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Compressive Strength of Autoclaved Aerated Concrete Blockwork

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Abstract: One of the basic problems in the design of masonry structures is the calculation of the compressive strength of masonry walls. This paper discusses the various parameters which affect the compressive strength of Autoclaved Aerated concrete blockwork with particular reference to the British Standard BS 5628: Part 1 and the Draft Eurocode EC6.
Thirty six blockwork wallettes made of Autoclaved Aerated concrete blockwork were built and tested together with the corresponding properties of the units. The parameters examined were unit strength, mortar strength and size of the units. For the range of the block width (i.e. 100mm and 200mm), The strength of the wallettes were not significantly affected by the height/width ratio of the unit. Higher block strength yielded higher wallette strength, but only a slight difference in the strength of wallettes built with mortar designation (iii) and (iv) (i.e. 1:1:6 and 1:2:9 by volume, cement: lime: sand respectively) was obtained. The methods used in the British Standard BS 5628 and the Eurocode EC6 for the determination of the compressive strength of masonry are reviewed and compared with the test results.

Keywords: Compressive strength, Blockwork, Walls, Concrete

Introduction

The basis of the codes of practice, BSS628 (1978) and ISO (1988) for the design of masonry in compression is an empirical approach in which the data have been derived from tests on story-height walls. The United Kingdom has taken a full and active part in drafting test methods for masonry in both the International Standards Organization (ISO) and within the Commite Europeen de Normalization (CEN). As a result of these activities, it is clear that there is a preference in some countries to base the design approach on data from tests on small specimens.
Edgell *et al* dgell *et al.* (1990) studied the effect of the size of the specimen on the compressive strength of masonry. It was found that there was no significant difference between formats, 1.5 blocks wide x 3 courses high and 2 blocks wide x 5 courses high. As the large specimen (2 x 5 courses high) is difficult to maneuver and in some cases relatively fragile, they concluded that the 1.5 blocks wide by 3 courses high was the appropriate format wallette.

Blocks:

Type and size: Solid blocks of the mean dimensions shown in Fig. 1 were specially made by the manufacturer from Autoclaved Aerated Concrete. The mean dimensions of the blocks were measured at four positions for checking the height and at seven positions for checking the thickness according to the British Standard BS6073 (1981). The blocks were divided into six types according to the thickness and strength. A representative sample of ten blocks from each type was randomly selected from the stack and then capped for test perposes. Data on the mean dimensions of these samples is shown in Table 1.

Capping Procedure: The mortar used in the capping procedure was prepared as a 1:1 Ordinary Portland Cement : sand mix by volume. The sand used in the mortar mix had a maximum grain size of 1mm and a sieve analysis complying with the requirements of grading zone 2 of BS1200:Part 2 (1976). The quantity of water sufficient to produce a mortar having a consistence value between 6mm and 9mm in accordance with BS6073: Part 1 (1981) was determined using the dropping ball test specified in BS4551 British Standards Institution, (1990). A steel plate was covered with a 5mm thick layer of this mortar and the bed face of the block was then pressed firmly to the mortar bed so that the vertical axis of the block is perpendicular to the plane of the plate. The depth of the mortar bed was adjusted to 3mm thickness, this dimension was checked at the four corners of the block with a steel rule. After a period of at least 16 hours, the blocks were removed and opposite bed face was bedded in the same way. Three cubes were taken from each mix of the capping mortar to determine the compressive strength.

Curing of the Blocks: The ten blocks from each type were prepared and immersed in water at a temperature between 15°C and 25°C for at least 24 hours. The blocks were then removed and allowed to drain for about 30 minutes under damp sacking before capping with mortar. When the first and second faces of the blocks were capped, the blocks and mortar bed were covered with damp cloth. This cover remained for the whole period of curing until testing.

Test Procedure: When the mortar strength reached a cube strength of at least 28N/mm^2, the blocks were tested. The cube strengths of the mortar capping mixes and the age at which they were tested are presented in Table 2. The load was applied at a rate of 5 ± 0.5 N/mm^2 per minute for blocks of specified strength less than or equal to 7 N/mm^2, or 10 ± 1 N/mm^2 per minute for blocks of specified strength greater than 7 N/mm^2 as recommended by the British Standard BS6073: Part 1 (1981).

Results

The average values of the ultimate load of the ten blocks from each block type with the corresponding values of the ultimate compressive stress are shown in Table 1. The standard of deviations and coefficient of variations varied between 0.13 and 0.32 and between 2.63% and 4.80% respectively. The ultimate compressive stresses shown in Table 1 were evaluated based on the measured cross sectional area of the blocks.

Mortar

Mix Details: Two mix compositions of 1:1:6 and 1:2:9 by volume, cement:lime:sand, were designed to confirm to designations (iii) and (iv) to BS5628: Part 1(1978) respectively. The quantity of water required to achieve acceptable workability was assessed using the dropping ball test with a penetration of 11 ± 0.5mm. By using a constant source of supply throughout the test program and carefully batching each mix, the mortar properties were kept as consistent as possible from bath to bath.

Compressive Strength: Six 100mm cubes were made from each mix, three were taken at the start of the wallette construction (just after mixing, usually, in the morning), and the other in the afternoon. These were tested at 7 days and 28 days. In order to get a representative strength of the mortar mix and because of the drying operation during construction, It was necessary to test cubes taken at different times from the same mix (i.e. cubes taken in the morning and in the afternoon). The results are presented in Table 3. The compressive tests on 1:1:6 mortar yielded mean strengths between 2.93 N/mm^2 and 3.07 N/mm^2 at 7 days and between 4.1 N/mm^2 and 4.31 N/mm^2 at 28 days and tests on 1:2:9 mortar mix gave mean strengths between 1.47 N/mm^2 and 1.76 N/mm^2 and between 2.43 N/mm^2 and 2.52 N/mm^2 at 7 days and 28 days respectively.

Wallettes

Wallette specimen: Six wallettes from each block type were built having dimensions complying with the recommendations given in Table 5.2 and Fig. 5.1 of the document CEN/TC 125, N63 British Standards Institution (1990). Half of the wallettes were built with mortar designation (iii), i.e. 1:1:6 (cement:lime:sand), and the other half with mortar designation (iv), i.e. 1:2:9. All the wallettes had the same dimensions, 675mm high, 670mm long, i.e. 3 courses high (stretcher bond) and 1.5 blocks long with either 100mm or 200mm thick. Half blocks were produced by cutting the blocks. they were built on a horizontal flat surface (steel channel) having dimensions larger than the wallette specimens. Fig. 2 shows wallette specimen, dimensions and the steel channel.

Preparation and Curing: Appropriate measures were taken to prevent the test wallettes from drying out during the first three days after construction. This was achieved by covering the wallettes with polythene sheets for at least the first 3 days. Thereafter, the cover was removed and the wallettes left uncovered in a laboratory temperature of 20 ± 5° C and relative humidity of 60 ± 10% until tested when they were in an air-dried condition.

The load distribution faces of the wallettes were flat and parallel to one another and at right angles to the main axis of the wallette. This was achieved by using a testing machine provided by steel plates at the top and bottom. A polythene bag filled with building plaster was placed at the top of the specimen in the testing machine. The top platen of the testing machine was then lowered and allowed to rest under its own weight on the building plaster. The wallette was then tested after a few hours (3 or 4 hours) by which time the plaster had set to give a crushing strength in excess of the masonry blockwork strength.

All the wallettes were tested at an age of 28 days or 29 days when a certain specified mortar strength was reached for the appropriate class (iii) or (iv), determined from the mortar cubes at the age at which the wallettes were tested.

Test Procedure: The wallette was placed in the testing machine with the load application faces in full contact with the platens of the machine. A wallette ready for test is shown in Fig. 3. The load was increased steadily so that failure was reached after 10 to 20 minutes. The maximum load, the length of time from the start of loading until the maximum load was achieved and the loaded area were recorded.

Results

The mode of failure obtained for all wallettes involved cracking through the blocks and mortar joints which developed very rapidly just before failure. A typical example of a wallette after failure is shown in Fig. 4. The results for the ultimate load and the corresponding stress for all wallettes are summarized in Table 4. The ultimate stresses were evaluated based on the cross sectional area of the wallettes. Each value is an average of three wallette tests. The standard of deviations and the coefficient of variations varied between 0.06 and 0.45, and between 1.93% and 15.8% respectively. The major influence is likely to be the variability of block strength and workability.

Performance of wallettes compared to codes of practice:

British Standard BS5628: Part 1

In the British Standard BS5628: Part 1(1978), the compressive strengths of brickwork and blockwork masonry are presented in the form of tables in terms of the shape and compressive strength of the units and the designation of mortar. The values given in the tables are valid for ratios of height to least horizontal dimension of the unit of 0.6, and between 2.0 and 4.0. Linear interpolation within and between the tables (for a ratio of height to least horizontal dimension between 0.6 and 2.0) is permitted. In addition, when the loaded area of a masonry wall is less than 0.2m^2, the compressive strength is multiplied by a reduction factor (0.7 + 1.5A) where A is the loaded area in m^2. This reduction factor has not been included in the analysis.

Eurocode EC6: Eurocode EC6 International Standards Organisation (1988) proposes a relationship between the characteristic compressive strength of masonry and the mean strengths of the units and the mortar as follows:

$$f_k = k \,.\, (f_b)^{\alpha} .\, (f_m)^{\beta} \qquad (1)$$

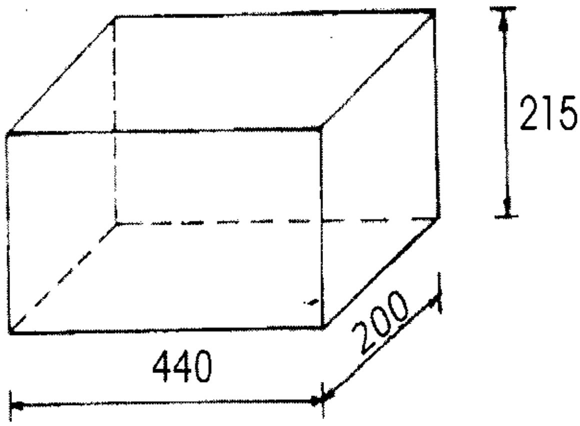
Where:

k, α and β are coefficients f_b is the mean strength of the masonry units, tested in the way they are to be laid, normalized to allow for the units being dry and factored by a coefficient to allow for the dimensions of the units. f_m is the mean compressive strength of the mortar.

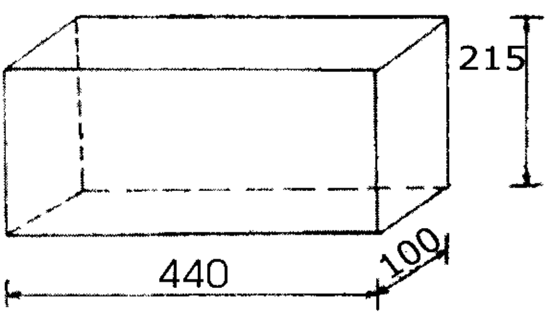
The suggested approach in the preface is given by:

$$f_k = 0.4\, \varphi \;(\delta f'_b)^{0.75} .\, (f_m)^{0.25} \qquad (2)$$

Where: φ is a factor to allow for the formula underestimating f_k when the strength of the units is below 15 N/mm^2 and the mortar is not greater than 10 N/mm^2 and given by: $\varphi = (15/f_b)^{0.33} < 1.5$, otherwise $\varphi = 1.0$ δ is a shape factor which tabulated to account for the effect of shape of the units. f'_b is the dry mean compressive strength of the unit which is 10% greater than the wet strength for clay units and 20% greater than for concrete units.



Block Type 4, 5 and 6



Block Type 1, 2 and 3

Fig. 1: Block Dimensions

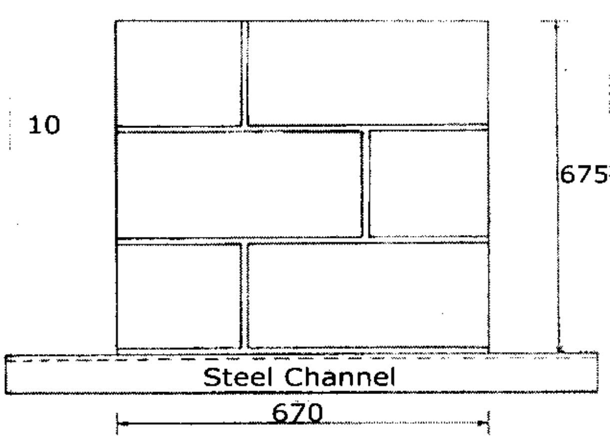


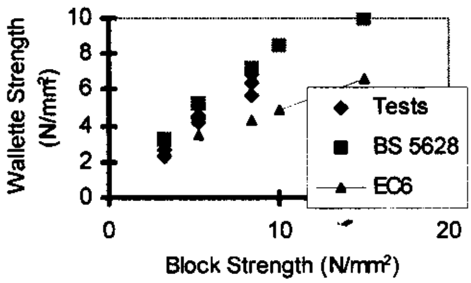
Fig. 2: Test Wallette (All dimensions are in mm)

Fig. 3: A Wallette Ready for Test

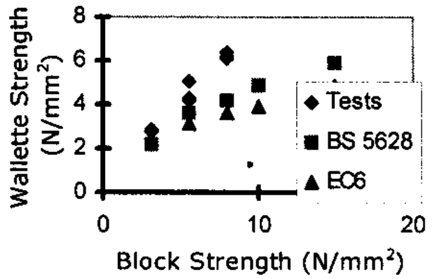
Fig. 4: Typical failure of Wallettes

Comparison with Test Results: The compressive strength of the blockwork wallette specimens calculated using the proposed relation (equation 2) in EC6 and the tabulated values given in Table 2 of the British Standard BS5628:Part 1, together with the test results are given in Table 5 and shown in Figs. 5 and 6.

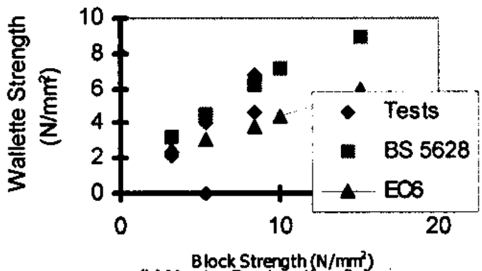
For most of the wallettes, the Eurocode EC6 seems conservative except for block type 1, whereas the British Standard BS5628 seems unconservative for Wallettes with block thickness of 100mm and conservative for wallettes with block thickness of 200mm. The ratio of the test values to the corresponding values calculated using the EC6 equation and the BS5628 tables varied between 0.87 and 1.85, and between 0.7 and 1.45 respectively. Both codes are more conservative at higher block strength but less so at lower values and both indicated that the size of masonry units had an effect on the



(a) Mortar Designation (iii)

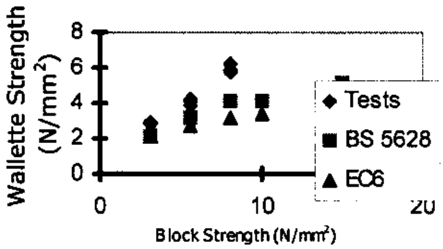


(a) Mortar Designation (iii)



(b) Mortar Designation (iv)

Fig. 5: Comparison with codes of practice (h/t=2.15)



(b) Mortar Designation (iv)

Fig. 6: Comparison with codes of practice (h/t=1.075)

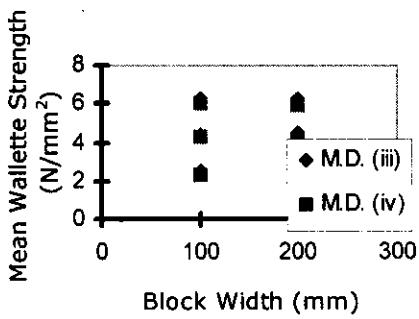


Fig. 7: Effect of width on the compressive strength

compressive strength of masonry. However, using the recommendations given in the draft European Standard CEN N63 BSI (1990), where the characteristic compressive strength is taken as the smaller of f /1.2 or f_{min} (f is the mean compressive strength of the test wallettes and f_{min} is the smallest individual value achieved in the tests), better agreement was obtained (see columns 7 and 8 in Table5). Results from the limited tests in this project on Autoclaved Aerated concrete blockwork showed that wallettes built from different sizes (100mm and 200mm wide) all exhibited approximately similar strength (Fig. 7). Egwell (1989) in his discussions of the effect of unit shape indicated that, although there seemed to be some shape effect on unit strength, small panels built from different size units of Autoclaved Aerated concrete had similar strength. Consequently, there is clearly a need to examine panels built from different block types and size units and their relationship to masonry strength.

Conclusions

From the limited test results, the following conclusions are obtained: (a) Both the British Standard BS5628:part 1 and the Eurocode EC6 are very conservative when compared with the test results for wallettes built from block 200mm thick, whereas for wallettes 100mm thick, BS5628 seems to be unconservative, while the EC6 code appears to be conservative except for block type 1. However, using the recommendations given in the draft CEN 125, N63 BSI (1990), better results for wallettes 200 mm thick were obtained.

Table 1: Dimensions and Strengths of the Blocks (Each value is an average of ten blocks)

Block Type	Length (mm)	Height (mm)	Thick-ness (mm)	Area (mm^2)	Loading Rate kN/min	Ultimate Load kN	Ultimate stress N/mm^2	S.D	C.V.
1	439	214	100	43870	220	141	3.21	0.13	4.16
2	439	214	99	43754	220	231	5.28	0.14	2.63
3	436	215	100	43600	220	366	8.38	0.32	3.80
4	436	214	199	86772	440	276	3.18	0.14	4.47
5	438	214	200	87616	440	493	5.62	0.27	4.80
6	439	214	199	87425	440	704	8.06	0.29	3.70

Note: S.D. = Standard of Deviation , C.V. = Coefficient of Variation

Table 2: Mortar strengths for capping of the blocks (mix 1:1, cement:sand, by volume)

Block Type	Side. No.	S11	S12	S13	S21	S22	S23	Dropping Ball (mm)	Age at Test (days)	Average (N/mm^2)
1	1	40.02	39.1	36.1				9.0	8	38.46
	2				37.1	35.7	37.4	8.0	7	36.43
2	1	35.2	37.1	35.4				8.0	8	36.03
	2				36.3	33.0	35.8	8.5	7	35.03
3	1	48.4	44.9	48.1				9.0	8	47.13
	2				47.2	46.2	48.5	8.0	7	47.30
4	1	47.1	48.0	46.6				9.5	8	47.23
	2				43.3	43.3	46.5	8.5	7	44.36
5	1	46.8	45.8	45.2				9.0	8	45.93
	2				47.7	46.8	45.7	9.0	7	46.73
6	1	40.0	46.0	45.9				8.5	8	44.0
	2				41.0	43.0	44.2	9.0	7	42.73

Notes: S12 Indicates mortar mix 1 and cube number 2

Table 3: Mortar strengths at 7 and 28 days

Block Type	Wallette	Mortar Designation	Mortar proportion (by volume)	Mortar Strength (N/mm2) Made in the morning C1	C2	C3	Made in the afternoon C4	C5	C6	Dropping Ball (mm)	Age at Test (days)	Average (N/mm^2)
T1,T2	All	(iii)	1:1:6	2.92	3.30	2.82				11.0	7	3.01
T3	wallettes						4.35	4.62	3.96	10.4	28	4.31
T4	All	(iii)	1:1:6	3.19			2.68			10.5	7	2.93
	wallettes	(iii)			4.08	4.22		4.15	4.31	10.0	28	4.19
T5	All			3.18			2.96			11.0	7	3.07
T6	Wallettes	(iii)	1:1:6		4.36	4.28		3.85	3.77	10.5	28	4.10
T1,T2	All			1.65	1.67	1.54		2.53	2.34	10.5	7	1.62
T3	Wallettes	(iv)	1:2:9				2.42			11.5	28	2.43
T4	All		1:2:9	1.56			1.9			11.0	7	1.47
	wallettes											
and	of T4	(iv)										
T5	and T5-W6				2.53	2.61		2.39	2.44	11.4	28	2.49
T6	All											
	wallettes			1.76							7	1.76
And	of T6	(iv)	1:2:9							11.5		
T5	and T5-W4											
	T5-W5				2.60	2.44					28	2.52

(Notes: C1 Indicates mortar cube number 1)

(b) The linear interpolation between the tables in the British Standard BS5628: Part 1 for the calculation of the compressive strength should be reconsidered.
(c) The general form of the relationship of the compressive strength of masonry as given in EC6 is widely accepted but when trying to apply it to a wide range of unit types and mortar strength, even for a single material as shown in this project. The difference between the calculated and the test values is wide. The ratio of the test results to the calculated values varied from 0.87 to 1.95. In consequences, as changing more than one of the values, k, α and β, together can lead to a formula which may provide equally reasonable lower bounds of the test results. All the possible combinations (unit type and strength, mortar strength and shape of the units)

Table 4: Wallette Details and test results

Block Type	Mortar designation	Mortar Proportion (by Vol)	Thickness (mm)	Block Strength (N/mm²)*	Age at test (days)	Ultimate load (KN)	Ultimate Stress (N/mm²)*	S.D.	C.V. %
1	(iii)	1:1:6	100	3.21	28	167.71	2.50	0.20	8.00
	(iv	1:2:9	100	3.21	29	150.37	2.25	0.20	9.00
2	(iii)	1:1:6	100	5.28	28	294.13	4.38	0.15	3.54
	(iv)	1:2:9	100	5.28	29	284.61	4.25	0.19	4.52
3	(iii)	1:1:6	100	8.38	28	419.34	6.28	0.45	7.20
	(iv)	1:2:9	100	8.38	29	400.49	6.03	0.95	15.80
4	(iii)	1:1:6	200	3.18	28	376.00	2.80	0.06	2.16
	(iv)	1:2:9	199	3.18	29	361.00	2.70	0.25	9.50
5	(iii)	1:1:6	200	5.62	28	609.00	4.53	0.39	8.67
	(iv)	1:2:9	200	5.62	29	546.00	4.06	0.14	3.50
6	(iii)	1:1:6	200	8.06	28	836.00	6.21	0.12	1.93
	(iv)	1:2:9	200	8.06	29	795.00	5.92	0.21	3.61

(Each value is an average of three wallettes)(*Indicates average of ten block)
Notes: S.D. = Standard of Deviation, C.V. = Coefficient of Variation (%)

Table 5: Comparison between test results and codes of practice

Block Type	Mortar designation	Mortar Proportion (by Vol)	Ultimate Stress (N/mm²)*	Characteristic Strength (N/mm²)*			Comparison Between test results and codes of Practice			
			Test* (1)	Doc.N63 (2)	BS5628 (3)	EC6 (4)	1/3 (5)	1/4 (6)	2/3 (7)	2/4 (8)
1	(iii)	1:1:6	2.50	2.08	3.20	2.86	0.78	0.87	0.65	0.73
	(iv	1:2:9	2.25	1.87	3.20	2.51	0.70	0.89	0.58	0.75
2	(iii)	1:1:6	4.38	3.65	5.20	3.53	0.84	1.24	0.70	1.04
	(iv)	1:2:9	4.25	3.54	4.56	3.11	0.93	1.36	0.78	1.14
3	(iii)	1:1:6	6.28	5.23	7.22	4.29	0.87	1.46	0.72	1.22
	(iv)	1:2:9	6.03	4.69	6.25	3.77	0.96	1.60	0.75	1.24
4	(iii)	1:1:6	2.80	2.33	2.21	2.34	1.26	1.19	1.05	0.99
	(iv)	1:2:9	2.70	2.25	2.10	2.06	1.28	1.31	1.07	1.09
5	(iii)	1:1:6	4.53	3.77	3.63	3.12	1.24	1.45	1.04	1.21
	(iv)	1:2:9	4.06	3.38	3.18	2.73	1.27	1.48	1.06	1.24
6	(iii)	1:1:6	6.21	5.17	4.20	3.63	1.32	1.71	1.23	1.42
	(iv)	1:2:9	5.92	4.93	4.07	3.19	1.45	1.85	1.21	1.54

Notes: * Indicates that each value is an average of 3 wallettes

need to be considered so that an acceptable formula can be reached. Another point which should be mentioned here is that for high mortar strength (>10 N/mm²) and low unit strength, EC6 predicts a compressive strength of masonry higher than the compressive strength of the unit. EC6 formula may also need to be modified so that the type of unit is in accordance with the type of mortar.
(e) The test results indicated that small panels (wallettes) built from different size units all exhibited approximately similar strength. This confirms the earlier finding on Autoclaved Aerated blockwork by Edgwell (1989).
(f) For the range of mortar strength used in this investigation, i.e. mortar designations (iii) and (iv), the strength of concrete blockwork is not significantly affected by the type of mortar.

Recommendations for further work: It would appear from the test results and the discussion that the following points should be examined, and where necessary and possible, form the subject of further research with a view to affecting such improvement:

(a) Methods for allowing for the size effect of various types of blocks.
(b) The design formula for the calculation of the compressive strength of masonry as given in EC6 should be re-examined. Different values of α, β and k may be needed for various types of blocks.
(c) Further consideration should be given to the effect of mortar strength of specimens built from low block strength on the compressive strength of masonry. Both EC6 and BS5628 over-estimate the strength of masonry at low strength.

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