THE PREDICTION OF COMPRESSIVE STRENGTH OF GROUTED HOLLOW CONCRETE BLOCK MASONRY BASED ON THE CONTRIBUTIONS OF ITS INDIVIDUAL COMPONENTS

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ABSTRACT

The competitiveness of masonry as a choice for a building material depends considerably upon its compressive strength as its most important mechanical property. Masonry design codes suggest one of two options to determine the characteristic compressive strength (f'_m) of masonry for design. The first option is to test masonry prisms built from the same materials used in actual construction. The second approach is to use tables of masonry strength based on the unit block strength and the type of mortar. These tables are derived from empirical relationships developed based on limited number of test results reported in the literature. These tables are also continuously reported to be conservative, especially for grouted concrete masonry. Thus, as more test results became available it is worthwhile to re-evaluate the tabulated values given by the masonry design codes. In this paper, a large database of compressive test results of masonry prism was used to develop a simple, empirical formula to predict f'_m of grouted hollow concrete block masonry based on the contributions of individual materials used in its construction rather than correlated to unit strength only. The assembled database was also utilized to evaluate the reliability of the major international masonry design codes at calculating f'_m of grouted hollow concrete block masonry. The codes analyzed include CSA S304.1-04 (Canada), TMS 402-11 (US), AS 3700-2001 (Australia), and BS 5628-2:2005 (UK). The study showed that the proposed formula gives the lowest coefficient of variation and the second lowest average $f'_{m\ experimental} / f'_{m\ predicted}$ ($f'_{m\ Exp} / f'_{m\ Pred}$) ratios. The masonry codes, on the other hand, underestimate the compressive strength of grouted masonry with high coefficients of variation. The proposed formula can replace the tabulated masonry compressive strength values.

KEYWORDS: concrete blocks, compressive strength, grouted masonry

INTRODUCTION

Compressive strength is the most important characteristic of masonry upon which the ultimate design strengths for masonry elements and structures are based. However, determining f'_m is not a simple task due to the non-homogeneous nature of masonry construction. As a result, a large number of experimental investigations over the past decades have been devoted to understanding the behavior and strength of ungrouted and grouted masonry under compressive loads, and these experiments have typically involved testing specimens such as those shown in Fig. 1. The results of these tests have shown that many factors, both material and experimental, influence the compressive behaviour of masonry prisms. A summary of previous research [1-19] on the compressive behaviour of grouted masonry prisms including the factors investigated is presented in Table 1.

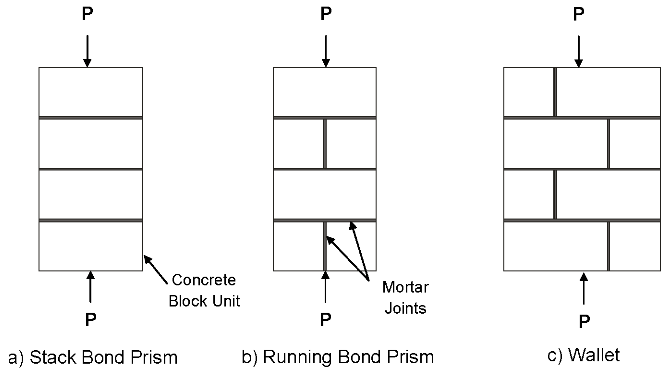

Fig.1 Configurations of concrete block masonry prisms.

Design codes usually offer one of two methods to determine f'_m of masonry. The first method is to test small masonry samples usually 2 to 5 units in height (either prisms or wallets, as shown in Fig. 1). The measured compressive strengths from these tests are then correlated to the strength of the masonry structure by factors that account for the height to thickness ratio of the tested samples. The second method, known as the unit strength method, involves testing individual samples of masonry components: namely the unit and mortar (and sometimes grout, in the case of grouted construction). In this approach, the compressive strength of masonry is estimated from tabulated values based on block strength and mortar type. These tables are developed through empirical relationships between the unit compressive strength and masonry strength for each group of mortar types. However, the data used to develop these tables have often been limited; and these tables typically do not account for the effect of grout strength. Instead, they either treat grouted masonry as solid block masonry or as ungrouted masonry. Moreover, it is widely acknowledged that tabulated values of f'_m in design codes are conservative (Drysdale and Hamid [20], Korany and Glanville [21], Gayed and Korany [22], Ross and Korany [23]). As more test results become available, it is worthwhile to review the reliability of these tabulated values.

The primary objective of this research is to derive an accurate empirical formula to estimate f'_m of grouted masonry based on the contributions of its components (the unit, mortar and grout) while taking into account other main parameters that affect f'_m. Statistical analysis will be used to develop this formula based on a large database of test results assembled from the literature. The reliability of the proposed formula will be assessed by comparing it with the predictive capability of the four major international masonry design codes: AS 3700-2001[24] (Australia), BS 5628-2:2005[25] (UK), CSA S304.1-04 (Canada) [26] and the TMS 402-11[27] (US).

EXPERIMENTAL DATABASE

A large database of compressive tests on grouted concrete block masonry prisms was assembled from available literature [1-19] (see Table 1). A total of 157 average masonry compressive strength data points, representing the test results of 542 individual prisms, was collected. The database covers the main parameters that affect the compressive strength of concrete masonry prisms (see Table 2). Only test results reported and published in journal papers, conference proceedings or institutional reports were included in the database (test results reported in academic dissertations were not included).

Table 1: Summary of experimental investigations on the compressive strength of grouted hollow concrete block masonry.

No.	Author	Year	Experimentally Studied Factors											
			Unit		Mortar		Grout Strength	Prism						
			Geometry	Strength	Type or Strength	Thickness		Size	h/t	Mortar Bedding	Bond Pattern	Capping	Age and Moisture	Other
1	Drysdale and Hamid	1979	X				X			X				
2	Boult	1979		X					X					
3	Hamid et al.	1979			X		X							
4	Drysdale &Hamid	1983		X			X							
5	Wong and Drysdale	1985	X				X		X	X		X		
6	Roman and Romagna	1988		X	X		X							
7	NCMA Tests	1988		X	X		X							
8	Scrivener and Baker	1988		X	X		X			X				
9	Kingsley & Noland	1989		X					X					
10	Khalaf et al.	1992		X		X	X	X						X
11	Steadman et al.	1995		X			X							
12	Baba and Senbu	1995		X			X							
13	Khalaf	1996		X	X	X	X	X	X					
14	Thompson et al.	2002											X	
15	NCMA Tests	2012		X	X		X							
16	Hegmier et al.	1977												X
17	Cheema and Klingner	1984												X
18	Sakr and Neis	1989												X
19	Thomas and Scolforo	1995												X

Table 2: The ranges of values for different parameters covered in the database

Parameter	Range of the Parameters
Unit Compressive Strength (MPa)	12.50 – 41.6
Mortar thickness (mm)	9.5
Mortar Compressive Strength (MPa)	4.5- 26.8
Grout Compressive Strength (MPa)	6.3 - 43.8
h/t Ratio	2.0 - 6.3
Total No. of prism sets	157
No. of N mortar prism sets	40
No. of S mortar prism sets	117

The collected database will be used for three purposes. Firstly, the data was reviewed to explore the main factors that affect the compressive strength of grouted masonry. Secondly, the database was used to derive a formula to predict the compressive strength of grouted concrete block masonry. Finally the database was utilized to evaluate predictive abilities of the international masonry codes compared to those of the proposed formula.

FACTORS AFFECTING f'_m OF GROUTED CONCRETE BLOCK MASONRY

It can be concluded from the database review that the main parameters that affect the compressive strength of grouted masonry are: the unit strength, the mortar strength, the grout strength and the height to thickness ratio. In Fig. 2, the compressive strengths of grouted prisms are plotted against the values of these factors and specific series of tested prisms are highlighted in the cloud of data to illustrate the dependence of masonry strength upon these factors.

Multiple researchers [2,4,6-9,11-13,15] have shown that the compressive strength of masonry prisms increases with increasing compressive strength of the unit (f_{bl}) (see Figure 2 a). It would appear that within the range of common block strengths the relationship between prism strength and block strength is roughly linear. Numerous tests [3, 6-8,14,15] have indicated that the mortar strength (f_{mr}) and type marginally affect f'_m. It can be seen in Fig. 2 b that there is considerable scatter in the data when mortar strength is plotted versus f'_m. Many researchers [1, 3-8,10-13,15] have studied the effect of grout strength on the f'_m. The general trend is that increasing the grout strength results in increasing the prism strength for all different block strengths (see Figure 2c).

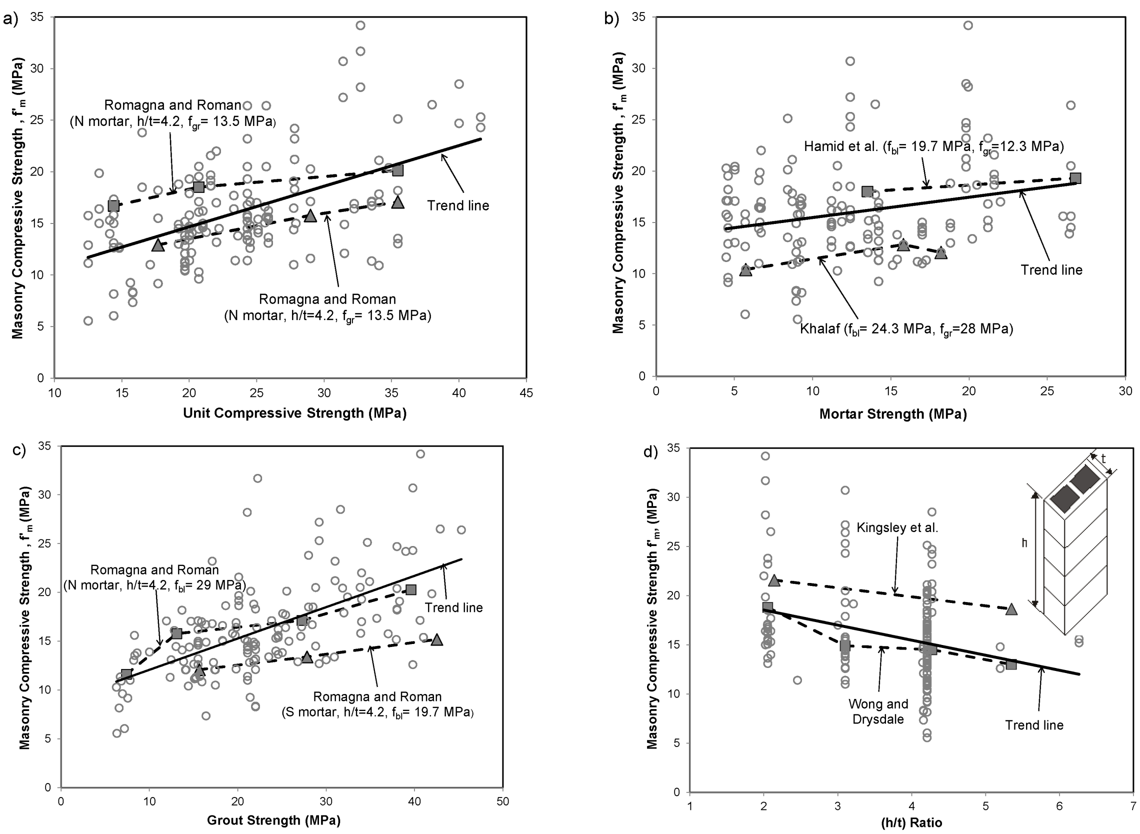

Figure 2: Effects of different factors on the Compressive Strength of Grouted Masonry

It is well known that the ratio of a prism height to its thickness (h/t) affects it compressive strength. Many researchers [2,5,9,13] have shown that as h/t increases, measured compressive strength decreases, though above a certain height, the effect of h/t becomes negligible. This can be attributed to the decreasing influence of platen restraint [5,9]. The general linear trend is about a 7.5% reduction in compressive strength per unit increase in h/t ratio (see Fig 2 d). This 7.5% reduction will be used in the proposed model following the CSA S304.1, AS 3700 and BS 5628-2 approach which considers an h/t of 5 as the standard for determining f'_m. It is worth mentioning that the TMS 402 code considers an h/t of 2 as the standard for determining f'_m. Figure 6 shows the correction factors for h/t ratios in different international codes.

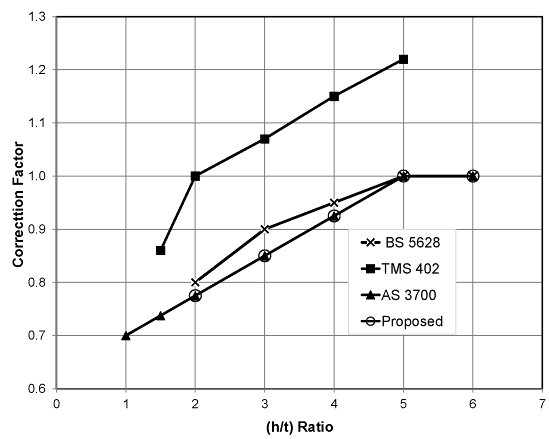

Figure 3: Codes correction factors for h/t ratios

DATA ANALYSIS

In the experimental investigations covered in the assembled database, different procedures were used to test the units, mortar and prisms and in reporting the results. Unit compressive strength was reported in terms of either net or gross areas. The database was unified to be expressed in terms of net area. Mortar compressive strength in the literature was measured by testing cubes or cylinders. It was decided to unify the mortar compressive strength in terms of cube compressive strength. A factor of 1/0.85 was used to convert cylinder compressive strength to cube compressive strength. Grout strengths were determined by testing different types of specimens: cubes, cylinders or absorbent block moulded prisms. The grout compressive strength is unified based on cylinders of height to diameters ratio of two. A factor of 0.85 was used to convert cube compressive strength to equivalent cylinder compressive strength. To convert grout compressive strength of block moulded prisms to equivalent cylinder compressive strength, the empirical formula developed by Neville [28] and adopted by Hamid et al.[3] was used:

$$\frac{P_{cy}}{P} = \frac{0.85}{\left(0.56 + 0.697\,\frac{d}{\left(\frac{V}{6h} + h\right)}\right)} \qquad (1)$$

Where:

P_{cy} = Cylinder compressive strength

P = Prism compressive strength

d = The maximum lateral dimension of the grout prism in

h = Height of the grout prism in

V = Volume of the grout prism in^3

REGRESSION ANALYSIS

The majority of the experimental results were reported without variation values (standard deviation or coefficient of variation). Hence, the derivation of the proposed model was based on experimental average test results of the prisms and the average strength of masonry components (unit, mortar and grout). Regression analysis was used with the compressive strength of masonry prisms, f'_m (normalized for equivalent h/t ratio of 5 using a factor of $\left(\frac{1}{1-0.075\left(5-\frac{h}{t}\right)}\right)$) considered as a dependent variable, while the independent variables were: block strength, f_{bl} ; mortar strength, f_{mr} and grout strength, f_{gr}. Different linear, power and multiple linear regression models were analyzed to obtain a more representative formula. The adequacy of these regression models has been verified based on the following checks [29]: coefficient of multiple determinations (R^2), test for significance of regression, tests on individual regression coefficients and residual analysis on normal probability plots of residuals and residual versus predicted values.

Table 3 shows formulas results from different regression models with their values of multiple determinations (R^2). It can be seen that correlating the compressive strength of grouted prisms to only the unit compressive strength leads to formulas with less representation (lower coefficient of determination) of the experimental database of grouted masonry prisms. The multiple linear model (Equation 2) exhibited the highest coefficients of determination of 73% (see Fig. 4a) and gives an average $f'_{m\ Exp} / f'_{m\ Pred}$ of 1.0 with a coefficient of variation of 15%.

$$f'_m = 0.287 f_{bl} + 0.114 f_{mr} + 0.252 f_{gr} + 0.62 \qquad (2)$$

Table 3: Coefficients of multiple determination for different statisical models

Statistical Models	R^2
$f'_m = 0.350\, f_{bl} + 6.08$	0.30
$f'_m = \mathbf{2.296}(f_{bl})^{0.582}$	0.34
$f'_m = 0.0048(f_{bl})^2 + 0.105 f_{bl} - 8.98$	0.35
$f'_m = 0.287 f_{bl} + 0.114 f_{mr} + 0.252 f_{gr} + 0.62$	0.73

When used for design purposes, the proposed model needs to be associated with a margin of safety through setting a confidence lower limit. Gayed and Korany [22] and Ross and Korany [23] used the 90% confidence lower limit, and this model will use the same. The 90% confidence lower limit can be calculated by subtracting 1.28σ, where σ is the standard deviation, from the arithmetic mean. For a mean of 1.0 and a standard deviation of 0.15 the confidence lower limit is 0.81. Thus the proposed formula will be:

$$f'_m = 0.81\ \{0.287 f_{bl} + 0.114 f_{mr} + 0.252 f_{gr} + 0.62\} \qquad (3)$$

Figure 4 c represents a graphical form of Equation 3 which can further eliminate the calculations needed for determination of f'_m. For grouted masonry prisms built with h/t other than 5, f'_m can be predicted by Equation 4

$$f'_m = 0.81\, C_h\ \{0.287 f_{bl} + 0.114 f_{mr} + 0.252 f_{gr} + 0.62\} \qquad (4)$$

Where C_h is a factor to account for the h/t ratio which can be taken as:

$$C_h = \begin{cases} \dfrac{1}{\left(1 - 0.075\left(5 - \frac{h}{t}\right)\right)} & \dfrac{h}{t} < 5 \\ 1 & \dfrac{h}{t} \geq 5 \end{cases} \qquad (5)$$

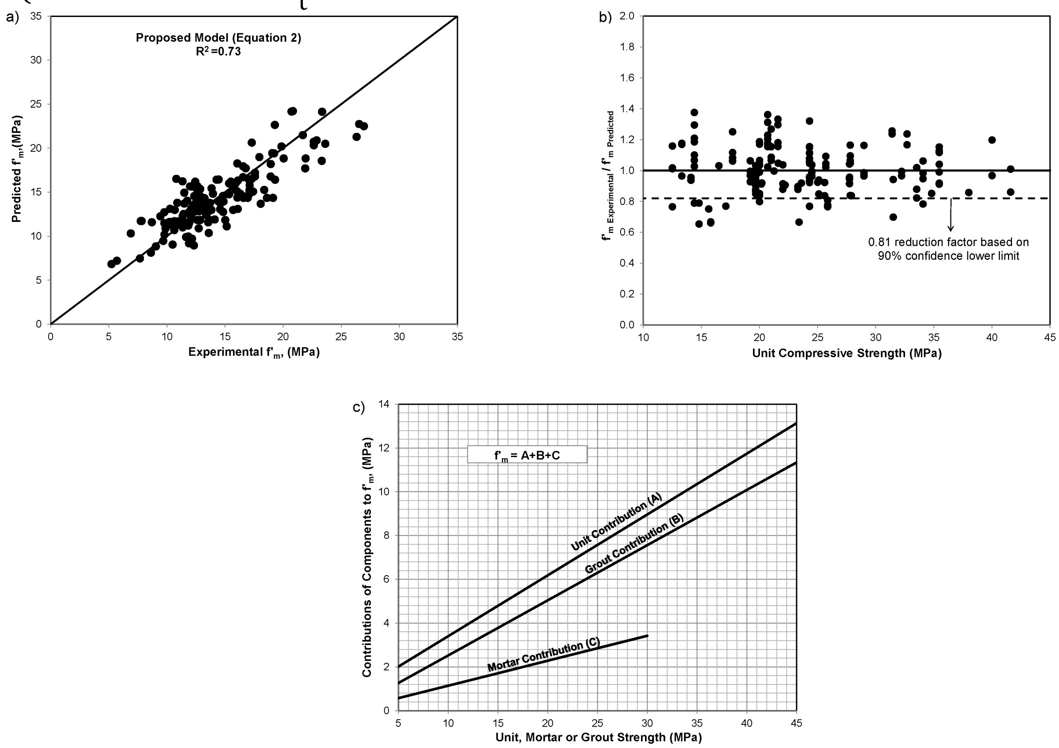

Figure 4: Development of the proposed model

RESULTS AND DISSCUSSIONS

The predicted characteristic compressive strengths of the tested prisms covered in the current database were calculated using the proposed model (Equation 3) and four international masonry design codes [23-26]. The ratio of $f'_{m\ Exp}/\ f'_{m\ Pred}$ were determined for each data point in the database. The BS 5628-2, CSA S304.1 and the TMS 402 codes predictions were generated using tabulated values presented in the codes. Interpolation for intermediate values was used. The AS3700 predictions were generated using Equation 6, which is adopted from the code (the compressive strength in the code's equation is expressed in terms of force unit):

$$f'_m\,(\text{grouted}) = f'_m(\text{ungrouted})\,\frac{A_b}{A_g} + 1.4\left(\sqrt{\frac{f_{cg}}{1.3}}\right)\frac{A_c}{A_g} \qquad (6)$$

Where:

A_b = the bedded area of ungrouted masonry

F_{cg} = characteristic cylinder compressive strength of grout

A_c = the area of the grout

Table 4 summarizes the predictive ability for the masonry codes along with the proposed model. Figure 5 shows the graphical representations of theses comparisons. The AS3700, BS 5628-2, and CSA S304.1 codes all significantly underestimate f'$_m$ by considerable margins, with average $f'_{m\ Exp}/\ f'_{m\ Pred}$ ratios of 1.97, 1.66 and 1.5, respectively. This underestimation of f'm is likewise associated with high variation. The CSA S304.1 code, for example, had the highest coefficient of variation (COV) of 30%. The proposed model had a lower ratio of $f'_{m\ Exp}/\ f'_{m\ Pred}$ at 1.23. While marginally higher than the TMS 402 ratio of 1.16, the proposed model had a COV of only 15%, considerably less than the TMS COV of 25%.

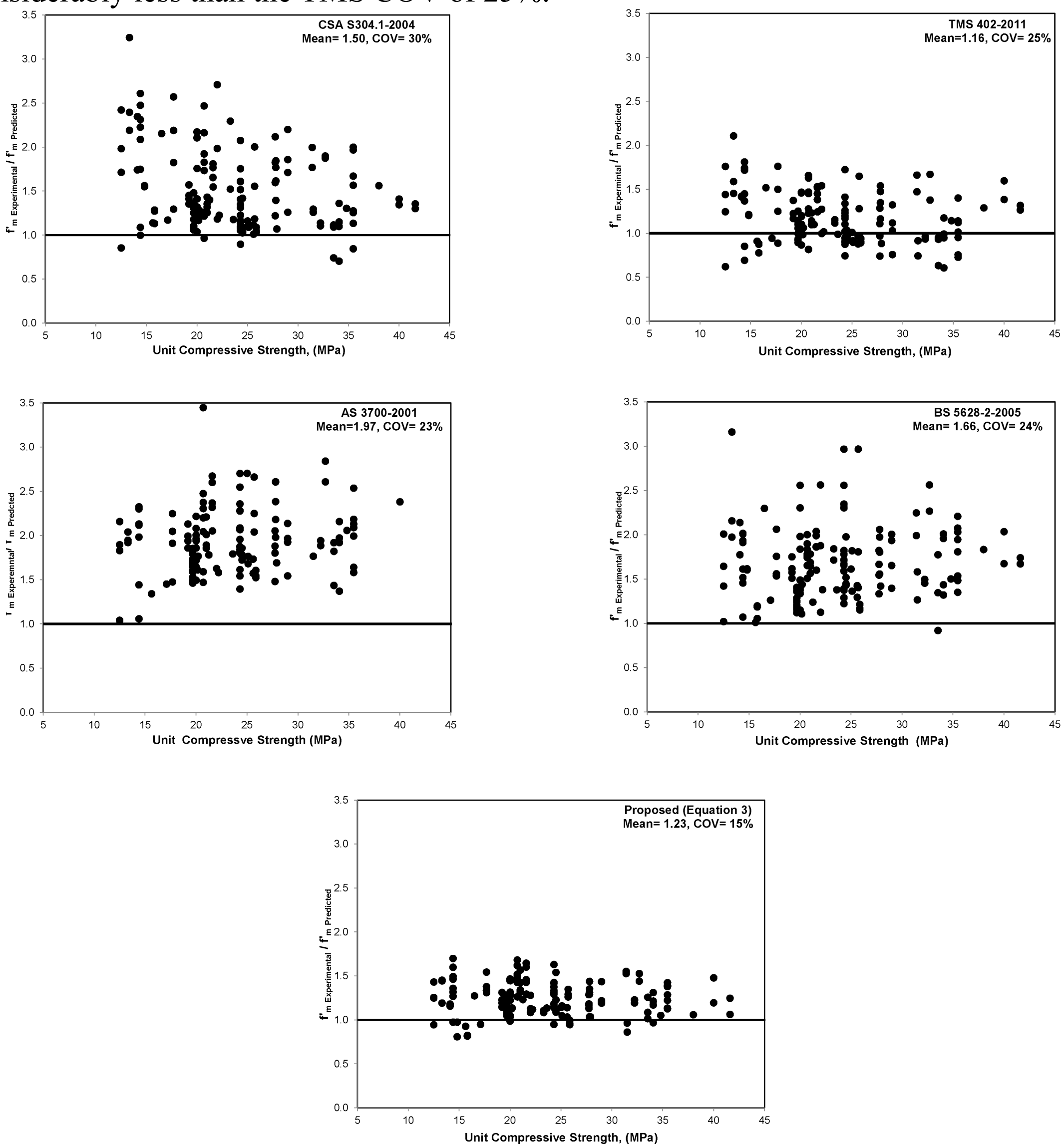

Figure 5: The predictive ability of the proposed model and masonry design codes

Table 4: The values of mean of ($f'_{m\ exp}/\ f'_{m\ pred}$) ratios, standard deviation, coefficient of varion a for the proposed formula and the major International masonry codes

Masonry Design Code	$\frac{f'_m \text{ average experimental results}}{f'_m \text{ predicted (based on average unit strength)}}$								
	All the database			N-mortar prisms			S-mortar prisms		
	Mean	Standard deviation	COV %	Mean	Standard deviation	COV %	Mean	Standard deviation	COV %
CSA S304.1-04	1.50	0.45	30	1.86	0.53	28	1.37	0.34	25
TMS 402-11	1.16	0.28	25	1.19	0.35	29	1.15	0.26	23
AS 3700-2001	1.97	0.44	23	1.86	0.31	17	2.01	0.48	24
BS 5628-2:2005	1.66	0.40	24	1.74	0.41	24	1.63	0.40	24
Proposed	1.23	0.19	15	1.23	0.21	17	1.23	0.18	15

As an example of the improved predictions of f'_m offered by Eq. (3), consider a typical design situation wherein an engineer is designing a masonry component with 15 MPa block, type-S mortar with a strength of 12.5 MPa and 20 MPa grout (all strengths being specified strengths). The CSA S304.1 code indicates that f'_m is 7.5 MPa, whereas Eq (3) calculates f'_m to be 9.2MPa, an increase of 23%. The ability of Eq. (3) to better predict experimental results can also be demonstrated by considering a series of prisms tested by NCMA (2012) where the strengths of each component were measured. These prisms were built out of 14.1 MPa block, 14 MPa (Type S) mortar and 24.8 MPa grout. The average measured f'_m (corrected for h/t ratio) was 12.25 MPa. Eq. (3) predicts a compressive strength of 10.14 MPa, whereas S304.1 predicts a compressive strength of 7.05 MPa. Thus, in-situ compressive strengths of masonry components can be more accurately calculated using Eq. (3) than Table 4 from S304.1 given accurate block, mortar and grout strengths.

The breakdown of the database into N and S type mortar prism illustrate that the CSA code underestimates the compressive strength of type N mortar prisms more than those of type S mortar prisms. As shown in Table 4, the CSA code produces a mean of 1.86 for the ratio of $f'_{m\ exp}/ f'_{m\ pred}$ for type N mortar prisms and 1.37 for type S mortar prisms. Any revision of the CSA S304.1 tabulated masonry strength values should target grouted masonry with type N mortar. Furthermore, as type N mortar prisms make up only 26% of the database, more experimental work is needed for prisms with this type of mortar. Adopting the proposed formula can address this problem (see Fig. 6).

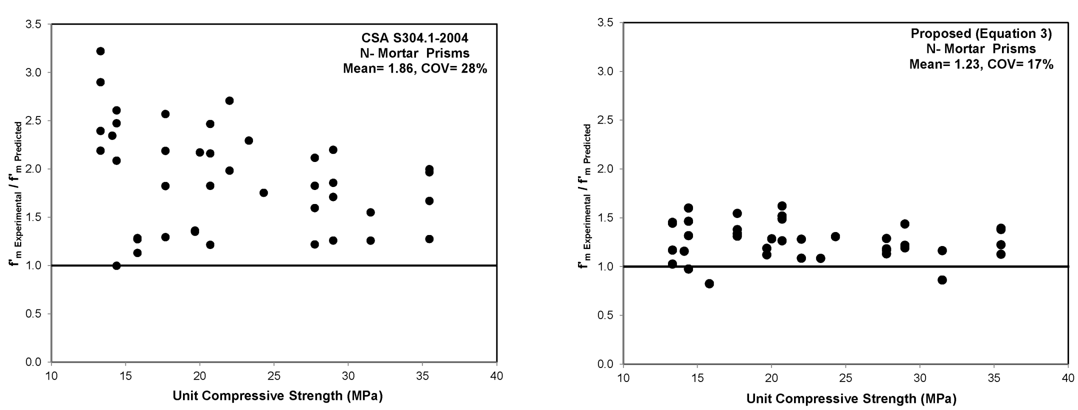

Figure 6: Comparison of predictive ability for the proposed formulas and CSA S304.1 design code for type N mortar prisms

With the exception of AS 3700, the masonry codes do not account for the effect of grout strength on f'_m. However, the AS 3700 code highly underestimates f'_m for the entire range of grout strengths covered in the database. Conversely, the TMS 402 code overestimates f'_m for grout strengths of 15 MPa or less. This overestimation may cause safety issues for masonry structures designed with the TMS 402 code since the general trend in masonry construction is to use low strength grouts. The proposed model gives more consistent predictions for the entire range of grout strengths covered in the database (see Figure 7).

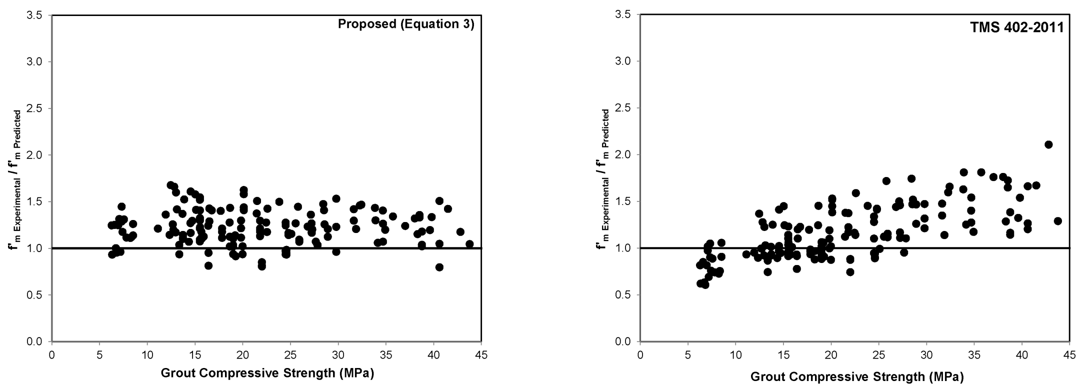

Figure 7: Comparison of predictive ability for the proposed model and TMS 402 code for the range of grout strength

CONCLUDING REMARKS

A statistical analysis led to an accurate, simple formula to predict f'_m of grouted hollow concrete block masonry based on the contributions of its individual components. The proposed model achieves a safe confidence margin of 90% and gives the lowest coefficient of variation and the second lowest mean of $f'_{m\ Exp}$/ $f'_{m\ Pred}$ for the assembled database. The BS 5628-2 and the AS3700 codes significantly underestimate f'_m for grouted masonry associated with high variation. The CSA S304.1 underestimates f'_m of type N mortar prisms while the TMS 402 code, on the other hand, overestimates f'_m of prisms with grout strength of 15 MPa or less. The proposed model gives consistent predictions for the entire range of the different factors that affect f'_m of and can replace the tabulated masonry compressive strength values.

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