EFFECT OF HEIGHT-TO-THICKNESS RATIO ON COMPRESSIVE STRENGTH OF HOLLOW CONCRETE MASONRY

S. Das[1], J. Liu[2], M. El Sayed [3] and G. Sturgeon[4]
[1,2,3] Department of Civil and Environmental Engineering, University of Windsor, Windsor, ON, N9B 3P4, Canada, sdas@uwindsor.ca
[4] Technical Services Engineer, Canadian Concrete Masonry Producers Association, Toronto, ON, M5M 3X0, Canada, bbstek@telus.net

ABSTRACT

A prism or prism specimen is a small segment of masonry intended to be representative of a larger masonry member, such as a wall. To determine masonry prism compressive strength, prisms are tested to failure by applying a monotonically increasing axisymmetric axial compression load. Multiplying the resulting prism compressive strengths by an appropriate "correction factor" to account for prism height and thickness establishes the specified compressive strength of the masonry. This strength is then used for designing masonry members having markedly similar materials and construction. Canadian standard CSA S304.1-04 suggests using prisms with a height-to-thickness ratio of five for determining the specified compressive strength, without the need for correction. A tall test-frame is required for testing such tall prisms. For convenience and economy, many labs prefer to use a prism with a smaller height-to-thickness ratio, preferably in the range of two (2) to three (3). It is generally believed that the height-to-thickness ratio has a significant effect on the apparent compressive strength of masonry prisms. Accordingly, for prisms with a height-to-thickness ratio less than five (5), S304.1-04 requires that the strength of an individual prism specimen be multiplied by a height-to-thickness correction factor (provided in Table D.1, S304.1-04), which is essentially a strength reduction factor, before calculating the specified compressive strength of the masonry used in design. However, Table D.1 shows that the correction factor for hollow concrete masonry construction does not change even if the height-to-thickness ratio changes in the range of five (5) to three (3). A few studies were undertaken in the past and one study found that the height-to-thickness ratio of hollow concrete masonry construction has no influence on its apparent compressive strength. Other studies have found that the compressive strength of hollow prisms indeed is influenced by the height-to-thickness ratio. Therefore, the current research project was completed to study the effect of height-to-thickness ratio on the compressive strength of hollow concrete prisms, to resolve conflicting results reported by previous research, and to verify h/t correction factors in CSA S304.1-04. The study found that the specified compressive strength of hollow prisms increases as the height-to-thickness ratio decreases. Hence, this study found that Table D.1 of CSA S304.1-04 is unconservative. This paper provides a summary of the literature review and discusses the test matrix, test method, and test results obtained from this study.

KEYWORDS: hollow concrete masonry, compressive strength, height-to-thickness ratio

INTRODUCTION

Masonry is an assembly, consisting of masonry units bonded together by mortar. In modern structural masonry construction, concrete block units are commonly used and whereas these units may be bonded together by Type S or Type N mortar, typically Type S mortar is used The specified compressive strength of concrete masonry (f'_m) is an important parameter required in structural design. One means to establish strength for design is by direct testing of a small, representative assembly of the masonry member, known as a "prism". A prism is typically 2 to 5 courses in height and one course in width, and constructed using the block units and mortar intended for the member under design. By this method, the prism is tested to failure by applying a monotonically increasing axisymmetric axial compression load. This load is applied normal to the bed face. For statistical significance, five or more prisms are usually tested to determine the specified compressive strength (f'_m).

It is believed that the height-to-thickness ratio (h/t) of the prism has an effect on its compressive strength, and that as this ratio decreases the compressive strength of concrete masonry increases. With smaller height-to-thickness ratios the end confinement effect becomes significant whereas the slenderness effect reduces.

There is no universal rule for the minimum height-to-thickness ratio required for appropriate representation of the structural behaviour of a masonry member. In Canada, (and implied by Table D.1 of S304.1-04 [1]) not less than a five-course high prism is considered suitably representative [1]. For convenience and economy, many labs use two or three-course high prisms. In the United States, common practice is to test two course high prism specimens made of half block units [2]. Testing five-course high prisms of concrete block needs a taller load frame and special handling equipment. As a result, Table D.1 in Canadian Standard CSA S304.1-04 provides strength correction factors for prisms with smaller height-to-thickness ratios. Of particular note for ungrouted hollow and semi-solid concrete block masonry, this table requires no correction in the strength for prisms (correction factor = 1.0) other than for two-course high (correction factor = 0.9). Whereas the requirements of CSA S304.1-04 are consistent with the findings by Wong and Drysdale [3], other studies found that the compressive strength of a hollow prism specimen increases as the height-to-thickness ratio decreases [4] [5] [6]. The requirements of CSA S304.1-04 are inconsistent with most research findings. Hence, the current study was undertaken to reinvestigate the effect of height-to-thickness ratio on the compressive strength of hollow concrete masonry prisms, to resolve conflicts reported by previous research, and to verify h/t correction factors reported in Table D.1 of the current Canadian masonry design standard, CSA S304.1-04 [1].

TEST SPECIMENS AND TEST METHOD

All prisms were constructed using standard 200 mm concrete block (stretcher) units compliant with CSA A165.1-04 [7], and Type S Portland-cement lime mortar manufactured in accordance with the proportion specification of CSA 179-04 [8]. All prisms were built by a qualified mason.

Typically, the prisms were constructed in running bond pattern with face shell bedding as shown in Figure 1a. [Figure 1b shows the effective cross-sectional area (shaded area) for the calculation of the prism strength, as required by CSA S304.1-04.] Additionally, two sets of hollow prisms were built and tested to study the effect of two other parameters: stack pattern and full mortar bedding. The effect of full mortar bedding was studied for academic purposes only since it is understood that full bedding is rarely used in hollow masonry construction.

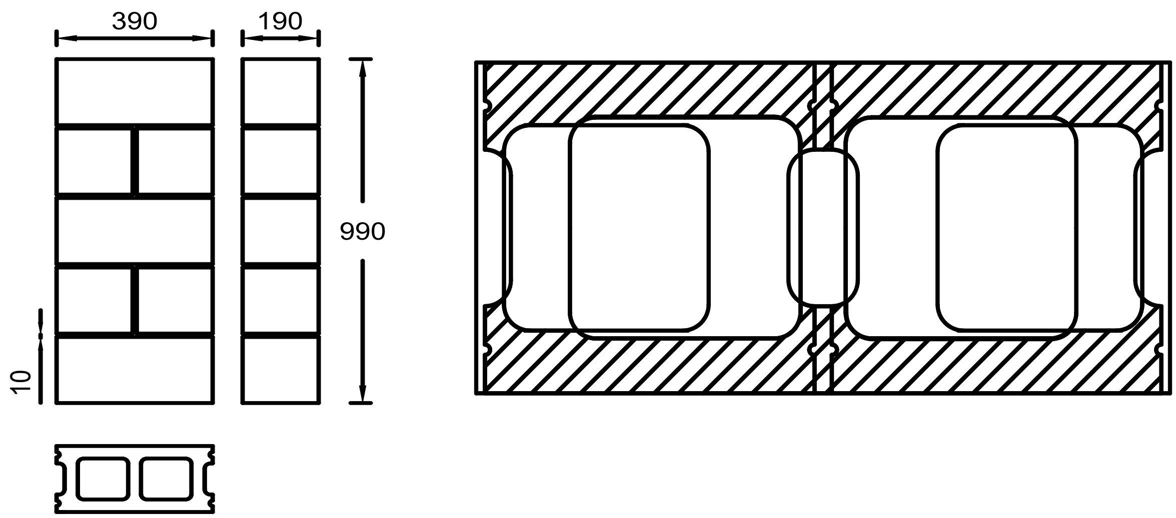
The prism test matrix is shown in Table 1, which identifies prism type, height-to-thickness ratio (h/t), bond pattern, mortar bedding, and prism nominal dimensions. The identification of a given prism type (Column 1) was chosen such that it indicates the main attributes of the prism. The first number in the ID indicates the height of the prism in terms of number of courses. The first letter (R or S) identifies the bond type: running or stack. The last two letters (FB or FS) indicate whether face shell (FS) mortar bedding or full mortar bedding (FB) was used. For example, specimen 4RFS is a four-course high (4) prism built in running bond (R) with face shell (FS) bedding. Thus, specimen 4RFB is an identical prism specimen but constructed with full mortar bedding (FB). The last column in Table 1 ("Remark") shows the reason why this particular prism type was built and tested. As is standard for concrete block masonry construction, the actual dimensions of the prisms are 10 mm less than the nominal dimensions stated in Table 1. Five identical prism specimens for each prism type were built and tested, as required for the determination of specified compressive strength under CSA S304.1-04.

Table 1: Prism matrix

Prism type	Height/thickness (h/t)	Bond type	Mortar bedding	Nominal dimensions (mm) L x W x H	Remark
2RFS	2	Running	Face shell	400 x 200 x 400	To study effect of h/t
3RFS	3	Running	Face shell	400 x 200 x 600	
4RFS	4	Running	Face shell	400 x 200 × 800	
5RFS	5	Running	Face shell	400 x 200 x 1000	
4RFB	4	Running	Full	400 x 200 x 800	To study effect of full mortar bedding
2SFS	2	Stack	Face shell	400 x 200 x 400	To study effect of stack pattern

In addition to the prism testing, five (full) concrete block units were tested in compression in accordance with CSA A165.1-04 [7] to determine the strength of block units. The actual dimensions of the standard concrete block units used in the prism construction were 390 mm long × 190 mm wide ×190 mm high (and hence, the nominal dimensions are 400 mm × 200 mm × 200 mm). The specified compressive strength of block units, calculated in accordance with CSA S304.1-04, was found to be 28 MPa with a C.O.V. of 2.1%. The average 28-day compressive strength of the Type S mortar, tested in accordance with CSA A179-04 [8], was 21 MPa with a C.O.V of 3.3%.

All the prisms were cured in the lab (room temperature) for a minimum of 28 days. The prisms were covered with a plastic sheet with water buckets placed underneath to introduce and maintain a humid environment. The ends of each prism specimen were capped after two weeks of their construction. Hard capping material (hrdrostone) was used to cap 75 mm steel plates positioned at the top and base of each prism (Figure 2a).



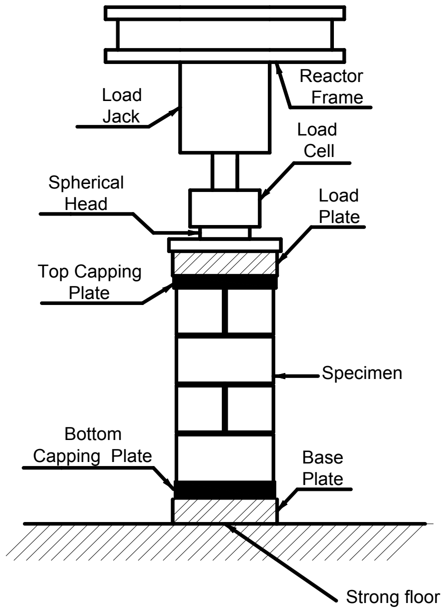
(a): Running bond construction (b): Face shell mortar bedding (shaded area)

Figure 1: Running bond construction and face shell bedding area calculation

Schematic test setup is shown in Figure 2a and a photo of the test setup is shown in Figure 2b. The capped prism specimens were placed between top and bottom loading plates which were 100 mm thick steel plates. A 3000 kN capacity actuator was used for loading. A swivel head was placed in between the load cell of the loading actuator and the top loading plate to ensure the load was vertical and applied concentrically. The test was conducted in displacement control. The load was applied and increased slowly as required by CSA S304.1-04. The load and displacement data were acquired through the loading actuator's load cell and LVDT. Each specimen was tested to its complete destruction, with peak load recorded.

TEST RESULTS AND DISCUSSION

Average and specified compressive strength of all the prism types are stated in Table 2. In determining the effective area of prisms with face shell (FS) bedding, one course of block was placed over the lower course and the overlay area (shaded area in Figure 1b) was calculated with the help of AUTOCAD yielding an effective area of 27590 mm^2. Similarly, the effective area of full mortar bedded area for running bond pattern was also calculated. It was found that the effective area of full bedded prism and face shell bedded prism with running bond differed little. However, the effective area of stack bond prisms (2SFS) was found to be 24510 mm^2 which is about 11% less than the other prisms. In accordance with CSA S304.1-04, the specified compressive strength must be calculated based on the test results of a minimum five specimens having a C.O.V. less than 15%. Hence, five identical specimens of each prism type were built and tested. The largest C.O.V was found to be 13.5%, this being prism type 2SFS as shown in Table 2. All prism specimens were tested between the 28th and 30th day after building.



(a): Schematic of test setup

(b): Photo of test setup

Figure 2: Test setup

Table 2: Prism compressive strength

Prism type	h/t	Bond type	Mortar bedding	Strength (MPa)		C.O.V (%)
				Average (f_{av})	Specified (f'_m)	
2RFS	2	Running	Face shell	27.8	24.8	6.6
3RFS	3	Running	Face shell	25.1	24.3	1.9
4RFS	4	Running	Face shell	22.5	19.8	7.5
5RFS	5	Running	Face shell	21.4	18.0	9.7
4RFB	4	Running	Full	24.1	23.1	2.5
2SFS	2	Stack	Face shell	28.6	22.3	13.5

Effect of h/t

Table 3 shows the correction factors for hollow concrete prism for various height-to-thickness ratios (h/t) obtained from this study, using the specified compressive strength calculated from the prism sets built with running bond and face shell bedding. The prism with h/t of five (five-course high) is considered as the reference value as identified in CSA S304.1-04 [1]. In Table 3, the required correction factors from the Canadian standard CSA S304.1-04 [1] and the American Standard ASTM C1314 (2012) are also stated. It should be noted that ASTM C1314 [2] provides only one set of correction factors for both hollow and grouted prisms. In addition, ASTM C1314 uses h/t of two (2) as the reference value for calculating the correction factors. Hence, in Table 3, ASTM correction factors are shown recalculated using a reference value for h/t of five. Table 3 shows that the current requirements under CSA S304.1-04 are unconservative when compared with the correction factors obtained from this study. Work by Khalaf [4] studied the effect of various parameters on the compressive strength of hollow and grouted prisms of three and six courses high. This study found that the reduction in strength of hollow prisms is 30% when height-to-thickness ratio changes from three to six. Hence, Khalf's findings agree well with the present study. The requirements in Table D.1 in CSA S304.1-04 are seen to be unsuitable given the results of this study and of other studies, and in contrast to the correction factors stated in the U.S. standard. The results of this study support a need to change the correction factors of Table D.1 in CSA S304.1-04 to better reflect the apparent increase in compressive strength as hollow prism's height-to-thickness ratio decreases.

Table 3: Correction factors for hollow concrete block masonry as function of h/t

h/t	Correction factors		
	Test data	CSA S304.1	ASTM C1314
2	0.73	0.9	0.82
3	0.74	1.00	0.88
4	0.91	1.00	0.94
5	1.00	1.00	1.00

Effect of Mortar Bedding Type

By comparing the test results of the two mortar bedding types (4RFS vs. 4RFB in Table 2) it is seen that the average compressive strength (f_{av}) for prisms with full bedding (24.1 MPa) is about 7% higher than the average compressive strength for prisms with face shell bedding (22.5 MPa). The specified compressive strength for prism (f'_m) built with full mortar bedding (23.1 MPa) is somewhat larger (about 14%) than that of prism built with face shell bedding (19.8 MPa). The C.O.V. (7.5%) for prism set with face shell bedding (4RFS) is much higher than the C.O.V. (2.5%) for prisms set with full mortar bedding. As a result, the difference in specified compressive strength between these two sets of prisms (4RFS vs. 4RFB in Table 2) becomes larger than the difference between their average compressive strength. Hence, it can be concluded that the effect of mortar bedding type on compressive strength is not significant. The independent sample t-test was used to assess the significance of this strength difference. The null hypothesis was accepted ($P=0.089>0.05$) and thus, in combination with the limited test data, it should be concluded that the strength difference between full bedding and face shell bedding is statistically insignificant.

Effect of Bond Type

By comparing the test results of two bond types (2RFS vs. 2SFS in Table 2) the average compressive strength (f_{av}) for prism with stack pattern (28.6 MPa) was found to be 2.8% higher than that of a prism with running bond (27.8 MPa). When considering the average compressive strength, it can be concluded that the bond type has no significant effect on prism strength. However, the trend reverses if the specified compressive strength (f'_m) is considered. The specified compressive strength (f'_m) for prism with stack bond (22.3 MPa) was found to be 10% lower than that of a prism with running bond (24.8 MPa). The trend in these two strengths reverses because the C.O.V for stack bond prism set (2SFS) is relatively high (13.5%). Given this reversal, that strength difference is minor, and considering the limited test data, it should be concluded that bond type has no considerable effect on the specified compressive strength. Null hypothesis was conducted to determine if the effect of bond type on the compressive strength is significant. The null hypothesis was accepted ($P=0.713>0.05$) and hence, shows that the difference in two compressive strengths obtained from these two prism types is statistically insignificant.

Failure Modes

Three to five-course high prisms failed in classical tensile splitting. Vertical cracks initiated on the web, propagated vertically as the load increased, and gradually extended through the entire height of the block unit and into the adjacent block units (Figure 3a), followed by sudden failure. The same cracking pattern and failure mode were observed in prism specimens built with both face shell bedding and full bedding.

The prism with h/t of two (two-course high prism) failed in a different mode. Like prisms with other h/t values, vertical web cracks initiated however, they propagated little. Rather, the top course slid against the bottom course through the mortar joint (Figure 3b). This was observed in both the stack pattern and running bond prisms of two-course high. Hence, this study found that two-course high prisms do not fail in the same manner as other (higher) prisms.

(a): Web crack formation just before failure (b): Sliding shear conical failure mode

Figure 3: Two different failure modes found in this study

CONCLUSIONS

The following conclusions are made based on the test data obtained from the hollow concrete masonry prisms tested in this study.

1. As prism height-to-thickness ratio decreases, the prism compressive strength increases. This observation is consistent with most previous research.
2. The correction factors stated in Table D.1 of the Canadian Standard, CSA S304.1-04 should be changed to better reflect the apparent increase in hollow prism's compressive strength as prism's height-to-thickness ratio decreases. The stated values in S304.1-04 are unconservative.
3. Strength difference between hollow prisms built with full mortar bedding vs. face shell bedding is statistically insignificant.
4. The effect of bond pattern, stack vs. running, on the compressive strength of two course high hollow prisms is also statistically insignificant.

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