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SIMPLIFIED SMEARED AREA COMPRESSION MODEL FOR CALCULATING COMPRESSION STRENGTH OF HOLLOW CONCRETE BLOCK MASONRY

Hunt, B.R.[1] and Sherwood, E.G.[2]

ABSTRACT
This paper summarizes a new model developed to predict the compression strength of hollow concrete block masonry prisms known as the Simplified Smeared Area Compression Model (SSACM). The original Smeared Area Compression Model (SACM) can predict the compression strength of hollow concrete block prisms with high accuracy and low variation, but due to the iterative solution the model is suited for implementation through a computer and not directly transferable to design code application. This paper presents a new simplified model that can predict the compression strength of hollow concrete block prisms in a method suitable for "back of the envelope" calculations. This new method gives an average experimental to predicated compression strength ratio of 1.01 with a COV of 11% from a database of over 200 prism tests. The application of this new simplified method is further demonstrated through proposed design equations that give an average experimental to predicated compression strength ratio of 1.37 with a COV of 18%.

KEYWORDS: *hollow concrete block masonry, compressive strength, masonry design code*

INTRODUCTION
Accurately predicting the compression strength of masonry, f'_m, is very important in design of masonry structures, as it is often the basis of all designs. However, determining the compression strength of masonry is not a simple task. This is because each material (hollow concrete masonry blocks, mortar, and possibly grout) has different material properties and responds in a different non-linear manner when subjected to compression.

Masonry design codes generally provide two methods to determine compression strength: masonry prism testing or unit strength. The first method, masonry prism testing, consists of constructing three to five masonry prisms with site representative materials; testing the prisms in a universal testing machine under compressive loading; and correcting the average compression strength

[1] PhD Candidate, Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada, bradley.hunt@carleton.ca
[2] Assistant Professor, Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada, ted.sherwood@carleton.ca

determined from testing by a factor that accounts for the height to thickness ratio of the tested prisms. This method has certain practical limitations in terms of the complexities of transporting samples and the capacity and size of available testing machines. Furthermore, there are disagreements on the values of the height to thickness correction factors as each international code provides different values. The second method, known as the unit strength method, involves testing individual samples of masonry component materials. In this approach, the compressive strength of masonry is estimated by either an equation or through tabulated values based on block strength, mortar type or strength, and possibly grout strength.

The unit strength method is more widely used by engineers due to its simplicity when compared to the masonry prism test method. In addition, in design applications the unit strength method provides savings in both time and cost. However, the data used to develop these equations and tables has been limited, and not based on a full dataset of all available compressive tests. Furthermore, it is widely acknowledged that values of f'_m in design codes are typically over conservative [1,2].

The purpose of this paper is to review the unit strength methods from four different design codes, review the results of the smeared area compression model (SACM), and propose and evaluate new equations for predicting the compression strength of masonry. A database of 123 ungrouted and 101 grouted masonry prisms reported in the literature is assembled, and the compression strengths are predicted based on the four design codes, SACM, and newly developed equations.

CSA S304-14

The current Canadian masonry design standard CSA S304-14 [3] prescribes masonry compression strengths using the unit strength method in a table format, based on block strength and mortar type. This table (Table 1) has been modified from past versions, with a decrease on the upper limit of block strengths from 40 MPa to 30 MPa. Currently, the values listed are based on research that was carried out in the 1970s and 1980s [4,5] and were developed from a linear regression analysis between average concrete block compressive strength values and average prism compressive strength values. A 20% reduction was then applied to obtain the values listed in Table 1 [4]. The low values of f'_m in Table 1 relative to typical concrete compressive strengths (f'_c) puts masonry at a competitive disadvantage relative to reinforced concrete.

Table 1: CSA S304-14 Unit Strength Values [3]

Net Area Specified Compressive Strength of Block (MPa)	Type S Mortar		Type N Mortar	
	Ungrouted Hollow Blocks (MPa)	Solid or Grouted Hollow Blocks (MPa)	Ungrouted Hollow Blocks (MPa)	Solid or Grouted Hollow Blocks (MPa)
30 or more	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

2013 MSJC

Prior to the 2013 MSJC code [6], masonry compression strength values were developed using prism test results collected from the 1950s through the 1980s [6]. These compression strengths had high variability, which caused design values to be conservative. In 2010, the National Concrete Masonry Association [6,7] began research that would permit the development of a new unit strength table for hollow concrete masonry. Based on this research, a new unit strength table was included in the 2013 code, as presented in Table 2.

Table 2: 2013 MSJC Code Unit Strength Values [6]

Net Area Compressive Strength of Concrete Masonry (MPa)	Net Area Compressive Strength of Concrete Masonry Blocks (MPa)	
	Type M or S Mortar	Type N Mortar
11.72	---	13.10
13.10	13.10	14.84
13.79	13.79	18.27
15.51	17.93	23.44
17.24	22.41	28.96
18.96	26.89	---
20.69	31.03	---

AS 3700-2011

The Australian standard AS3700-2011 [8] provides an equation to determine masonry compressive strength from the block strength modified by the block height to mortar thickness ratio. For ungrouted masonry the characteristic compressive strength of hollow concrete blocks, is:

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

where k_h is a joint thickness factor equal to:

$$k_h = \min\left\{1.3\left(h_b / 19t_j\right)^{0.29}, 1.3\right\} \tag{2}$$

where h_b is the height of the block and t_j is the joint thickness, and f'_{mb} is the characteristic compressive strength of the masonry defined as:

$$f'_{mb} = k_m \sqrt{f'_{uc}} \tag{3}$$

where k_m is a compression strength factor equal to 1.4 or 1.6 for full bedding mortar and face shell bedding mortar respectively and f'_{uc} is the characteristic unconfined compressive strength of the blocks.

For grouted masonry, the compressive strength is:

$$f_m' = \frac{f_{ug}' A_b + k_c \sqrt{\frac{f_{cg}'}{1.3}} A_c}{A_g} \tag{4}$$

where f_{ug}' is the ungrouted compression strength, A_b is the area of the block not including the area of the webs, k_c is a strength factor for grout in compression equal to 1.4 for hollow concrete masonry blocks of density greater than 2000 kg/m^3, f_{cg}' is the design characteristic compressive strength of grout equal to the lesser of the cylinder compression strength of grout or $1.3f_{ug}'$, A_c is the cross-sectional area of grout equal to $A_g - A_b$, and A_g is the gross cross-sectional area of the prism.

UK Eurocode 6

The Eurocode 6 code [9] suggests using the following formula to determine the compressive strength of masonry:

$$f_m' = K f_b^{\alpha} f_m^{\beta} \tag{5}$$

where K, α and β are constants given in the national Annex for a particular country, f_m is the compressive strength of the mortar and f_b is the normalised mean compressive strength of the blocks, defined as:

$$f_b = k_c \delta f_u' \tag{6}$$

where k_c is a conditioning factor equal to 1.0 for air-dried blocks, δ is a shape factor to account for block thickness and height from EN 772-1 [10], and f_u' is the declared average compressive strength of the block. In the UK [11] the values of the constants are 0.52 (for hollow concrete block which have more than 25% but less than 60% of formed vertical voids or cavities, which pass completely through the block), 0.7 and 0.3 for K, α and β respectively. If the prism is grouted the compression strength is determined with $K = 0.55$ (Group 1) with f_b set to the normalised compressive strength of the blocks or of the concrete infill, whichever is the lesser.

The method of measurement for mortar in Eurocode 6 is done in accordance with BS EN1015-11 [12], where the compressive strength is determined on the broken parts of a flexural strength specimen. Ferguson [13,14] demonstrated that, on average, the strength of such specimens is 1.28 times that of mortar cubes. As such, the f_m values used to predict f_m' were the mortar cube strength increased by a factor of 1.28.

Smeared Area Compression Model

The smeared area compression model (SACM) is a model developed by Hunt and Sherwood [15] for predicting the compressive strength of masonry prisms, using equilibrium, compatibility, and material stress-strain relationships. The model consists of a hollow concrete masonry block, mortar (either full bedding or face shell bedding), and the prism can be either grouted or ungrouted. The model considers the central block in a prism of three or more courses to eliminate the platen restraining effect. An axial load is applied and gradually increased until failure of the modeled prism occurs. The model is shown to be highly accurate and is capable of predicting the general accepted failure modes of masonry prisms. Due to the iterative nature of the non-linear solution the model is best suited for computer simulations and not directly applicable to design code application.

SIMPLIFIED SMEARED AREA COMPRESSION MODEL

Due to the complexities of SACM, a simpler model with similar accuracy is desired.

Ungrouted Full Bedded Prisms

Based on the SACM simulations to predict the strength of ungrouted full bedded prisms, it was found that the average degradation factor in the block, β_z^{bl}, was 0.9. This reduction in block compression strength is a result of the biaxial tensional in the block caused by different material properties of the block and the mortar. This would imply a net area masonry compression strength of:

$$f_m' = 0.9 k_1^b k_2^b f_{c,b}' \tag{7}$$

where $f_{c,b}'$ is the reported block net area compression strength, and k_1^b and k_2^b are correction factors depending on the capping method used to determine the block compression strength. The capping correction factor [16], k_1^b, is equal to:

$$k_1^b = \begin{cases} 1.00 & \text{if soft capped} \\ 0.81 & \text{if hard capped} \end{cases} \tag{8}$$

and k_2^b is a block capping bedding correction factor [16]:

$$k_2^b = \begin{cases} 1.00 & \text{if full capped} \\ 0.80 & \text{if faceshell soft capped} \\ 0.75 & \text{if faceshell hard capped} \end{cases} . \tag{9}$$

Where soft capping materials allow for lateral expansion at the platen such as fiberboard and hard capping are materials that cause platen restraint such as hydrostone [16]. To account for the reduction in compression strength due to increasing mortar thickness, the masonry compression strength can be determined by:

$$f_m^{'} = \min\left\{\frac{h^b - t^m}{h^b}, 0.9\right\} k_1^b k_2^b f_{c,b}^{'} \quad (10)$$

for ungrouted full bedded masonry, where h^b is the height of the block and t^m is the thickness of the mortar joint.

Ungrouted Face Shell Bedded Prisms

Face shell bedded masonry typically fails by splitting of the webs of the blocks [4,17,18,19,20]. This behaviour can be accurately captured through a Mohr-Coulomb failure criteria cast in the form of principal stresses, by setting the first principal stress equal to the block tensile strength and solving for the third principal stress. The masonry compression strength, based on minimum cross sectional area (ie. mortar bedding area), is:

$$f_m^{'} = \frac{2c\cos\varphi - f_t^b(1+\sin\varphi)}{1-\sin\varphi}\frac{t^b \rho_{\text{solid}}^b}{2t^{fs}} \quad (11)$$

where c is the cohesion of the block, taken as $k_1^b k_2^b f'_{c,b}/4$, and the angle φ is the angle of internal friction of the block, which can be taken as 35^{o}. The tensile strength of the block, f_t^b, is taken as $0.1 k_1^b k_2^b f'_{c,b}$, t^b is the block thickness, ρ_{solid}^b is the percent solid of the block, and t^{fs} is the thickness of the block face shell.

Grouted Prisms

Grouted masonry has a much more complex behavior than ungrouted masonry. It is well known that the compression strength of grouted masonry is not the superposition of the capacities of the hollow prism and the columns of grout in the cells [21]. Suggested causes for this include incomplete grout compaction, plastic and drying shrinkage of the grout, or geometric factors [22]. But one of the primary causes, as often suggested in literature [16,21,22] and determined by using the SACM, is incompatibility between the stress-strain properties of the block and grout. The block and grout do not reach peak strength at the same strain, typically with the block reaching its peak strain before the grout. In addition, the lateral expansion of the block and grout are normally different due to differences in Poisson's ratios which causes a reduction in compression strength of the block. Thus it is suggested that the grouted compression strength can be determined by:

$$f_m^{'} = \sqrt{\frac{\upsilon^b}{\upsilon^g}}\left[f^b \rho_{\text{solid}}^b + f^g\left(1-\rho_{\text{solid}}^b\right)\right] \quad (12)$$

where υ^b and υ^g are the Poisson's ratio of the block and grout respectively and ρ_{solid}^b is the percent solid of the block. The stress in the block, f^b, is defined by a Hognestad parabola; thus,

$$f^b = k_1^b k_2^b f_{c,b}^{'}\left[2\left(\frac{\varepsilon}{\varepsilon_o^b}\right) - \left(\frac{\varepsilon}{\varepsilon_o^b}\right)^2\right] \quad (13)$$

where ε_o^b is the strain at the reported block net area compression strength, $f'_{c,b}$, and the stress is determined at the stain, ε, defined as:

$$\varepsilon = \begin{cases} 0.8\varepsilon_{\min} & \text{if } \varepsilon_{\min} = \varepsilon_o^b \\ \varepsilon_{\min} & \text{otherwise} \end{cases} \tag{14}$$

where

$$\varepsilon_{\min} = \min\{\varepsilon_o^b, \varepsilon_o^g\} \tag{15}$$

and ε_o^g is the strain at the reported grout compression strength, $f'_{c,g}$. Similarly, the stress in the grout is defined as:

$$f^g = k_1^g k_2^g f'_{c,g} \left[2\left(\frac{\varepsilon}{\varepsilon_o^g}\right) - \left(\frac{\varepsilon}{\varepsilon_o^g}\right)^2 \right] \tag{16}$$

where k_1^g and k_2^g are correction factors depending on the method used to determine the grout compression strength. The grout specimen correction factor, k_1^g, is equal to:

$$k_1^g = \begin{cases} 1.00 & \text{if cyclinder specimen} \\ 0.85 & \text{if cube specimen} \\ 0.85[0.56 + 0.697/\{(V/152h_g d) + (h_g/d)\}] & \text{if block moulded prism specimen [23]} \end{cases} \tag{17}$$

where V is the volume, h_g is the height, and d is the maximum lateral dimension of the block moulded prism. The grout absorbency correction factor, k_2^g, is a equal to:

$$k_2^g = \begin{cases} 1.00 & \text{if absorbent mould} \\ 1.53 - 0.01k_1^g f'_{c,g} & \text{if non-absorbent mould [24]} \end{cases}. \tag{18}$$

If either υ^b or υ^g, or both Poisson's ratios are unknown the $\sqrt{\upsilon^b/\upsilon^g}$ term can be replaced with 0.75. If ε_o^b is unknown 0.0022 can be assumed, while if ε_o^g is unknown it can be assumed to be equal to $0.0011\left(k_1^g k_2^g f'_{c,g}\right)^{0.306}$.

RESULTS AND DISCUSSION

The four international codes, the SACM, and the SSACM were used to predicted the compressive strengths of the 224 average masonry prisms compression strengths [13,15]. The prisms were constructed of various block dimensions and strengths, mortar strengths, and grout strengths (see Table 3). The prisms had to be constructed of three or more blocks to reduce the effects of platen restraint.

Table 4 summarizes the results of various codes and models in terms of experimental to predicted compression strength ratio ($f'_{m,exp}/f'_{m,pred}$). All reported compression strengths were corrected by each codes height to thickness factors, no correction is needed for the SACM or the SSACM. The SACM gives the best average $f'_{m,exp}/f'_{m,pred}$ ratio and the lowest coefficient of variation (COV) for the entire database or any individual subset of the data. However, due to the complex nature of the SACM it is not suited for direct implementation into any design code, but the SSACM produces the second best average $f'_{m,exp}/f'_{m,pred}$ ratio and the second lowest COV for the entire database or any individual subset of the data. CSA S304-14, AS3700-2011, and UK Eurocode 6 have a high COV and as illustrated in Figure 1 they tend to considerably underestimate f'_m. It can also be seen that although the MSJC 2013 exhibited a low average $f'_{m,exp}/f'_{m,pred}$ ratio, it has a high COV and it gives non-conservative predictions ($f'_{m,exp}/f'_{m,pred}$ of less than 1.0) for more than 35% of the entire database. This is because the unit strength table used in MSJC 2013 is derived based on two block high prisms, which tend to overestimate the compression strength due to platen restraint.

It is worth while to point out that all of the code methods are based on curve fits to experimental data. The SACM and the SSACM are based solely on fundamental application of mechanics of materials. As such, strength predictions generated by the SACM and the SSACM are true predictions.

When used for design purposes, SSACM needs to be associated with a margin of safety through setting a confidence lower limit. Assuming the $f'_{m,exp}/f'_{m,pred}$ ratios to be normally distributed, the 95% confidence lower limit can be calculated by subtracting 1.96σ from the arithmetic mean, where σ is the standard deviation. For example, consider the simplified SACM for the full bedded ungrouted prisms. The lower confidence limit for an average of 1.01 and a standard deviation of 0.08 is 0.85; thus, with this limit we can be 95% confident that the $f'_{m,exp}/f'_{m,pred}$ ratio will be equal to or greater than 1.0. Applying the same idea to the face shell bedded ungrouted prisms and grouted prisms results in a lower confidence limit of 0.77 and 0.67 respectably. Thus, the proposed SSACM formulas can be rewritten as:

$$f'_m = \min\left\{\frac{h^b - t^m}{h^b}, 0.9\right\} 0.85 k_1^b k_2^b f'_{c,b} \quad \text{if ungrouted, full bedded mortar} \tag{19}$$

$$f'_m = 0.23 \frac{t^b \rho^b_{\text{solid}} k_1^b k_2^b f'_{c,b}}{t^{fs}} \quad \text{if ungrouted, faceshell bedded mortar} \tag{20}$$

$$f'_m = 0.50\left[f^b \rho^b_{\text{solid}} + f^g\left(1 - \rho^b_{\text{solid}}\right)\right] \quad \text{if grouted} \tag{21}$$

These equations are referred to as the Design Smear Area Compression Model (DSACM) and result in a slight increase in the average $f'_{m,exp}/f'_{m,pred}$ ratio and coefficient of variation (see Table 4), but result in only 2% of the database having non-conservative predictions (see Figure 1).

Table 3: Database Range of Parameters

Parameter	Range of Parameters		
	Ungrouted Prisms		Grouted Prisms
	Faceshell Bedded Prisms	Fully Bedded Prisms	
Unified Block Compressive Strength[a] (MPa)	6.70 – 33.1	7.40 – 31.5	6.17 – 49.8
Block Thickness (mm)	140 – 240	140 – 220	140 – 240
Block Height (mm)	188 – 200	189 – 203	189 – 194
Block Percent Solid (%)	50 – 75	52 – 73	51 – 73
Faceshell Thickness (mm)	24 – 58	25 – 50	17 – 40
Unified Mortar Compressive Strength[b] (MPa)	5.00 – 24.6	4.20 – 31.0	4.50 – 31.4
Unified Grout Compressive Strength[c] (MPa)	N/A	N/A	8.57 – 44.9
Prism h/t Ratio	2.97 – 9.98	2.97 – 6.24	2.46 – 5.21

Notes:

[a] Unified to soft full capping strength

[b] Unified to absorbent cube strength

[c] Unified to absorbent cylinder strength

Table 4: Values of Average $f'_{m,exp}/f'_{m,pred}$, Standard Deviation, Coefficient of Variation for the International Masonry Codes, SACM, and Proposed Equations

Design Provision	Entire Database (224)			Ungrouted Prisms									All Grouted Prisms (101)		
				All Ungrouted Prisms (123)			Faceshell Bedded Prisms (60)			Full Bedded Prisms (63)					
	Average	STDV	COV (%)	Average	STDV	COV (%)	Average	STDV	COV (%)	Average	STDV	COV (%)	Average	STDV	COV (%)
CSA S304-14	1.42	0.42	29	1.35	0.25	18	1.39	0.26	19	1.31	0.22	17	1.50	0.54	36
2013 MSJC	1.08	0.28	26	1.12	0.24	21	1.16	0.27	23	1.08	0.20	18	1.03	0.31	30
AS 3700-2011	1.78	0.42	24	1.73	0.41	24	1.71	0.44	26	1.76	0.37	21	1.83	0.44	24
UK Eurocode 6	1.50	0.42	28	1.38	0.22	16	1.41	0.26	18	1.34	0.16	12	1.66	0.55	33
SACM	1.00	0.05	5	1.00	0.05	5	1.00	0.04	4	1.01	0.05	5	1.00	0.05	5
SSACM[a]	1.01	0.11	11	1.01	0.10	10	1.01	0.12	11	1.01	0.08	8	1.02	0.18	17
DSACM[b]	1.37	0.25	18	1.24	0.13	11	1.30	0.15	11	1.18	0.09	8	1.53	0.27	17

Notes:

[a] With simplified grouted prism assumptions the average becomes 1.02 with a STDV of 0.17 and COV of 17% for grouted prisms

[b] Based on simplified grouted assumptions

Number in bracket is the number of average prism tests compared

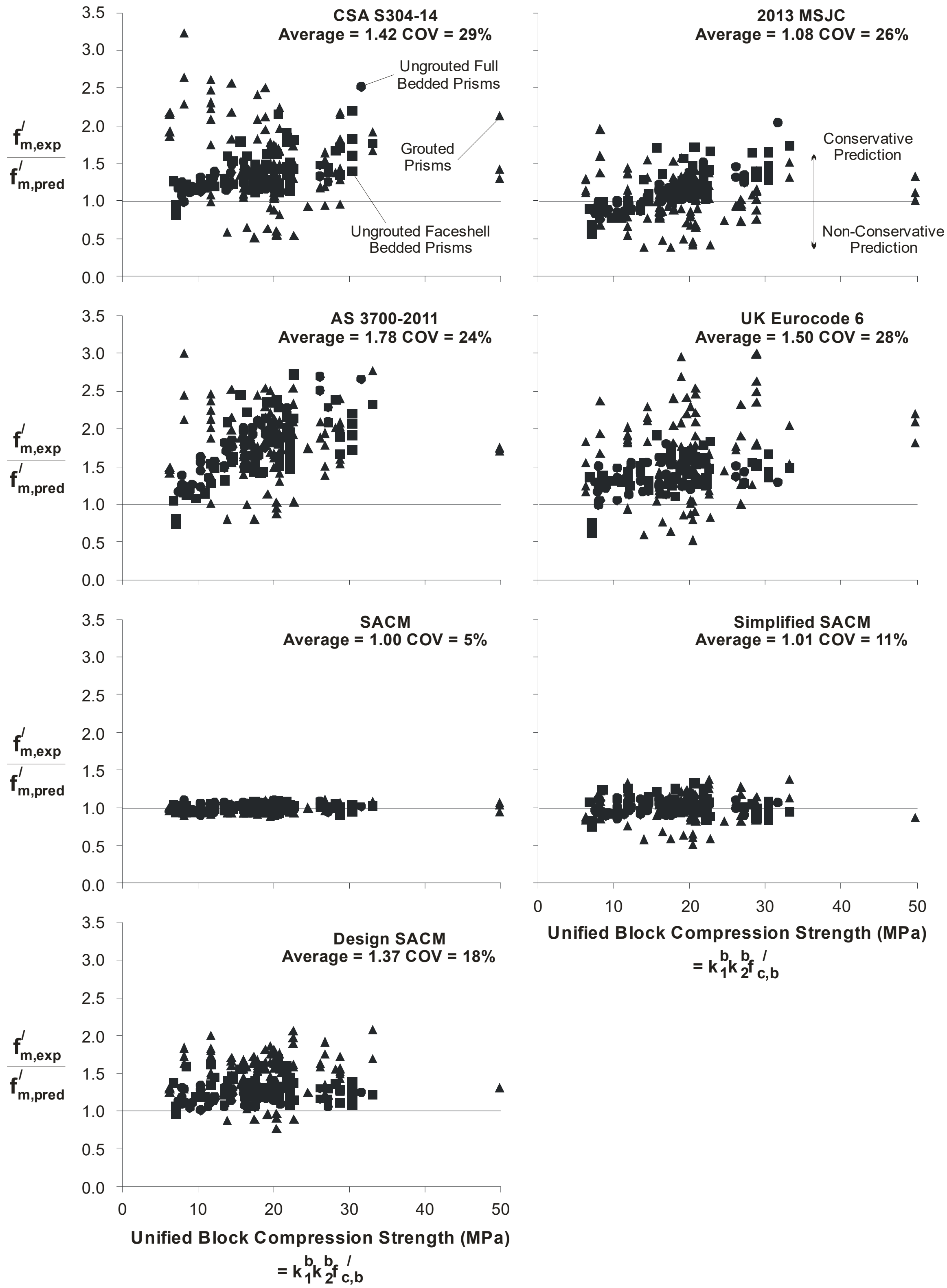

Figure 1: Comparison of Predictive Ability for the International Masonry Codes, SACM, and Proposed Formula for the Entire Database

CONCLUSION

Understanding the compression behavior of hollow concrete masonry is challenging, partly due to the number of variables that affect the behavior. Over 200 prism tests have been reported in papers during the past 90 years and this paper presents results from these tests as compared to four international design codes, a model, and a set of newly proposed equations in this paper.

The SACM summarized in this paper uses equilibrium, compatibility, and material stress-strain relationships, to produce highly accurate results. Using SACM requires an iterative approach, thus is more suited for special-purpose computer programs and not practical for "back of the envelope" calculations. While complex, the theory is accurate and the average ratio of experimental-to-predicted compression strength of the 224 average prism tests is 1.00 with a COV of only 5%.

This paper also presents a simplified version of the SACM. While simple, the method provides excellent predictions of hollow concrete masonry compression strength. The average ratio of experimental-to-predicted compression strength of the SSACM is 1.01 with a COV of 11%.

Of the international masonry design codes considered in this study the CSA S304-14, AS3700-2011, and UK Eurocode 6 codes significantly underestimate f'_m and are associated with high variation for the entire database. MSJC 2013 exhibited a low average ratio of experimental-to-predicted compression strength, but it has a high coefficient of variation and it gives non-conservative predictions for more than 35% of the entire database.

The proposed DSACE give consistent predictions for the entire database. The average ratio of experimental-to-predicted compression strength of the design equations is 1.37 with a COV of 18%. These efforts will enhance the economic competitiveness of masonry as a choice for structural engineers.

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