database includes 875 samples, which are composed of a minimum of 6 to a maximum of 19 specimens. Thus, of the full database is composed of 5,381 test results of concrete structural block; 5,514 test results of hollow prism; 6,905 results of grouted prism tests; 5,248 results of mortar tests; and 4,378 data of tests of grout.

A verification of the coefficient of variation (COV) of the samples was carried out, disregarding cases with COV greater than 20%. This limit was chosen because this is the assumption in the Brazilian code when specifying the formulation to calculate the 95%-confidence characteristic value of an ample as per Jaquadre [18] and ABNT NBR 16868-1 [1], remaining 864 contributions.

The samples were separated into three ranges, based on the strength of the concrete blocks, namely: Range 1 (up to 8 MPa), Range 2 (8 to 18 MPa) and Range 3 (above 18 MPa).

Furthermore, for the analysis of hollow and grouted prisms, results in which the average mortar strength was less than 4 MPa – specified as a minimum by the ABNT NBR 16868 (2020) – and those outside the range of 0,7f_{bk} and 1,5f_{bk} were disregarded. For grouted prisms, also the results whose the grout resistance was less than 15 MPa –specified as the minimum value by the Brazilian standard – were disregarded.

The applied filters limits are indicated by NBR 16868-1 [1] and by Parsekian et al. [7]. Furthermore, studies carried out by Martins et al. [19] confirm that it is interesting to use mortar with compressive strength close to the compressive strength of the useful area of the block. It is not effective to use a mortar that is much more resistant than the blocks, as this does not result in greater gains in load capacity for the masonry. Also, it is not efficient to use grout with resistance much higher than that of the blocks (considering the net area), as this could lead to premature failure due to transverse cracking of the blocks caused by the high lateral expansion of the grout.

The database study used a quantitative approach, employing statistical analysis to develop models that represent the strength of the hollow and grouted prism as a function of the most influential covariates. The proposed models were adopted as linear, with the possibility of considering the intercept at origin or not, and options for exponential correlation models were explored. The evaluation of the models confidence levels was carried out through hypothesis tests. To ensure 95%-confidence level in the resistance estimate, an adjustment factor was implemented in the model.

To validate the study, a comparative analysis of the proposed models is compared to literature-available models. This made it possible to evaluate the effectiveness and reliability of the proposed models in relation to normative models, highly regarded and recognized in the scientific and productive environment. Data processing and statistical analyses were performed using the *R* programming language and the RStudio software, which is free and open source. These tools allowed estimating the parameters f_p and f_p* from f_b, f_a and f_g.

4 RESULTS AND DISCUSSION

4.1 DATA FILTER

In order to obtain results suitable for use in statistical analyses, it was necessary to carry out a thorough filtering in the database. As previously mentioned, 875 contributions were received from samples of test results, each with a minimum of 6 and a maximum of 19 specimens for determining the resistance of block, mortar, hollow prism, grout and full prism.

Based on the test reports, characteristic and mean strengths of the blocks and prisms were calculated to facilitate and to apply the filters. Table 7 presents the quantity of filtered items, and [17] provides the contributions with respective strength values for each element.

Table 7. Data processing.

	Total	875
Filters	Variation greater than 20% - Block	10
	Variation greater than 20% - Hollow prism	10
	Variation greater than 20% - Grouted prism	2
	Grout (f_g < 15 MPa)	105
	Mortar (f_a < 4 MPa; f_a < 0.7f_b; f_a > 1.5f_b)	303
Total after filtering (there are data points that have been excluded in more than one filter)		559

After applying the filters, the data were separated into block-strength ranges for hollow and grouted prisms, as shown in Table 8. The models were developed based on the average values of the samples strengths. Table 9 presents the resistance intervals for each element according to their ranges.

Table 8. Quantity separated by compression strength range.

Compression strength Range	Total
1 (≤ 8 MPa)	65
2 (> 8 MPa and < 18 MPa)	325
3 (≥ 18 MPa)	169

Table 9. Compression strength of other components with reference strength range.

Compression strength Range	Compression strength (MPa)		
	Concrete block	Mortar	Grout
1	5.35 – 7.97	4.02 – 9.68	15.58 – 38.73
2	8.02 – 17.89	4.88 – 25.32	15.02 – 43.93
3	18.08 – 34.36	11.51 – 35.40	22.78 – 50.78

4.2 MODELS BY RESISTANCE RANGES

The study begins with the analysis of hollow prism models, which include a linear formulation without intercept, a linear formulation with intercept and an exponential formulation similar to that specified in Eurocode 6 [11]. The three formulations are presented for each strength range in Table 10. It should be noted that for such models (Table 10), the contributions of all the elements that make up the hollow prisms were considered, namely: structural concrete block and mortar. Table 10 also presents the results of the R-square, AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) analyses for defining the models that present the best adjustments to the values contained in the database.

To interpret the values presented in the statistical analyses in Table 10, it is important to highlight that the closer the *R*-squared value is to 1.0, the better the adaptation of the model to the data. Regarding the AIC and BIC criteria, the lowest values obtained indicate models with better adjustments to the available data [20]. Based on these criteria, the selected models were those presented in Equations 8, 11 and 14. For Range 1, due to the reduced number of samples contained in the Database (65 samples), the evaluation of the adjustment was made through the coefficient of determination.

Table 10. Proposed models for hollow prisms.

Compression strength range	Equation	R^2	AIC	BIC
1	$f_{pk} = 0.662\, f_{bk} + 0.081\, f_a$ (8)	0.973	176.36	182.88
	$f_{pk} = 3.931 + 0.141 f_{bk} + 0.052\, f_a$ (9)	0.737	155.55	164.25
	$f_{pk} = 3.227 f_{bk}^{0.179} \text{ x } (0.75 f_a)^{0.087}$ (10)	0.802	155.32	164.02
2	$f_{pk} = 0.548 f_{bk} + 0.167 f_a$ (11)	0.979	1158.91	1170.26
	$f_{pk} = 0.157 + 0.535 f_{bk} + 0.167 f_a$ (12)	0.713	1160.73	1175.86
	$f_{pk} = 0.828 f_{bk}^{0.629} \text{ x } (0.75 f_a)^{0.283}$ (13)	0.902	1162.07	1177.21
3	$f_{pk} = 0.530 f_{bk} + 0.161 f_a$ (14)	0.971	665.94	675.79
	$f_{pk} = 3.512 + 0.389 f_{bk} + 0.152 f_a$ (15)	0.737	656.27	675.33
	$f_{pk} = 1.439 f_{bk}^{0.521} \text{ x } (0.75 f_a)^{0.271}$ (16)	0.732	654.57	667.08

After the models were defined, it was necessary to associate the equation to a confidence level by defining a lower confidence limit. In this work, the lower limit of 95% confidence was considered, as adopted by [21], [22]. The lower 95% confidence limit can be calculated by subtracting 1.65*d*, where d is the standard deviation of the arithmetic mean of the experimental strength values by theoretical strength. Figure 2 shows the confidence limits and the respective safety factors calculated for the hollow prism models. It is important to note that the safety factor, referred to in this study as the fitting factor, plays the role of adjusting the model to ensure a 95% confidence level in strength accuracy.

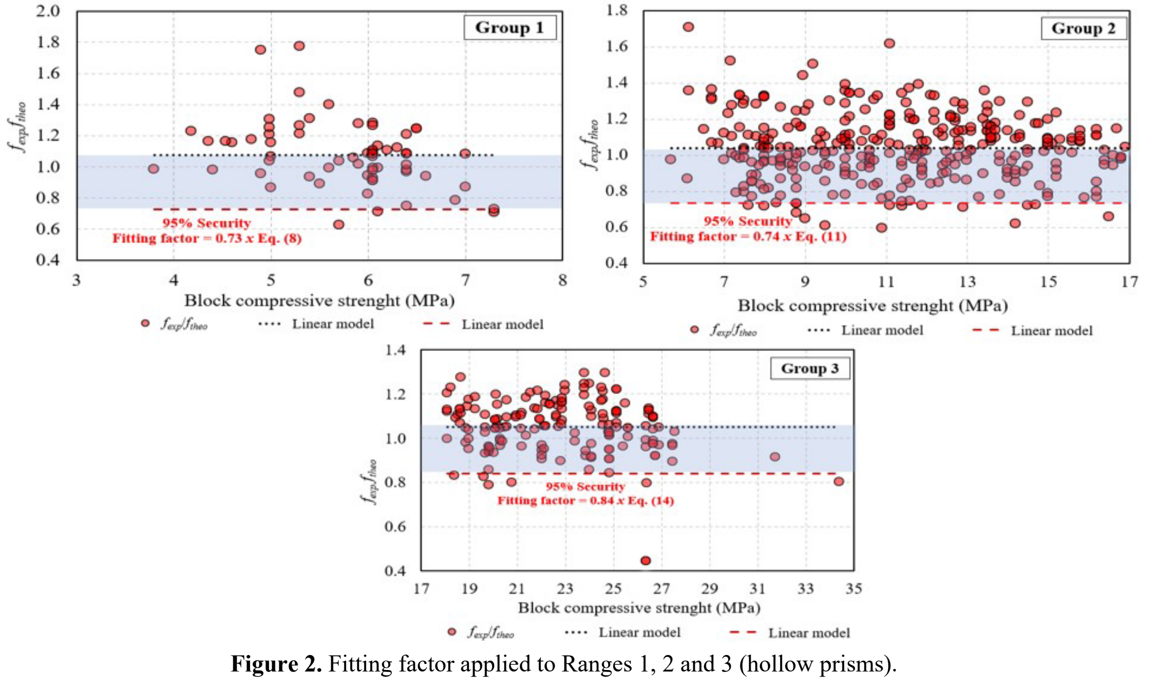

Figure 2. Fitting factor applied to Ranges 1, 2 and 3 (hollow prisms).

For the grouted prisms, the same procedures were performed. The increase in shaping is due to the grout contribution to the strength. Table 11 presents the models and analyses that helped in the selection of models that best fit the data.

Table 11. Proposed models for grouted prisms.

Compression strength range	Equation	R^2	AIC	BIC
1	$f_{pk}* = 2.33f_{bk} - 0.811f_a + 0.140f_{gk}$ (17)	0.960	105.90	110.08
	$f_{pk}* = 7.566 + 1.417f_{bk} - 0{,}775f_a + 0.079f_{gk}$ (18)	0.222	105.94	111.16
	$f_{pk}* = 0.182\, f_b^{1.574} \times (0.75f_a)^{-0.367}$ (19)	0.382	106.09	110.27
2	$f_{pk}* = 0.631f_{bk} + 0.155f_a + 0.235f_{g,k}$ (20)	0.980	1001.12	1014.56
	$f_{pk}* = 0.842 + 0.584f_{bk} + 0.161f_a + 0.223f_{gk}$ (21)	0.651	1002.23	1019.04
	$f_{pk}* = 2.261f_b^{0.587} \times (0.75f_a)^{0.209}$ (22)	0.250	1043.16	1056.60
3	$f_{pk}* = 0.537f_{bk} + 0.08f_a + 0.280f_{gk}$ (23)	0.989	823.532	836.027
	$f_{pk}* = 7.676 + 0.351f_{bk} + 0.087f_a + 0.192f_{gk}$ (24)	0.406	808.803	824.422
	$f_{pk}* = 4.545 \times f_b^{0.408} \times (0.75 \times f_a)^{0.152}$ (25)	0.792	824.018	836.513

Note 1: For Equations 19, 22 and 25, fb should be the smaller value between the characteristic compressive strength of block (f_{bk}) and the characteristic strength of the grout (f_{gk}).

The correlation equations that best represented the experimental strength data for the grouted prisms were Equations 17, 20 and 23, for Ranges 1, 2 and 3, respectively. In this way, the safety factors for 95% were calculated, following the same procedures described for hollow prisms. Figure 3 shows the calculated fitting factors and the graphs of the study carried out.

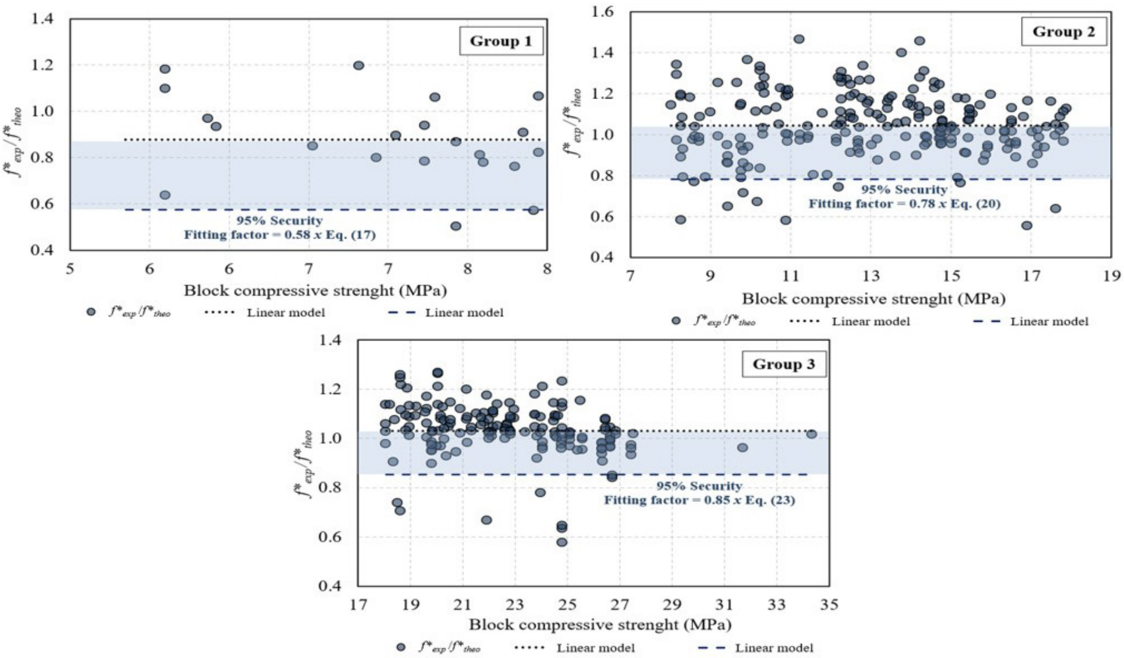

Figure 3. Fitting factor applied to Ranges 1, 2 and 3 (grouted prisms).

4.3 COMPARISON OF PROPOSED MODELS WITH CODE AND LITERATURE SPECIFICATIONS

The models generated by resistance range were compared with the resistance estimates provided in the main design standards in order to validate the study models. The standards used for this analysis were the Brazilian, the Australian, the European, the American and the Canadian standards.

To continue the comparison study for hollow and grouted prisms, it is important to remember that the Brazilian standard ABNT NBR 16868-1 [1] considers the gross area of the structural block, while others consider the net area.

Therefore, it is necessary to adjust the values to ensure correct comparisons. Specific considerations were considered for the use of normative models of hollow and grouted prisms, taking into account different parameters and constants used in the different standards:

- AS 3700 [10]: For hollow prisms, it is necessary to know two parameters, the mortar joint factor (k_h), obtained from Table 4, and the compressive strength factor (k_m), which can be obtained from Table 3. The values for the study in question are 1.3 and 1.4 for k_h and k_m, respectively. For grouted prisms, it is recommended to use Equation 3, which requires knowledge of the reduction capacity factor (φ) and the grout compressive strength factor (k_c). The adopted value of φ, or non-reinforced grouted masonry subjected to compression efforts, is 0.60, and the value of k_c is 1.4 for concrete blocks;
- Eurocode 6 [11]: For hollow prisms, the constant to calculate masonry compressive strength (K) is 0.45 for Group 2, to which the studied masonry belongs. For grouted prisms, the K constant is 0.55 for Group 1, which grouted masonry fits into. It is necessary, later, for both cases, to divide by 0.7 the resistance value found and calculated by Equation 4;
- TMS 602 [9] and CSA S304 [12]: the values used for cases of hollow and grouted prisms are those associated with type M mortar for TMS 602, since the mortar used in the study is similar to type M, as established by ASTM [23] based on compressive strength, and type N for CSA S304. It is important to point out that TMS 602 [9] does not provide estimates for grouted prisms.

For the models generated in the study, the value with 50% confidence and 95% confidence was considered. Table 12 displays the model estimate values for hollow prisms. Figure 4 shows the estimated values of the American and Canadian standards, as shown in Table 13.

Table 12. Comparison between proposed models for hollow prism and standards/literature.

f_{bk} (MPa)	f_a (MPa)	Range	f_{pk} (MPa)					
			Model[1]	Fitting factor	NBR 16868 [1]	AS 3700 [10]	Eurocode 6 [11]	Fortes et al. [13][2]
3.00	4.00	1	2.31	1.69	2.40	1.88	2.10	-
4.00	4.00	1	2.97	2.17	3.20	2.17	2.57	-
6.00	6.00	1	4.46	3.26	4.50	2.66	3.86	-
8.00	6.00	2	5.39	3.99	6.00	3.07	4.72	-
10.00	8.00	2	6.82	5.05	7.00	3.43	6.01	-
12.00	8.00	2	7.92	5.86	8.40	3.76	6.83	10.86
14.00	12.00	2	9.69	7.17	9.80	4.06	8.59	11.88
16.00	12.00	2	10.78	7.98	10.40	4.34	9.44	12.76
18.00	14.00	3	11.80	9.92	11.70	4.60	10.73	13.53
20.00	14.00	3	12.87	10.81	12.00	4.85	11.55	14.23
22.00	18.00	3	14.57	12.24	12.10	5.09	13.32	14.85
24.00	18.00	3	15.63	13.13	13.20	5.31	14.15	15.43

[1]Linear Model - Equations 8, 11, and 14; [2]Model: $f_{pk\,(net\,area)} = 13.17\ \ln(f_{b,k(net\,area)}) - 20.13$.

Table 13. Code estimates.

TMS 602 [9]		CSA S304 [12]		
f_b (MPa)[1]	f_p (MPa)	f_b (MPa)[2]	f_p (MPa)	f^*_p (MPa)
6.89	6.89	5.00	3.25	4.40
8.95	7.75	7.50	5.00	6.59
11.20	8.62	7.50	5.00	8.79
13.44	9.48	15.00	8.75	11.87
15.51	10.48	-	-	-

[1]Mortar type M e S; [2]Mortar type S.

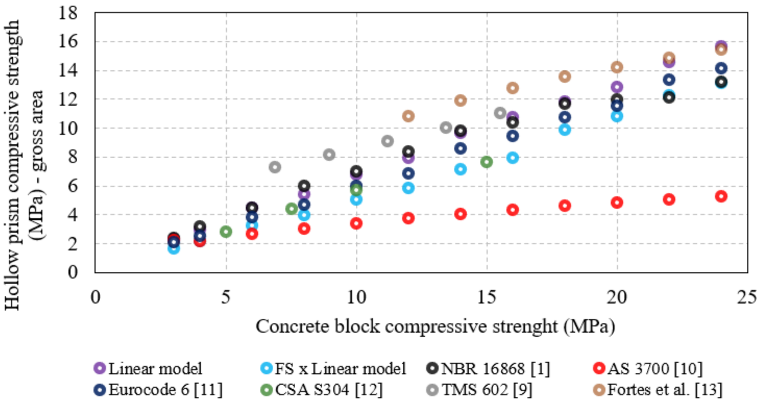

Figure 4. Comparison between models for estimating the strength of hollow prisms – gross area.

By analyzing the graph shown in Figure 4 and the data in Table 12, it is possible to conclude that the Australian standard presents a conservative behavior in relation to concrete blocks with strength greater than 6.0 MPa, when compared to the values obtained from of the proposed linear model, as well as the values resulting from the application of the factor of safety. That is, the Australian norm is mostly conservative.

The standards, American and Canadian, have a limited scope when it comes to block resistances. They mainly cover blocks with low and moderate strengths. The American standard recommends in its tables higher values for compressive strength of ungrouted prism, when compared to the various estimates of standards plotted in the graph.

The model proposed by Fortes et al. [13] is consistent with the linear model for high block resistance values. However, for smaller resistance values, the model by Fortes et al. [13] tends to overestimate the resistance of the prisms when compared to the estimates of the study in question and the regulations.

Additionally, it was verified that the estimates obtained based on the European standard are the most similar and present a better adjustment to the linear models considering a confidence of 95%. The results obtained with the European standard are practically parallel to the results of the models generated in the study, with an average difference of 13% in relation to the estimates. The models generated in the study, for grouted prisms, were compared at 50% confidence of the lower limit and 95% confidence. Table 14 displays the values of the estimates of the study models and the regulations.

Table 14. Comparison between proposed models for grouted prism and standards/literature.

f_{bk} (MPa)	f_a (MPa)	f_{gk} (MPa)	Range	$f_p{}^*{}_k$ (MPa)					
				Model[1]	Fitting factor	NBR 16868 [1]	AS 3700 [10]	Eurocode 6 [11]	Fortes et al. [13][2]
3.00	4.00	15.00	1	4.77	2.75	4.80	3.12	4.17	-
4.00	4.00	15.00	1	7.10	4.09	6.40	3.62	5.11	-
6.00	6.00	15.00	1	9.61	5.53	7.90	4.62	7.66	-
8.00	6.00	20.00	2	10.98	8.60	10.50	6.07	9.37	-
10.00	8.00	20.00	2	12.66	9.91	12.30	7.07	11.94	-
12.00	8.00	25.00	2	15.10	11.82	13.40	8.58	13.56	18.15
14.00	12.00	25.00	2	17.18	13.46	15.70	9.58	15.76	19.53
16.00	12.00	30.00	2	19.62	15.37	16.60	11.16	17.91	20.72
18.00	14.00	30.00	3	19.55	16.68	18.70	12.16	18.75	21.77
20.00	14.00	35.00	3	22.02	18.79	19.20	13.82	20.89	22.72
22.00	18.00	35.00	3	23.52	20.07	19.40	14.82	22.53	23.57
24.00	18.00	40.00	3	25.99	22.18	21.10	16.59	24.73	24.35

[1]Linear Model - Equations 17, 20, and 23; [2]Model: $f_p{}^*{}_k = 8.942\ \ln(f_{b,k(net\ area)}) - 10.27$.

In Figure 5, the values of Table 14 and the estimated values of the Canadian standard (Table 13) are inserted, in order to fully verify the behavior of the proposed models compared with the estimates of the standards.

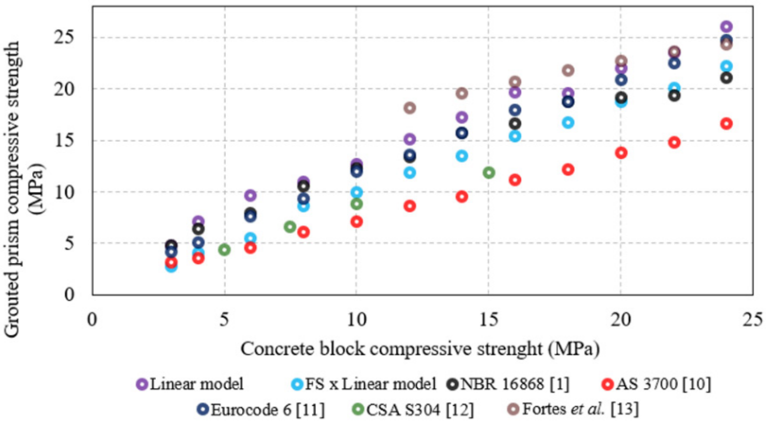

Figure 5. Comparison between models for estimating the strength of grouted prisms.

It was found that the proposed linear model estimates values with an average 13% higher than the values estimated by the European standard. This is the one that best fits our study, when compared with the values estimated by the models proposed here. In addition, the Australian standard adopts conservative values for the grouted prism resistance, when compared to the model proposed without considering the 95% confidence. When considering the model with the adjustment factor, it is noticed that there is an average estimate of 15% lower than the estimates of the Australian standard. It was noted that the Canadian standard is more conservative than the estimates of the model proposed by the study, considering whether or not the adjustment factor for 95% confidence.

The model proposed by the study by Fortes et al. [13] estimates high strength values of grouted prisms, for blocks with strength of up to 20 MPa. For higher values of block resistance, the model by Fortes et al. [13] is more conservative in relation to the Range 3 model proposed in this study, without considering the adjustment factor.

Furthermore, Nalon et al. [5] point out that the empirical equations and tabulated values in current standards have significant limitations, making it necessary a careful review. In their study, they suggest that the prism test method would be more appropriate to estimate masonry compressive strength than the formulations and tables proposed in the standards. The authors highlight ABNT NBR 16868-1 [1] for presenting a table with reference values of compressive strength of prisms based on the resistance of the block, mortar and grout, but emphasize that these values must be confirmed with experimental tests of prisms of masonry during the previous characterization of the materials and during the quality control of the construction. In addition, control by prism test method is required by ABNT NBR 16868-2 [8], unless the characteristic compressive strength of the prisms obtained in the initial characterization tests is greater than or equal to twice the compressive strength design feature.

5 CONCLUSIONS

In this article, calculation models were developed to estimate the compressive strength of hollow and grouted prisms in structural masonry, using experimental data from test reports carried out by companies in the sector. The results of the analyses underscore the importance of segmentation into resistance ranges to capture the observed variations in the data. It is important to highlight that there are several ratios limited to masonry units with low and moderate compressive strength, as indicated by the American and Canadian standards.

This study covers a wide range of compressive strength values for structural concrete blocks, making the estimates applicable both for masonry made with blocks of low and moderate compressive strength, as well as for high strength units. A significant result obtained in this study is the identification of distinct relationships for grouted and ungrouted prisms.

The adoption of models with separation of resistance ranges is recommended, as this strategy proved to be more efficient and accurate and allows the consideration of different groupings. For hollow prisms, it is suggested to use Equations 8, 11 and 14, respectively, for Ranges 1, 2 and 3. For grouted prisms, it is recommended to use Equations 17, 20 and 23, also respectively, to Ranges 1, 2 and 3. In addition, an adjustment factor was proposed to provide the model a confidence of 95%.

The proposed models, with separation of ranges, were compared with national and international regulations, and presented satisfactory results when demonstrating that some regulations are conservative in relation to other models. However, it is worth mentioning that the sampling for resistance range 1 was limited, and we suggest a need for companies to contribute more in order to increase the number of samples and make more accurate models.

5.1 RESEARCH SUGGESTIONS

For future studies, it is suggested to expand the data set to generate the proposed models, in order to increase the precision and reliability of results. It would also be interesting to carry out additional tests to validate the suggested models. In addition, it is suggested the use of artificial intelligence techniques, such as machine learning and neural networks, to generate more accurate and personalized models. Other variables could be considered, such as thickness, thin joint, block size and type of construction, which may lead to the consideration of specificities of the structural masonry used.

6 NOTATIONS

f'_m = characteristic compressive strength of the masonry (MPa);
f'_{uc} = characteristic compressive strength of the masonry unit (MPa);
k_m = compressive strength factor;
k_h = joint thickness factor;
φ = capacity reduction factor;
f'_m = characteristic compressive strength of the masonry (MPa);
k_c = compression factor for the grout in compression stress;
f'_{cg} = characteristic compressive strength of the grout (MPa);
A_b = area of the masonry section;
A_g = area of the holes;
f_{pk} = characteristic compressive strength of hollow prism (MPa);
f_{bk} = characteristic compressive strength of the masonry block (MPa);
f_a = compressive strength of the mortar (MPa);
f_{gk} = compressive strength of the grout (MPa);
$f_{pk}*$ = characteristic compressive strength of the grouted prism (MPa);
f_k = characteristic compressive strength of the masonry (MPa);
K = constant for general purpose, thin layer, and lightweight mortars;
f_b = compressive strength of the blocks (MPa);
f_m = average compressive strength of the masonry mortar (MPa).

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