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ORIGINAL ARTICLE

The scale effect on small-scale modelling of cement block masonry

Navaratnarajah Sathiparan · W. A. V. Anjalee · K. K. S. Kandage

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Abstract This paper discusses the effect of scale on the structural behaviour of cement block masonry under various loading condition. A real scale model test makes possible to obtain data similar to real structures. Financial and practical restrictions on testing real scale models, reduced scale modeling becomes popular to understand the overall behaviour of the structure. But, when the reduced scale model used for testing, the scale might have affected its mechanical properties. Therefore, it is important to understand these changes in order to draw correct conclusion on the prototype behaviour. In general, this study was aimed at understanding of the scale model behaviour of masonry by testing masonry components to determine the masonry properties, looking at a comparison of masonry behaviour at prototype and scale models. The performance of four different scale cement masonry was evaluated. Water absorption, compressive strength of cement block, and compressive, shear and flexural tensile strength of masonry prism were measured on each type of scale model. These mechanical properties are used as indicators of potential performance in masonry. Test results show that; apart from the compressive strength of masonry which not significantly influenced by the scale, all other tested properties, namely; water absorption rate, porosity, shear strength and flexural bond strength seemed to be significantly influenced by the scale.

Keywords Cement block masonry · Reduced scale · Scale effect · Material strength

1 Introduction

Tests on masonry structures become necessary due to several reasons such as;

- To understand the structural behaviour of masonry structures under extreme natural events like windstorms, floods, earthquakes etc.
- To assess and may be strengthened existing historic masonry structures

A prototype model test makes possible to obtain data similar to real structures. However, financial and practical restrictions have been a major problem in experimental studies. In structural engineering, the relatively large size is a critical issue, not only due to limitations of space and construction cost, but also due to limited capacity of loading devices [11]. A resolution to this problem reduces scale modeling of structures, in which the dimensions of a specimen are reduced by a scale proportionally. Recently, structural tests of scaled models become larger and

N. Sathiparan (✉) · W. A. V. Anjalee · K. K. S. Kandage
Department of Civil and Environmental Engineering,
Faculty of Engineering, University of Ruhuna, Hapugala,
Galle, Srilanka
e-mail: nsakthiparan@yahoo.com

larger as the overall behaviour of the system can be understood from the scaled model as well.

Many studies [18, 30] have had success using reduced-scale model masonry to simulate the prototype masonry behavior. Long et al. [18] examined the behavior of half-scale masonry model to represent full-scale masonry properties. Test results showed that, a half scale model has an excellent correlation with full scale model an also found that the half-scale model shear walls exhibited similar load–displacement responses, failure modes and cracking patterns to the full-scale walls. Vaibhav and Durgesh [30] conducted a series of reduced half-scale model brick test to verify the suitability to predict the behavior of a full-scale masonry unit and assemblages. Test results showed that, although half-scale bricks exhibited higher strength than the full-scale bricks, the behavior of masonry assemblages under various loading conditions showed reasonable agreement in strength and stiffness. Several researchers [2, 17, 19] studied and documented the experimental seismic behavior of concrete block masonry buildings through 1:2 scale shaking table tests to provide the extensive and reliable data for the understanding of their behavior.

In structural modeling, there are two types of models; complete model and simple model used in the experimental analysis of masonry buildings depend on the materials used for the model construction [29].

- Complete model: Special model materials are used for the manufacturing of model. In such cases stresses are scaled to the geometric scale. However, strain remains the same in the prototype and model. Specific weight, poison’s ratio and damping are also same for model and prototype.
- Simple model: Prototype materials are used for the construction of the model. In such case, stress and strain are similar in both prototype and model.

Theoretically obtained scale factors corresponding to the characteristic physical quantities which determine the dynamic behaviour of structures are given in Table 1. Complete modeling approach, presenting a very difficult challenge to the masonry modeling. Material properties such as modulus of elasticity, stiffness and density should also be scaled down to produce a complete model. However, since masonry is a composite material, model all of its constituents: block or brick, mortar and bond between them cannot be achieved simply [11].

When simple model is used, making the construction of the models very simple, but basic requirements of similarity of both mass distribution and working stress level should be satisfied [29]. In addition to that in a reduced scale specimen, the scale might have affected its mechanical properties. Therefore, it is important to understand these changes in order to draw correct conclusions about the prototype behaviour. In general, this study was aimed at understanding of the scale model behaviour of masonry by testing masonry components to determine the masonry properties, looking at a comparison of masonry behaviour at prototype and scale models.

2 Scale effect on masonry

Scale effect is a phenomenon related to the change, usually an increase in strength that occurs when size is reduced [13]. Before going into the mechanical behaviour of masonry at different scale models, it is necessary to first look at those factors that influence masonry behaviour at reduced scale.

The strength and stiffness properties of bricks or cement blocks are mainly determined by minute flaws or cracks in their structure. There is usually a random distribution of such flaws in various sizes, and the largest of these will be responsible for the fracture of a solid [12]. According to the Griffith concept, the less surface area there is present, the stronger the material should be since there is less chance of flaws occurring [22]. This implies that for brittle materials like clay masonry, reduced scale models could be stronger than the prototypes because of this phenomenon.

Addition to size effect, porosity, water absorption, thickness of the mortar, compaction of mortar bed by masonry units and curing time also affect the strength of masonry. Curing is important variable influencing mortar strength. Two specimens of different sizes will cure differently because the surface to volume ratio increases with decrease in specimen size. The strength of the material will vary from the surface of the specimen to its center, depending on its size since hydration may not be uniform throughout the specimen at the time of testing. Drying of the specimen will also influence the gain in strength as a result of the surface to volume ratio, which varies inversely with the specimen size [13]. Masonry unit compressive strength varies over a wide range depending on the

Table 1 Scaling factors for different quantities (adopted from [29]

Physical quantity	Modeling factor		
	Relationship	Complete model	Simple model
Length (L)	$S_L = L_P/L_M$	S_L	S_L
Strength (f)	$S_f = f_P/f_M = S_L$	S_L	1
Strain (ε)	$S_\varepsilon = \varepsilon_P/\varepsilon_M$	1	1
Specific mass (γ)	$S_\gamma = \gamma_P/\gamma_M$	1	1
Force (F)	$S_F = S_L^2 S_f$	S_L^3	S_L^2
Displacement (d)	$S_d = S_L$	S_L	S_L
Velocity (v)	$S_v = (S_\varepsilon S_f/S_\gamma)^{0.5}$	$S_L^{0.5}$	1
Acceleration (a)	$S_a = S_f/(S_L S_\gamma)$	1	$1/S_L$
Time (t)	$S_t = S_L(S_\varepsilon S_\gamma/S_f)^{0.5}$	$S_L^{0.5}$	S_L
Frequency (ω)	$S_\omega = 1/S_t$	$1/S_L^{0.5}$	$1/S_L$

porosity of the masonry unit. Generally, the more porous is the masonry unit the lower is the compressive strength.

Mohammed [21] reported about brick masonry tests on prototype and model scales with a view to comparing their behaviour and strength under various scales. Four sets of brick masonry with different scales (prototype, 1/2, 1/4, 1/6) were studied in this comparison. Test results showed that; there was no discernable scale effect on the shear, flexural, bond and diagonal tensile strength test, the compressive strength tests showed a noticeable scale effect. In the compressive strength test, it was found that the masonry strength was primarily influenced by the unit compressive strength. Generally the unit compressive strength in the smallest model scales were higher than in the larger scales, resulting in higher masonry strength in the smaller scales. Different anisotropy and different mortar types used in these tests also influence the test results.

Lourenço and Barros [20] discussed the theoretical and experimental evidence of size effect in masonry subjected to flexure. This study demonstrated the need of defining the flexural strength as a function of the width of the masonry wall. Test results showed that; the reduction of strength follows an approximately linear law, as scale increased.

The main reason that motivated the present research was the scarce experimental information of scale effect on the mechanical properties of cement block masonry. In fact, most research programs in the scope of the scale effect on masonry focused on brick masonry. Even these experimental programs are on the compression behaviour of brick masonry and some studies on the shear and flexural behaviour were reported by Mohammed [21]. But, different anisotropy and different mortar types used in these experiments made difficult to make any concrete conclusion. Therefore, this study was aimed at understanding of the scale model behaviour of cement block masonry by testing masonry components to determine the masonry properties.

3 Experimental program

The objective of this research is to study on how changes in the scale of the cement block masonry impact the mechanical performance of the masonry. In addition to prototype; half, one-fourth and one-sixth scales were investigated for this comparison. The physical dimensions of the blocks are reported in Table 2. In masonry design, it is important to understand the properties of masonry such as compressive strength, shear strength, elastic modulus and others. In order to understand the mechanical behaviour of masonry, following test were chosen; (i) compression tests strength and water absorption test on masonry block, and (ii) compressive strength, shear strength and flexural strength test on masonry prisms.

The mechanical properties of the masonry depend on material absolute particle size, the mixing curing time and rate of loading [6]. Therefore, for the preparation mortar, the cement particle and sand particles themselves should also be reduced. But it is hardly practical in laboratory work and also the

Table 2 Average dimensions of prototype and scale blocks

Scale	Dimensions (mm)			Mortar joint thickness (mm)
	Length	Width	Height	
Prototype	300	180	120	12
Half	150	90	60	6
One-fourth	75	45	30	3
One-sixth	50	30	20	2

behavior of cement: sand mix mortar with very fine particle is under study. Venkatarama Reddy and Gupta [31] reported that, for a given condition, the compressive strength of mortar decreases with increase in fineness of sand. Also, Anderson and Held [1], and Groot [9] reported that, the mortars with finer sand particles give lower bond strength than with larger sand particles [31]. This study mainly focuses on a simple model, where same material used for prototype and scale models. Given the above considerations, the same grain sizes of aggregates were used for the preparation of joint mortar.

3.1 Material used

For preparation of cement block, Ordinary Portland cement (OPC) and clean, sharp river sand were used. The sand was free from clay, loam, dirt, and any organic or chemical matters. The first consideration in the preparation of specimen is mix proportion use for cement block. Since the main aim of the research was investigated small scale modeling of masonry in developing country like Srilanka; it was thought the same mix proportion used in the sites was suitable and adequate for meeting the aims of the research. Therefore, blocks were cast with mix proportion 1:5 by volume of cement: sand.

Traditionally, cement-sand mortar and cement-lime-sand mortar were used for masonry joint mortar. Lime has been used in mortar to improve its workability and water retention properties. It was thought that both of these properties were desirable considering possible difficulties in adequately placing mortar in the bed joints with small thickness in scale models. Therefore, it was concluded that a cement-lime-sand mortar mix was most appropriate for this study. Cement-lime-sand mortar of mix 1:1:6 (cement: lime: sand) by volume was used for joint mortar. Ordinary Portland cement, commercial grade hydrated lime, and river sand were used for the preparation of joint mortars.

3.2 Tests on masonry blocks

3.2.1 Compressive strength test

Solid masonry blocks for each scale were cast and tested in the displacement controlled testing machine under axial loading. Displacement rates were 3.6, 1.8, 0.9 and 0.6 mm/min for prototype, 1/2, 1/4 and 1/6 scale blocks, respectively. The average compressive strength of each case of the blocks was determined by averaging corresponding strength measurement. Compressive strength was calculated by the Eq. (1):

$$\text{Compressive strength} = \text{Ultimate load/Area of bed face.} \tag{1}$$

3.2.2 Water absorption test

The water absorption tests were carried out to investigate the saturated water absorption rate and porosity of the masonry blocks. First, the samples were in an oven, for a period of 24 h, and the dry weight of the blocks was measured. Then, the blocks were immersed in water for a period of 24 h and wet weight of the blocks was measured. Saturated water absorption and porosity were calculated by the Eqs. (2) and (3):

$$\text{Saturated water absorption (\%)} = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \times 100 \tag{2}$$

$$\text{Porosity (\%)} = \frac{\text{Volume of voids}}{\text{Bulk volume of specimen}} \times 100. \tag{3}$$

The volume of voids was obtained from the volume of water absorbed by an oven-dry specimen. The volume of block is given by the difference in mass of the block in the air and it's mass under the submerged condition in the water.

3.2.3 *Sorptivity test*

The sorptivity can be determined by the measurement of the capillary rises the absorption rate on reasonably homogeneous material. The cement blocks were dried in oven at about 50 °C until constant mass and then to cool to the ambient temperature [10]. Then, the samples were placed in a recipient in contact with the level of water capable to submerge them about one-tenth height of the specimen. At regular intervals ($t = 0$, 10, 20, 30, 60, and 90 min), the mass of the cement block was measured after removing the surface water using a dampened tissue. Defined the sorptivity as [26];

$$S = \frac{i}{\sqrt{t}}, \tag{4}$$

where S is the sorptivity measured in mm/min$^{1/2}$. i is the water absorption and t is the elapsed time in minutes.

$$i = \frac{\Delta_w}{A\rho} \tag{5}$$

Δ_w is the change in weight (weight of specimen after 30 min capillary—oven dry weight of specimen), A is the area exposed to the water and ρ is the density of water.

These i values were plotted against the square root of time. The gradient of the line of best fit was defined as the sorptivity coefficient of cement blocks.

3.3 Tests on masonry prisms

3.3.1 *Compressive test*

The axial compression tests were performed under displacement control in order to obtain the complete stress–strain curve of the specimens, according to BS EN 1052-1 BSI [3]. The prisms consisted of five blocks and four joints of mortar as shown in the Fig. 1a. The prisms were cured for a period of 28 days under moist burlap. The testing criteria, loading displacement rate and calculation of compressive strength of the prism were similar to the compression test on the block.

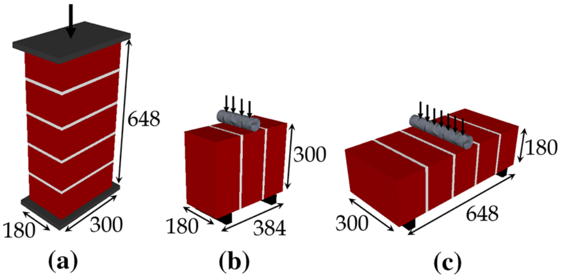


Fig. 1 Layout of prototype prisms used for **a** compression, **b** direct shear and **c** flexural bending

3.3.2 *Direct shear test*

To study the shear response; the triplet test has been adopted according to BS EN 1052-3 [5] provisions, because of its simplicity and wider acceptability amongst the researchers. The prisms consisted of three blocks and two joints of mortar as shown in the Fig. 1b. The triplet shear tests were performed while subjected to zero axial pre-compressive loads. The load was applied under displacement control at a rate 1, 0.5, 0.25 and 0.17 mm/min for prototype, 1/2, 1/4 and 1/6 scales, respectively. The direct shear strength was calculated using Eq. (6):

$$\text{Shear strength} = (P + W)/2A, \tag{6}$$

where, P is the ultimate load, W is the weight of the individual block, and A is the area of the failure surface.

3.3.3 *Three points flexural bending test*

The test prisms consisted of five blocks and four mortar joints. To determine the flexural bond strength, the masonry prisms were loaded under three pin loading method according to BS EN 1052-3 [4] as shown in Fig. 1c. An eccentric line load was uniformly applied to the middle block of the prism. The testing criteria and loading rates were similar to the direct shear test. The flexural bond strength was calculated using Eq. (7):

$$\text{Flexural bond strength} = My/I, \tag{7}$$

where M is the maximum bending moment due to ultimate load and self-weight of the prism, y is the distance from the natural axis to the bottom of the prism, and I is the second moment of area.

4 Results and discussion

One Way ANOVA analysis of all the strength results at a significance level of 5 % is summarized in Table 3. From the results, it is clear that there is a significant difference in the means of the compressive, shear and flexural bond strengths of prisms judging from the very low value of P, implying that there is a scale effect across the four scales.

4.1 Compressive strength and stiffness of individual block

The range and the mean compressive strength as well as the corresponding coefficient of variation (COV) for each scale of cement block are presented in Table 4. The maximum COV was 18.8 %, which can be regarded quite acceptable for masonry. As one would expect, the COV of the prototype and half scale block was generally lower than the smaller scale block. It can be seen that the compressive strength for the tests show no discernable size effect.

4.2 Water absorption rate and porosity

The masonry unit capacity to absorb water largely affects the masonry strength. If the brick absorbs too much water from the mortar mix, then water would be inadequate for cement hydration. On the other hand, the mechanism of bond between mortar and brick heavily relies on the brick capacity to absorb some mortar water, which carries cementitious materials dissolved in it. Therefore, a balance should be attained [28]. Masonry strength varies over a wide range, depending on the porosity of the masonry unit. Generally, the more porous is the masonry unit the lower is the strength.

Table 3 Analysis of one way ANOVA for the strength results

Test conducted	Calculated p value	Remarks
Compression—block	0.52868	Not significant
Compression—prism	0.00054	Significant
Shear—prism	0.00000	Significant
Flexural—prism	0.00008	Significant

Average water absorption rate and porosity with the various scale masonry unit are shown in Fig. 2a, b, respectively. Approximately water absorption rate and porosity of 1/4 and 1/6 scale masonry units are twice larger than prototype value. From the results, it is observed that water absorption rate and porosity value increased with reduce in scale. A possible reason for higher porosity in smaller scale is due to amount of compaction. To maintain the uniformity, compaction was given by same amount vibration on a vibration table. The less surface area there is present; there is less chance of flaws occurring. Therefore, compaction of larger scale specimen is higher when vibrating, thus the small scale will compact less and cause the higher internal porous.

4.3 Sorptivity

The results of water sorptivity of different samples are shown in Fig. 3. The initial water sorptivity coefficient at an early age is significantly higher than the subsequent water sorptivity coefficient at a later age for the same specimen. This indicates that the water absorption rate of cement block changes with time. Even though the subsequent water sorptivity coefficient showed the consistent value cross the different scales, however, the initial sorptivity coefficient increased with reduce in scale. Initial water sorption difference of cement blocks indicates different pore structures between them. More porous in smaller scale and thus had higher values of initial water sorptivity coefficient for 1/6 and 1/4 scale model than prototype model.

4.4 Compressive strength of masonry prism

The summary of the prism compressive strength across the four scales is shown in Table 5. Prism compressive strength normalized with block compressive strength is shown Fig. 4.

The scale model theory assumes that, if the mechanical properties of the masonry unit and mortar are similar then there should not be a significant strength difference between models and prototype [7, 15]. But, most small scale masonry model tests to date have shown that the models are stronger than the prototypes, as seen in [7].

Table 4 Summary of block compression test results

Scale	Compressive strength (MPa)	COV (%)	Young's modulus (MPa)	COV (%)
1	4.66	4.6	56.18	1.0
1/2	5.09	6.2	47.27	1.8
1/4	4.51	18.8	59.19	4.6
1/6	5.21	12.0	40.89	3.6

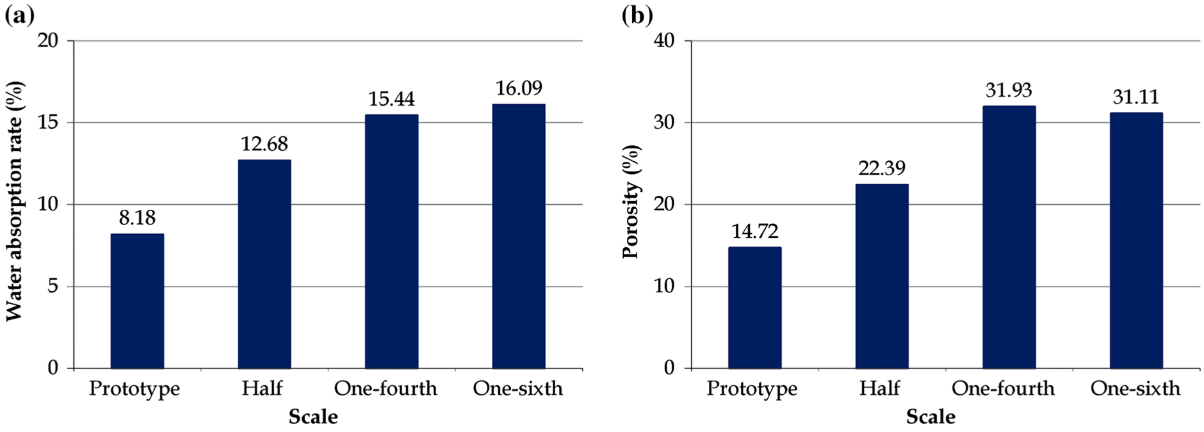
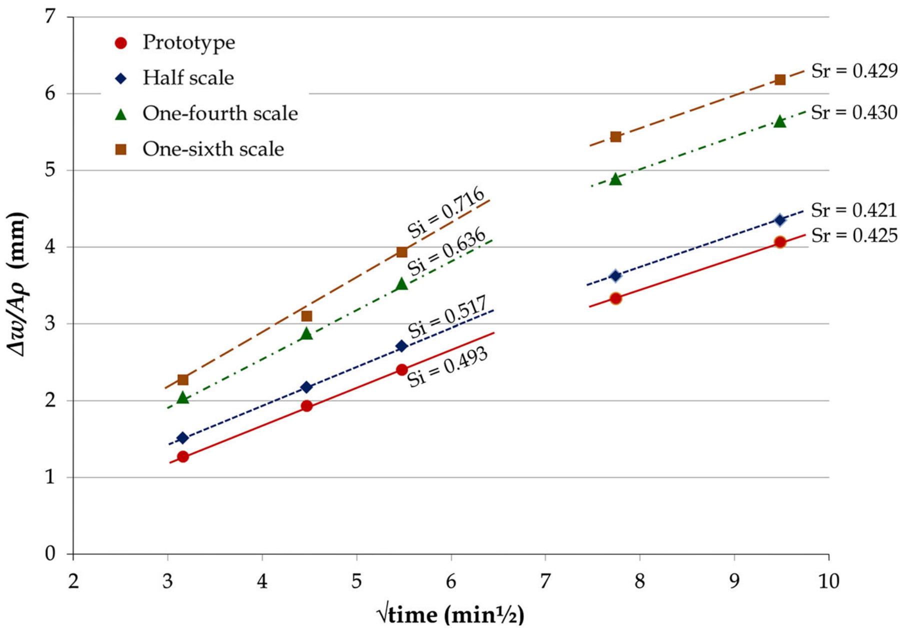


Fig. 2 Variations of **a** water absorption rate, and **b** porosity

Fig. 3 Water sorption of cement block at different scales (S_i—initial water sorptivity coefficient and S_r—subsequent water sorptivity coefficient)



From Fig. 4, which shows a summary of the normalized prism compressive strength across the four scales, it is seen from the fitted trend line in the figure that, there is an increase in the compressive strength as the scale is reduced as reported by various authors. Studies of the fracture of brittle materials

Fig. 4 Normalized compressive strength variation (prism strength/ block strength) across the four scales

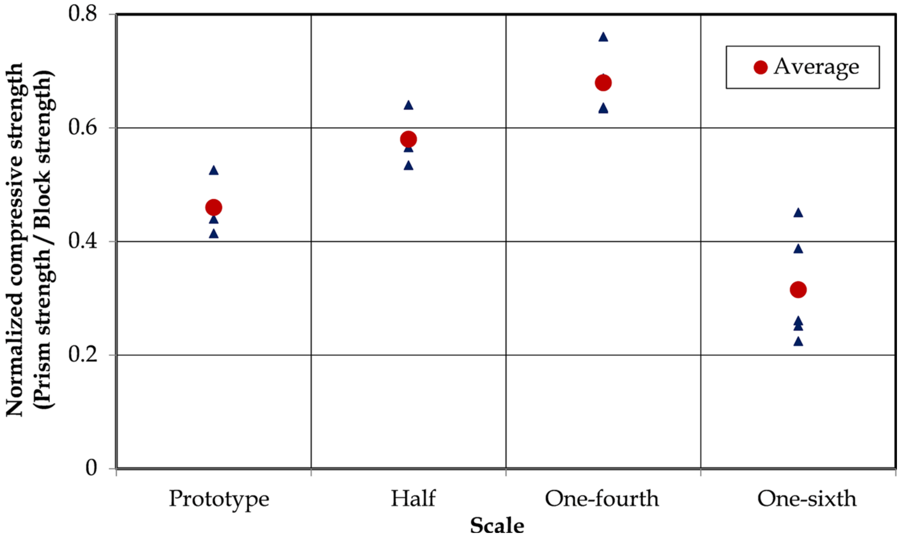


Table 5 Summary of compressive strength test results

Scale	Compressive strength (MPa)	COV (%)	Stiffness (MPa)	COV (%)
1	2.14	12.7	260.20	6.8
1/2	2.95	9.4	323.23	22.5
1/4	3.06	8.7	361.68	5.2
1/6	1.64	31.3	227.84	5.8

have shown that smaller sized specimens have higher strengths than larger specimens [25]. According to the Griffith theory of brittle fracture, the less the surface area of a material the stronger it is since there is less probability of flaws occurring [22].

Same time, the thinness of the mortar could also contribute to the masonry compression strength. Feng [8] reported that, masonry compressive strength increases as joint thickness decreases, but there exists an optimal joint thickness. When joint thickness is lower to 7–8 mm, masonry's compressive strength is decreased in turn. Nwofor and Sule [23] also reported that, the compressive strength increases with increased value of mortar thickness and maximized at 10 mm mortar thickness after which it started decreasing continuously. Considering this fact, thinness of the 1/6th scale masonry model joint may result the reduction in compressive strength of the model.

Some results from other researchers [7, 14, 16] show that reduced scale masonry models are softer than the prototype due to the amount of void percentage in small scale larger than the prototype. This shows the influence of unit size, mortar joint thickness and void in the cement block determining the strength properties of masonry at small scale.

4.5 Shear strength of masonry prism

Almost the entire prisms experienced shear bond failures at block mortar interface (Fig. 5); even though masonry prism investigated in this experimental program were constructed using lime added mortar. The researchers [24, 27] concluded that these failures mostly occurred when the block/mortar interface bond strength was lower than the mortar strength itself.

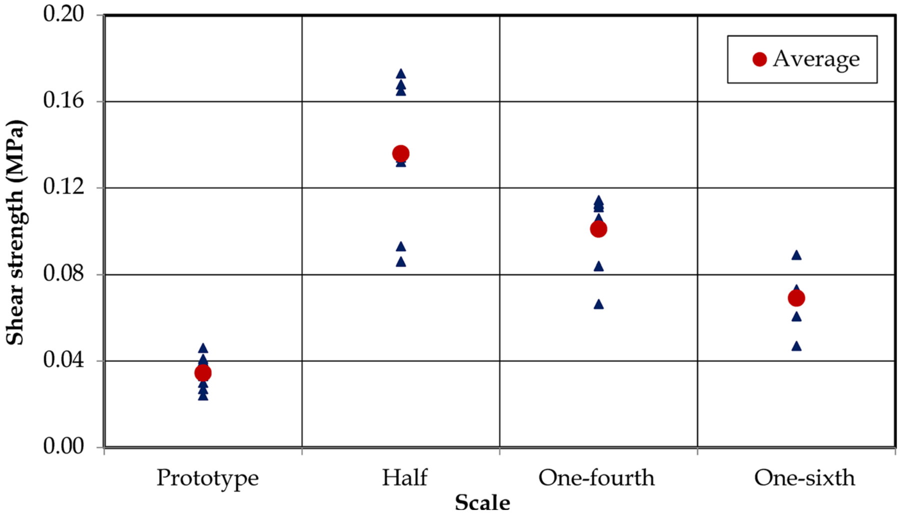
From Table 6 and Fig. 6, it can be seen that the shear strengths for the tests are varied with each other in different scale. Shear behavior between cement block and mortar influenced by the open pore structure of the brick/block surface and the mortar water retentively [27]. Smaller scale blocks provide high water retention that allows for maximum early curing of the cementitious materials and improves the

Fig. 5 Shear failure surface of cement block masonry

Table 6 Summary of shear strength of masonry prisms

Scale	Shear strength (MPa)	COV (%)	Shear modulus (MPa)	COV (%)
1	0.035	18.7	10.23	17.0
1/2	0.123	23.6	11.23	2.3
1/4	0.096	19.0	17.36	7.6
1/6	0.070	24.4	6.23	16.5

Fig. 6 Shear strength variation across the four scales



block/mortar interface bond strength to hold the masonry units together. Since this is not the case here, it may be that the open pore variation of the model and prototype block's surface may have resulted in the lack of clear trend seen in the results. Because, open pore of the block's surface finish increased with reduced scale, results adverse effect on shear strength.

The high shear strength of 0.14 MPa was on the half scale test. This is four times higher than the shear strength in the prototype test. But for smaller scale, it

Fig. 7 Flexural bending failure surface of cement block masonry

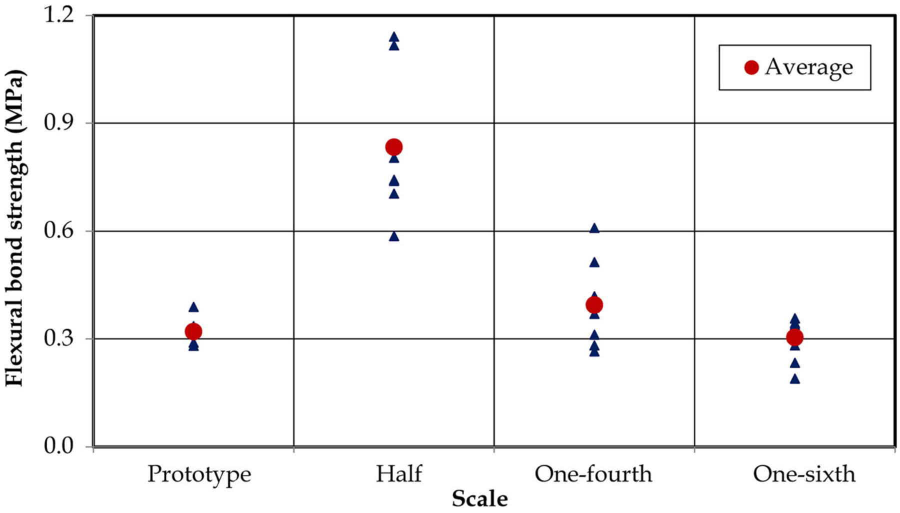


Fig. 8 Flexural bond strength variation across the four scales

is seen from the fitted trend line in the figure that generally there is a decrease in the direct shear strength as the scale is reduced.

4.6 Flexural bond strength of masonry prism

Failure of the specimen was occasioned by a single vertical crack at the mid section of the prism specimen (Fig. 7). Similar to direct shear test, almost the entire specimens experienced bond failures at block mortar interface.

Masonry flexural bending test results in the different scales are summarized in Fig. 8. The average value of the flexural strength for the prototype mortar was found to be 0.32 MPa, which is about 14 % of its compressive strength. It can be seen that the flexural bond strengths for the tests are varied with each other in different scale. The high shear strength of 0.83 MPa was on the half scale test. This is 2.5 times higher than the flexural bond strength in the prototype test. But for lower scale, it is closer to prototype strength value.

5 Conclusions

Various standard tests were considered on masonry prisms at different scales, with a view to understanding masonry behaviour across the scales considered. Masonry strength in the different scales is summarized in Fig. 9. Test results showed that;

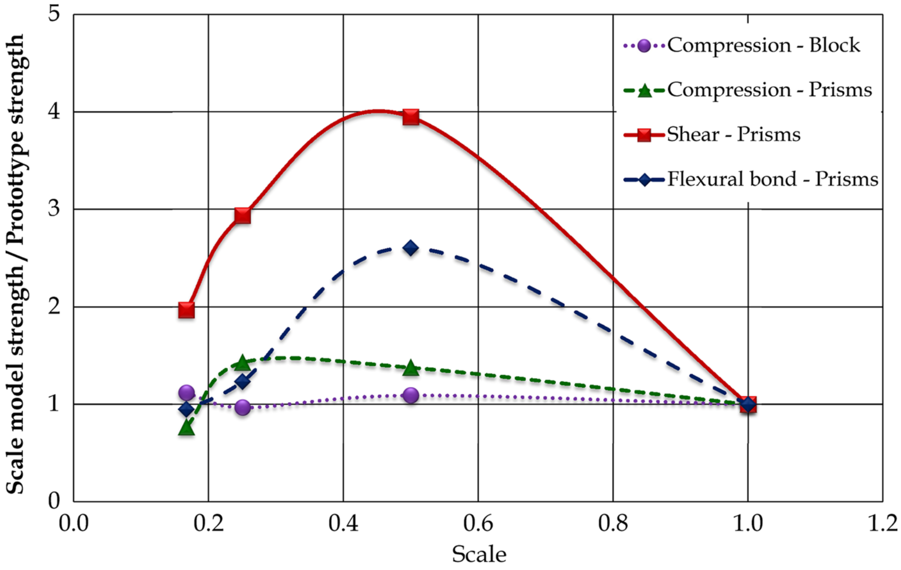


Fig. 9 Strength variation with different scales

- Unit strengths of cement block show no discernable size effect. But, the result of the compression tests on masonry prisms at different scales has shown that the strength of masonry prisms in compression was higher than the prototype in the half and one-fourth model scales, but the lesser to the prototype in the one-sixth scale.
- Decreasing the scale of a cement block contributed to increasing rates of water absorption, porosity and initial water sorption. Approximately, water absorption and porosity of 1/4 and 1/6 scale are twice larger than prototype value.
- Higher influence was observed in shear strength and flexural bond strength with variation of scale model factor. Both strength case half scale models show the higher strength compare to prototype. But for lower scale, it is seen that generally there is a decrease in the direct shear and flexural bond strength as the scale is reduced.

That apart from the compressive strength of masonry which not significantly influenced by the scale, all other tested properties, namely; water absorption rate, porosity, water sorption rate, shear strength and flexural bond strength seemed to be significantly influenced by small scale. The findings here are important for testing the properties and understanding the structural behaviour of masonry under various longing condition. The results show that the mechanical behaviour of cement block masonry varies with scales.

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