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RÉSUMÉ

Des essais de compression axiale ont été effectués sur des murets et des prismes constitués de quatre types d'éléments de maçonnerie : brique d'argile comprimée, brique d'argile extrudée, bloc d'argile extrudé creux et bloc de béton creux. Les essais avaient pour but de fournir des informations sur la résistance à la compression et le module de compression des échantillons de petite taille (prismes) et de grande taille (murs), et de permettre d'effectuer un contrôle ponctuel des valeurs contenues dans les tableaux et relatives à la résistance à la compression des éléments de maçonnerie. Les essais confirment que des prismes de maçonnerie peuvent être utilisés pour déterminer la valeur de base de résistance à la compression si les méthodes d'essai sont convenablement suivies. D'autres recherches seraient nécessaires en ce qui concerne l'effet de l'humidité sur la résistance des blocs de béton et la résistance des blocs alvéolaires liés au mortier et chargés sur la face extérieure (charges excentrées).

AXIAL COMPRESSION TESTS ON MASONRY WALLS AND PRISMS

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ABSTRACT

Short walls and prisms have been tested under axial compressive load using four types of masonry units: a pressed clay brick, an extruded clay brick, an extruded hollow clay block, and a hollow concrete block. The tests were designed to provide information on compressive strength and compressive modulus of both small (prisms) and large (walls) specimens and to act as a spot check on tabular values relating masonry to unit compressive strength. They confirm that masonry prisms may be used for determining basic compressive strength if proper test procedures are followed. Areas needing further investigation include the effect of moisture on the strength of concrete blocks and the strength of eccentrically loaded face-shell mortar-bedded hollow blockwork.

AXIAL COMPRESSION TESTS ON MASONRY WALLS AND PRISMS

A.H.P. Maurenbrecher

INTRODUCTION

Tests on short walls and prisms have been carried out using two types of clay brick, a concrete block, and a clay block. The objectives were to provide information on the compressive strength and compressive modulus of small (prisms) and large (walls) specimens and to act as a spot check on tabular values in the Canadian masonry design standard relating masonry to unit compressive strength. It was hoped, in addition, that the tests would provide a better understanding of test procedures and workmanship.

Small, single-wythe walls in running bond with height-to-thickness ratios of 10 and prisms with height-to-thickness ratios varying from 2.8 to 5 were built by a mason. As a check on workmanship a technician also built prisms. The specimens were tested in axial compression to failure, with compressive strain measured on all walls and on most prisms. Many replicates were tested for variability to improve the accuracy of the results.

MATERIALS

Brick and Block

A high-strength extruded clay brick, a low-strength pressed clay brick, an autoclaved hollow concrete block, and an extruded hollow clay block were used (Fig. 1). Their properties are listed in Tables 1 and 2.

Mortar

Types S and N mortar were used for the clay and concrete masonry, respectively; proportions of the ingredients by volume were 1:0.63:4.25, 1:0.5:4.5, and 1:1:6 portland cement to hydrated lime to sand for clay block, bricks, and concrete block, respectively. The mortar was batched by weight and mixed in a standard mortar mixer. Water was added to suit the mason, who sometimes added more later on (re-tempering). The average strength of moist-cured 50-mm cubes at 7 days was 6.4 to 6.8 MPa for the S mortar and 4.1 MPa for the N mortar.[1]

CONSTRUCTION

The high-strength bricks were removed from the pallets, as received, when the walls and prisms were being built. They were dipped in water (30 s) and allowed to stand 5 to 15 min. The other units, laid dry, were randomly redistributed to ensure a uniform distribution. The mason was told to build according to his normal practice, with the proviso that the specimens should be plumb. Normal practice consisted of deeply furrowing the mortar joints for the brickwork and face-shell mortar bedding for the blockwork. When plumbing sections of the wall, the mason sometimes tapped a unit already in position. Walls were built on levelled, ground steel plates covered with polyethylene. The brickwork walls and prisms were kept level and plumb using a level. A course rod was provided. The blockwork walls were built to a line. Half units, needed at the ends of every second course, were cut using a chisel for high-strength bricks, but the other units were cut by saw.

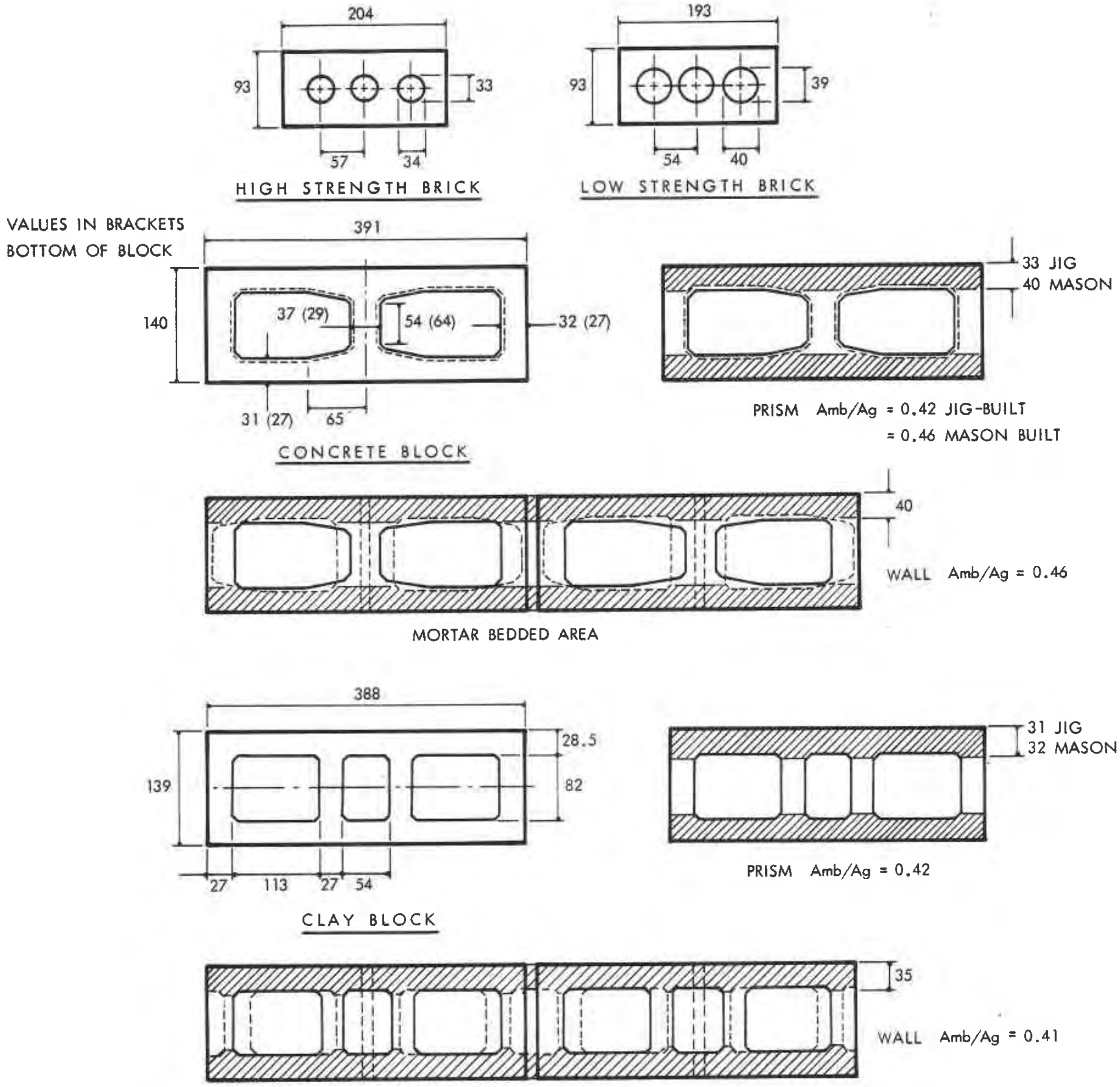


Figure 1. Unit dimensions and mortar-bedded area

To make the walls more representative of a longer wall the half units were placed with the cut end exposed, except for the high-strength brick walls and the first six low-strength brick walls where the un-cut end was exposed. This counteracted the mason's tendency to provide a full mortar joint at the ends of the wall.

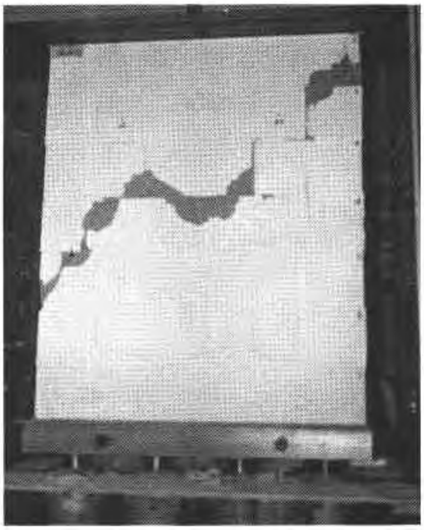
The technician built his prisms in a jig at the same time; these prisms will be designated "jig-built." Full joints were obtained by use of a metal mortar template 11 mm deep, allowing the mortar to be screeded flat before the next unit was placed. The units were tapped down to give a 10-mm thick mortar joint.

Brickwork and clay blockwork specimens were cured under polyethylene bags for seven and three days, respectively, then allowed to stand in the laboratory air until tested. Concrete masonry specimens were cured in air until tested. The walls and stretcher bond prisms were capped with Types S or N mortar. The cap was screeded flat with the help of two aluminum guides clamped to the sides of the specimen. Walls and some prisms were whitewashed for easier detection of cracks.

TEST PROCEDURE

Prisms were tested in a 1.8-MN Riehle hydraulic test machine and walls were tested in a 7-MN test frame (Fig. 2, 3). All specimens were capped top and bottom with 11-mm thick fibreboard over the whole cross-section for the brickwork and on the face-shells only for the blockwork. The loading rate for prisms where strain was not measured was set so that the test duration from half to maximum load would take approximately 1 to 2 min. Other specimens were tested at a lower rate to allow for strain measurements and crack detection. At failure the load controls were not altered. Strain was measured with 200, 300 and 600 mm handheld, mechanical gauges (Demec).

a)



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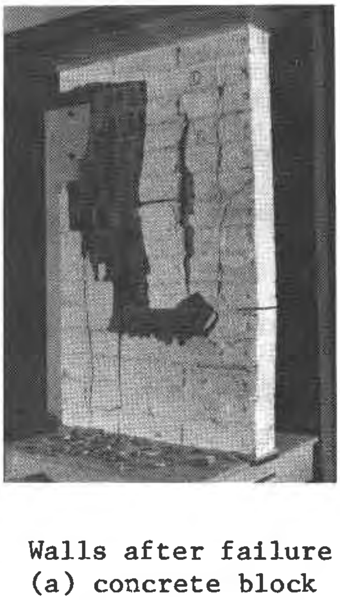


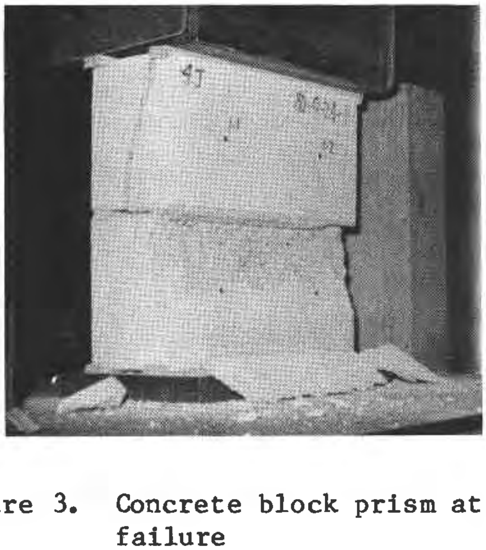


Figure 2. Walls after failure
(a) concrete block
(b) high strength brick

Figure 3. Concrete block prism at failure

TEST RESULTS

Ultimate Strength

Failure stresses (Tables 3-5) are based on gross area for brickwork and on mortar-bedded area for blockwork. The mortar-bedded area, used for hollow blockwork in the new edition of the Canadian masonry design standard,[5] is the horizontal area of mortar in full contact with blocks above and below. For concrete blockwork where mortar was laid on the face-shells only, the mortar-bedded area for the mason-built specimens was estimated to be 1.19 × area, based on the minimum face-shell width (Fig. 1). For jig-built prisms the increase was 1.09 × area. For clay blockwork with square cores and uniform face-shell widths the area was based on the actual face-shell width (the cross webs do not align in the wall (Fig. 4)). The webs in the prisms do overlap and as a result there is a small increase in mortar-bedded area, but for simplicity it has not been taken into account.

Cracking

Vertical cracks were first observed on the sides of the brickwork walls at 82% of the ultimate load and at the ends at 92% (v = 9 - 13%). The low-strength brick walls often showed minor local cracks at lower loads (usually along the top course). The concrete blockwork walls developed vertical cracks at the ends, down the centre of the webs, at 58% of ultimate (v = 9%); the clay block walls developed vertical cracks in the webs at the interface with the flanges at 70% of ultimate (60-70%). The clay block walls first cracked on the sides at 76% of ultimate (62-84%), but no cracks were observed on the concrete block walls before failure. Final failure was in both cases caused by vertical splitting within the face-shell of the block at the mortar joint (Fig. 2, 3).

The brickwork prisms built in running bond cracked at similar load levels, but with greater variation. Stack-bonded prisms are not a good indicator of crack loads since they cracked at higher loads (cracks were not monitored in the blockwork prisms).

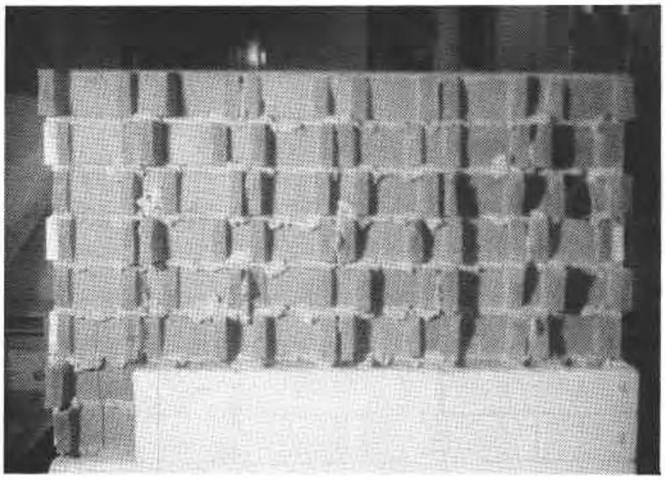
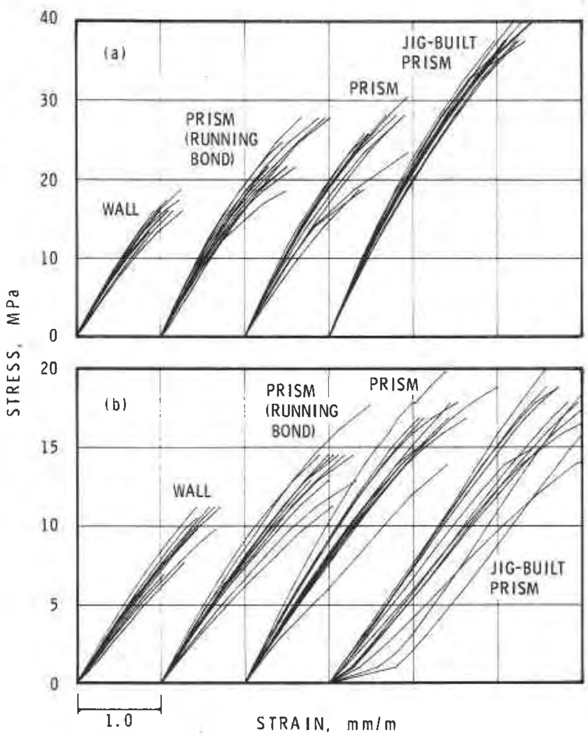


Figure 4. Non-alignment of cross-webs in hollow clay block wall

Stress-Strain Relation

The stress-strain curves for all the specimens tested are shown in Figures 5 and 6. The average initial elastic moduli are given in Tables 3 to 5. Some curves for concrete block prisms show a sudden change in slope, probably due to formation of a vertical crack in the webs of the blocks. The large initial concave portion of the curve of some jig-built, low-strength brick prisms is probably due to an incomplete bond between brick and mortar caused, in turn, by the high suction rate of some of the bricks. Jig-built prisms took longer to build, giving more time for the mortar to lose water before the next brick was placed. The strength of the prisms did not seem to be affected; the one with the largest initial concave curve failed at the second highest load. This problem did not occur with the mason-built prisms. A similar, smaller curvature may be seen with the hollow clay blockwork. In contrast, high-strength brickwork for which bricks were dipped in water beforehand shows very consistent curves. The concrete blockwork, laid with dry blocks, also shows consistent curves.



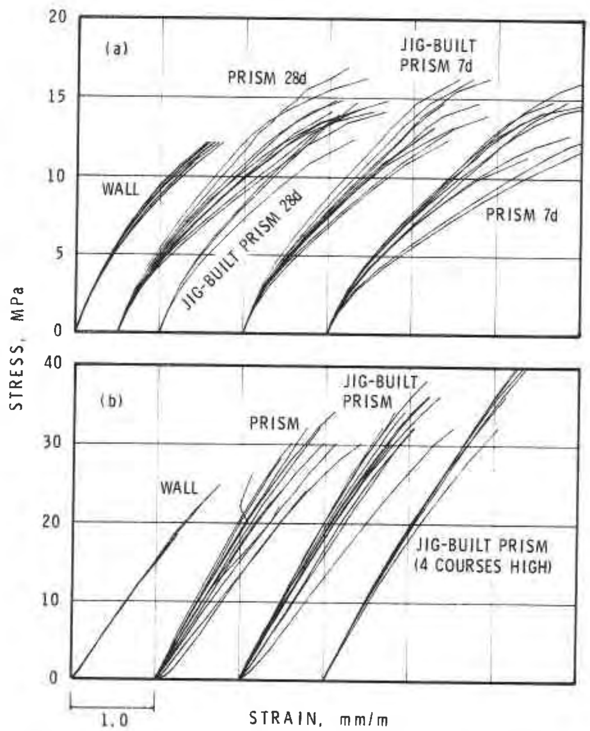


Figure 5. Stress-strain curves, brickwork; (a) high strength brick; (b) low strength brick

Figure 6. Stress-strain curves, blockwork; (a) hollow concrete block; (b) hollow clay block

DISCUSSION

Workmanship

Incomplete filling of the central part of the mortar joint due to furrowing of mortar (Fig. 7) reduced the strength of the mason-built, high-strength brick prisms to 66% of that of the jig-built prisms. This was not unexpected.[3,11] As a check on workmanship, a second mason built four-course, stack-bonded prisms singly and in rows of five to simulate wall construction. The single prisms were nearly as strong as the jig-built ones (ratio of 0.92). Prisms built in a line were weaker; the end prisms in the row were 3% weaker, while the middle three were 9% weaker, indicating that furrowing in single prisms is not so complete as in walls. Prisms should therefore be built in a line to simulate wall construction more closely. The Australian brickwork code requires this; the Canadian standard recommends it.[6,10]

The low-strength brickwork was less affected by workmanship, probably because of its large central perforations (ratio of mason-built to jig-built, 0.92). The face-shell mortar-bedded blockwork was also less affected; ratios of mason-built to jig-built were 0.96 and 0.84 for concrete and clay blockwork, respectively (a different mason was used for the concrete blockwork).

Capping

Fibreboard was used as a capping for the walls and prisms because it was simple and quick. In comparison to a hard capping such as dental plaster, fibreboard reduces frictional restraint, thereby lowering the compressive strength of masonry units; the ratio of fibreboard to that of plaster-capped units ranged from 0.82 to 0.85, except for hollow clay block where the lower ratio of 0.73 may be due to warped surfaces of some of the blocks. This reduction in frictional restraint was not significant for masonry prisms since failure is initiated at the mortar joints,[8] but there can be a reduction in strength if the prism surface is uneven. If surfaces are out of plane (say, by more than 1 mm), a hard capping should be used with or without fibreboard. The walls and running bond prisms were capped with mortar, while some hollow clay block prisms were capped with dental plaster.

Where face-shell mortar bedding is used the fibreboard should be placed on the face-shells only; otherwise, premature failure may occur.[8] As

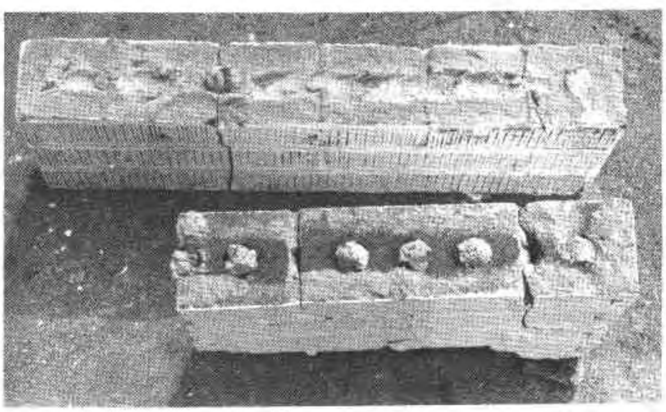


Figure 7. Furrowed mortar joint, high-strength brick wall

furrowing of the mortar could be considered equivalent to face-shell mortar bedding, the full fibreboard caps used on the brickwork prisms may have caused a reduction in strength. Checks of prisms with mortar strips on either side of the brick showed a large reduction in strength for low-strength brickwork (33%) but not for high-strength brickwork (9%). The large reduction did not occur for the mason-built prisms in the present tests, so that further study is needed to verify the effect of full fibreboard capping. Even with the possible negative effects of furrowed mortar and full fibreboard caps, the low-strength brickwork prisms gave failure stresses well in excess of the code tabular values.

Code Tabular Values

Values for compressive strength in the Canadian design standard are based on type of mortar and characteristic compressive strength, f_k, of the brick or block.[5] These values are compared with those of the prisms, which may also be used to determine compressive strength (Table 6). Prism strength is based on prisms with a height-to-thickness ratio of 5; lower ratios are permitted, but a reduction factor is applied to the compressive strength obtained.[6]

The tabular values are less than the experimental ones except for the mason-built, high-strength brick prisms. Those for brickwork are the same as those for inspected workmanship in the BIA brickwork code,[11] and assume full mortar joints with no gaps from furrowing such as occurred in the present tests. This illustrates the importance of good joints in load-bearing brickwork if tabular values are used. The low-strength brick prisms, on the other hand, gave much higher values. Large perforations in these bricks may make them less sensitive to furrowing of the mortar; as well, their highly variable strength ($v = 24\%$) means that characteristic strength is low. The high variability was not reflected in the walls and larger prisms, which had coefficients of variation ranging from 9 to 13%.

There are no tabular values for hollow clay block. The values in the brickwork table were suggested for possible use,[13] but further tests are necessary to check the behaviour of hollow block under eccentric load, where eccentricity is different top and bottom. Some preliminary prism tests using clay block gave approximately one-third of the expected failure load (sudden shear failure in the cross webs). Further tests are planned.

The masonry standard assumes that an increase in height-to-thickness ratio from 5 to 10 has no effect on the strength of axially loaded walls with flat end conditions. In the present tests, however, there was a reduction; the mean strength of the brickwork walls ($h/t = 10$) was 74 and 82% of the strength of running bond prisms. Similar reductions were found in other tests.[12] The mean strength of the concrete block wall was 91% of the prism strength, while that of the clay block wall was 92% (based on adjusted prism strength). The block walls had a more uniform strain on each side of the wall than did the brick walls. The mortar joints on one side of the brick walls had a concave finish; this may explain the greater strain difference for the two sides and, effectively, the larger eccentricity of load.

Moisture Content

The compressive strength of concrete block is sensitive to moisture content.[9] Blocks, both air-dry and soaked in water for 24 h, were tested in September before the wall tests and again in January after the tests (Table 2). The ratio of the compressive strength of soaked to air-dry blocks changed from 0.82 to 0.69 over this period. The air-dry block increased in strength by 31% compared to 11% for the soaked block. Humidity over the same period changed from 50-60% to 20-30%. This probably meant a lower moisture content in the air-dry block and a resulting increase in strength. Blocks used as control specimens should therefore be tested at the same time as walls and prisms (a requirement incorporated in the new CSA prism standard[6]). For quality control, more consistent results will be obtained if the blocks are tested in the saturated condition (required in the British standard[4]); oven drying of blocks is not practical. Moisture content has much less effect on clay units (Table 1).

Elastic Modulus

The Canadian design standard gives the elastic modulus in terms of characteristic failure stress, f_k: $E = 1000\ f_k \leqslant 20$ GPa. This agrees with values for the hollow concrete blockwork and mason-built, high-strength brickwork, but it overestimates the modulus for the other specimens where the range is 570 to 770 f_k. The Australian brickwork code uses a value of 750.[10]

CONCLUSIONS

The strength of concrete blocks can vary with age and moisture content. It is therefore important that they should be tested at the same time as walls or prisms to ensure good correlation.

Fibreboard capping makes testing easier, but it is important for the cap to have a configuration similar to that of the mortar joint. For example, if face-shell bedding is used, fibreboard should be placed only on the face-shell area. Stack-bonded prisms should be built in a line to simulate wall construction. This better reflects factors such as furrowing of the mortar joint and length of time the mortar is left exposed before the next unit is placed. Although their effect on strength has not been shown to be significant, cut ends of half units should face outward at the ends of test specimens so that the wall or prism will be more representative of a larger specimen.

The present tests confirm previous work showing that masonry prisms provide a good basis for determining compressive strength if proper test procedures are followed. Tests are normally carried out on axially loaded prisms, but they are not always a good indicator of how masonry behaves under eccentric load. A further test on an eccentrically loaded prism should be incorporated in any prism standard to be used for new types and shapes of unit. The load should be eccentric at the top (say, t/6) and axial at the bottom.

For load-bearing masonry buildings, especially those using solid masonry units, it is important that there be inspection to ensure full mortar joints if stresses are based on tabular values or on prisms with full mortar joints.

Factors that need further investigation include:
1) The effect of humidity on the strength of concrete blocks: increased humidity can reduce strength.
2) The strength of eccentrically-loaded, hollow blockwork with mortar on the face shells only: loads may be much lower than expected if the eccentricity is different top and bottom.
3) The experimental elastic modulus for masonry using clay units is lower than the recommended value in the Canadian standard: a value such as 700 f_k may be more appropriate.
4) The slenderness reduction factors for low slenderness ratios may need to be changed (walls less than storey height).

ACKNOWLEDGEMENT
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APPENDIX 2 - NOTATION

A_{fs} = face-shell area
A_g = gross area
A_{mb} = mortar-bedded area
A_n = net area
E_m = mean initial elastic modulus
f_m = mean compressive strength
f_k = characteristic compressive strength = $f_m(1 - 1.5\ v)$
h = height
n = number of replicates
t = thickness
v = coefficient of variation

APPENDIX 3 - TABLES

TABLE 1 - Brick

Property	High Strength n = 30 Mean	High Strength n = 30 v(%)	Low Strength n = 48 Mean	Low Strength n = 48 v(%)
Mass, kg	1.892	0.6	1.656	1.6
Density, kg/m^3	2086	0.4	2016	2.2
24-h water absorption, %,				
by wt	7.7	5.3	8.6	13
by vol	16.1	4.9	17.4	11
IRA, $kg/m^2/min$	1.9	17	3.16	37
Dimensions, mm, length	204	0.2	193	0.7
height	57	0.0	58	1.1
thickness	93	0.4	93	1.2
Percent solid	84	0.6	79	1.0
Compressive strength, MPa				
Dry Plaster cap	114(1)	7.8	33.4	24
Fibreboard cap	95(2)	8.5	27.4	22
Fibreboard cap	93(3)	6.5		
Wet Fibreboard cap	90(3)	8.0	-	

(1) n = 42; (2) n = 82; (3) n = 30
All tests on air-dry bricks stored in the laboratory or on wet brick stored in water for 24 h.
IRA based on net area. Compressive strength based on gross area of half bricks.[7]

TABLE 2 - Block

Property	Concrete n = 20 Mean	Concrete n = 20 v(%)	Clay n = 12 Mean	Clay n = 12 v(%)
Mass, kg	12.72	1.3	5.16	0.6
Density, kg/m^3	2129	0.9	1921	0.5
24-h water absorption, %,				
by wt	5.95	3.7	6.02	11
by vol	12.7	3.1	11.6	11
IRA, $kg/m^2/min$	-	-	0.71	20
Dimensions, mm, length	391	0.1	388	0.3
height	191	0.3	89	0.6
thickness	140	0.0	139	0.5
Percent solid	57.1	0.7	55.6	0.8
Compressive strength, MPa	(1)			
Dry Plaster cap	17.1/22.3	9.9/9.9	92.4	9.3
Fibreboard cap	14.4/18.9	11/7.3	67.4	5.9
Fibreboard cap	15.7/- (2)	9.2/-	71.9 (5)	3.6
Fibreboard cap	-/21.1 (3)	-/14		
Fibreboard cap	17.4 (4)	11		
Wet Fibreboard cap	11.8/13.1	9.5/8.1	-	-

(1) All tests on air-dry blocks stored in the laboratory or on wet blocks stored in water for 24 h. Compressive strength of whole concrete blocks and half clay blocks based on net area (percent solid).[2,7] Where two values are shown they are based on an average of ten blocks tested a month before the start of the wall tests and two months after completion.

(2) End blocks, A_n/A_g = 0.62.

(3) Face-shell area (32-mm wide fibreboard strips). A_{fs}/A_g = 0.43 (average contact area top and bottom).

(4) 40 blocks tested on the same dates as the prisms and walls.

(5) Face-shell area (29-mm wide fibreboard strips on a full, plaster-capped block), A_{fs}/A_g = 0.41.

TABLE 3 - Clay Brickwork

	Wall	Prisms					Brick
	15×3(1)	7×1.5	7×1	4×1	4×1 (7d)	7×1 (jig)	1×0.5 (plaster cap)
Low-strength brick							
f_m, MPa	12.5	15.3	17.6	17.9	14.6	19.1	33.4
v(%)	13	9	12	15	24	11	24
n	12	12	12	12	12	12	48
h/t	11.2	5.2	5.0	2.8	2.8	5.0	0.62
E_m, GPa(2)	7.76(3)	8.48	8.87	-	-	(4)	-
v(%)	11	11	13				
E_m/f_k	770	640	615				
High-strength brick							
f_m, MPa	20.3	27.1	28.9	31.4	25.2	43.5	114
v(%)	8.2	17	13	15	17	5.3	7.8
n	12	12	11	10	12	11	42
h/t	10.8	5.1	5.0	2.8	2.8	5.0	0.61
E_m, GPa(2)	18.1	20.4	20.7	-	-	24.0	-
v(%)	8.0	11	11			5.4	
E_m/f_k	1015	1010	890			600	

28 d (±1 d) test unless otherwise noted; stress based on gross area.
(1) Height × length in terms of courses and brick lengths.
(2) Linear slope of the stress-strain curve from the origin to approximately 20% of the failure stress.
(3) n = 11.
(4) Fault in stress-strain curves (Fig. 5).

TABLE 4 - Concrete Blockwork

	Wall 7×3(2)	Prisms 2 × 1				Block
	28 d	28 d		7 d		1 × 1
	(mason)	(mason)	(jig)	(mason)	(jig)	(plaster cap)
f_m, MPa (1)	13.9	15.3	16.0	14.8	15.2	20.5(3)
v (%)	4.9	6.7	12	9.2	8.8	11
n	10	20	13	20	20	40
h/t	10.1	2.8	2.8	2.8	2.8	1.4
E_m, GPa (4)	14.1	13.2	13.6	12.5	14.0	-
v (%)	2.5	8.2	-	9.7	7.0	
n	10	10	3	10	10	
E_m/f_k	1100	960	1050	980	1060	

(1) Net area for block and mortar-bedded area for walls and prisms. A_{mb}/A_g = 0.42 (jig-built) and 0.46 (mason-built).
(2) Height × length in terms of courses and block length.
(3) Assumed for plaster capping = 1.18 × 17.4 (fibreboard capping).
(4) Linear fit of the stress-strain curve from the origin to approximately 10% of the failure stress.

TABLE 5 - Clay Blockwork

	Wall	Prisms			Block
	15×3(2)	Mason	Jig		1×0.5
		5×1	5×1	4×1(6)	(Plaster cap)
f_m, MPa (1)	27.7(7)	32.7	38.9	44.9	92.4
v(%)	-	13	7.8	13	9.3
n	3	12	12	6	12
h/t	10.8	3.5	3.5	2.8	0.64
E_m, GPa (5)	15.7	19.1(3)	19.9(4)	20.7	-
v(%)	-	11	4.8	3.9	
E_m/f_k	-	725	580	570	-

(1) Net area for block and mortar-bedded area for prisms and walls. A_{mb}/A_g = 0.41. Wall tests (2 at 28 d; 1 at 56 d); 5 × 1 prism tests (8 at 28 d; 4 at 56 d); 4 × 1 prism tests (28 d).
(2) Height × thickness in terms of courses and block lengths.
(3) n = 10; two values deleted because of initial concave curve.
(4) n = 9; three values deleted because of initial concave curve.
(5) Linear fit of the stress-strain curve from the origin to approximately 20% of the failure stress.
(6) Built after the wall tests.
(7) Maximum 30.3, minimum 24.8

TABLE 6 - Tabular vs Experimental Values

	Strength, (f_k) MPa				Ratio	
	Unit	Table	Prism		Prism/Tabular	
			Mason	Jig	Mason	Jig
Brick						
High-strength	101	25(1)	20.2(2)	40.0	0.81	1.60
Low-strength	21.4	8.1	13.2	15.9	1.63	1.96
Block						
Concrete	17.1	10.1	13.8	13.1	1.37	1.30
Clay	79.5	22.8	24.3(3)	31.8(3)	1.07	1.40

(1) For brick strength ≥ 90 MPa.
(2) Running bond prisms.
(3) Includes h/t correction factor of 0.925.[6]