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Research Article

Prediction of Compressive Strength of Stabilized Earth Block Masonry

Kunasegaram Sajanthan, Balasingam Balagasan, and Navaratnarajah Sathiparan

Department of Civil Engineering, Faculty of Engineering, University of Jaffna, Ariviyal Nager, Killinochchi, Sri Lanka

Correspondence should be addressed to Navaratnarajah Sathiparan; sakthi@eng.jfn.ac.lk

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The present study investigates the compressive strength of cement-stabilized earth block masonry prisms with a number of masonry units and joint layer mortar combinations. The compressive strength of masonry was determined to be performed by uniaxial tests on 144 masonry prisms. The simple relationship has been identified for obtaining the compressive strength of stabilized earth block masonry from their corresponding block and mortar compressive strength. The predicted compressive strength of masonry prisms using the proposed expression is compared with 14 empirical equations and experimental data of past research available in the published literature. The compressive strength predicted by the expression proposed in the present study was found to be in good agreement with corresponding experimental data compared with other empirical equations available in the published literature.

1. Introduction

Locally available masonry units made with different materials and various manufacturing processes are being used for masonry construction. In the last couple of decades, there has been a focus on the use of cement-stabilized earth blocks as low-cost housing construction in developing countries [1]. Furthermore, in recent times, there has been an attention to the use of stabilized earth block masonry for construction of low story building due to the scarcity of river sand. Stabilized earth blocks exploit the use of local soil, whilst providing comfortable thermal and acoustic insulation properties [2]. Despite these advantages, however, the use of cement-stabilized earth blocks is restricted by limited understanding of some basic material properties and a lack of appropriate building standards. Although construction using cement stabilized earth block masonry has been practiced for sometimes, the exact behavior of this type masonry structures is yet to be understood completely.

Determining the compressive strength of masonry is a major requirement for structural design. Although the compressive behavior is well studied for brick masonry and cement block masonry, there continues to be a scarceness of the literature on the performance of stabilized earth block masonry. Also, the information available on the determination of compressive strength of cement block or brick masonry may be inadequate for the determination of stabilized earth block masonry. Masonry compressive strength can be measured experimentally; however, the tests are intense in material and labor. This leads to a search for empirical relations to predict masonry strength based on properties of masonry units (brick or block) and mortar used for joint layers, because brick, block, and mortar strength can be collected from the manufacturer or low-level laboratory testing.

The literature reveals that cement-stabilized earth block masonry generally consists of blocks, which are relatively weak and soft as compared to the mortar adopted. Cement stabilized earth blocks are found to have compressive strength in the range of 2–6 MPa and it is also observed that the compressive strength of cement mortar (1 : 6) adopted for the construction of masonry in developing countries is higher than that of the blocks [3]. The present study is aimed at predicting the empirical expression for stabilized earth block masonry compressive strength related to block and mortar compressive strength.

2. Literature Review

The compressive strength of masonry is studied by testing of prisms, wallet, or wall in the laboratory. However, testing of masonry elements to determine the compressive strength is not the usual practice. On the other hand, brick strength and mortar strength are readily available as data or can be obtained easily by performing laboratory tests. Therefore, many researchers have developed an empirical expression relating the compressive strength of the brick/block unit, mortar, and masonry [4–16].

Even though masonry compressive strength depends on masonry units (brick or block), mortar, the interfacial bond between masonry units and mortar, the moisture of the masonry unit at the time of the lazing, the thickness of mortar, the slenderness of masonry prism, workmanship, etc., it is mainly influenced by the properties of masonry units and joint mortar. Bennett et al. [8] proposed a simple equation between masonry compressive strength and brick compressive strength; with the masonry compressive strength equal to 0.3 times the brick compressive strength. However, in the majority of the other empirical expressions, the mortar strength is also considered.

When both the masonry unit and mortar strength are considered to determine the compressive strength masonry strength, the relationship can be in a form such as [17]

$$f_{\mathrm{m}} = K \times f_{\mathrm{b}}^{\alpha} \times f_{\mathrm{j}}^{\beta}, \quad (1)$$

where, K, α, and β are constant and f_{b} and f_{m} are the mean compressive strength of the brick unit and mortar, respectively.

Masonry unit is usually stronger and stiffer than the mortar and therefore the masonry compressive strength originated from the masonry unit than mortar. Therefore, most of the empirical expression, α would be a higher value than β.

Eurocode 6 [17] defines α and β values as 0.7 and 0.3, respectively. The K is the constant and it depends on the masonry unit type and masonry units—mortar characteristics. For clay brick and general purpose mortar, Eurocode 6 provides the value for K from 0.35 to 0.55. In most of the studies, both blocks/brick strength and mortar strength are considered and proposed the empirical expression in the form of equation (1). Mann [5] conducted tests on solid and hollow masonry units made of brick, concrete, lightweight concrete, and calcareous sandstone. Hendry and Malek [6] evaluated the compressive strength of stack-bonded and English-bonded brick masonry with mortar strength of 3.6 MPa. Bennett et al. [8] conducted tests on clay tile prisms in uniaxial compression with the bed joint at angles of 0°, 22.5°, 45°, 67.5°, and 90° to the horizontal. Mortar mix consisted of a one-half bag of type N masonry cement mortar thoroughly mixed with seven shovelfuls of sand is used for this experimental program. Dymiotis and Gutlederer [9] used a large dataset from published experimental data to develop a series of second-order polynomial equations. Gumaste et al. [10] proposed models to estimate the compressive strength of brick masonry in India for stack bonded and English bonded prisms. Kaushik et al. [11] conducted the tests to determine the uniaxial monotonic compressive stress-strain behavior and other characteristics of local hand molded burnt clay solid bricks, mortar, and unreinforced masonry prisms. In this study, tests were performed on 40 brick specimens manufactured by four different kilns, 27 mortar cube specimens of three different grades, and 84 specimens of masonry prisms. Christy et al. [12] derived a prediction model for determining the axial strength of brick masonry after conducting experiments on reinforced and unreinforced masonry prisms made with clay bricks and fly ash bricks. Lumantarna et al. [13] performed tests on 45 masonry prisms made with vintage clay bricks extracted from existing buildings in New Zealand. Sarhat and Sherwood [14] derived a prediction model from a large database of compressive tests on ungrouted concrete block masonry prisms and wallets from available published. A total of 248 average masonry compressive strength data points was used. Costigan et al. [15] conducted the test on fired clay brick masonry bound with hydrated lime, natural hydraulic lime, and a cement-lime mortar. Kumavat [16] carried out the tests in order to evaluate the uniaxial compressive stress-strain curves of brick units, mortar cubes, and masonry prisms constructed with mortar grade 1 : 4. For these tests, various blended mortars produced by 0, 10, 20, 30, and 40% replacement of sand with a clay brick waste were used. Based on their analytical model, each researcher proposed the empirical formulas for the prediction of the compressive strength of masonry. Summary of the empirical formulas for the estimation of masonry strength by various studies is provided in Table 1.

Although a number of empirical expressions have been proposed for compressive strength of brick masonry and cement block masonry, no study has suggested a simple empirical expression for compressive strength of stabilized earth block masonry. Understanding the behavior of stabilized earth block masonry is crucial for the use of a new construction material. At present, there is scarcely any organized data on the properties or empirical equation to predict the strength of stabilized earth block masonry. It is to be noted here that the prediction equations available on the strength of brick masonry may not be useful for understanding stabilized earth block masonry. Venkatarama Reddy and Gupta [18] and Bei and Papayianni [19] reported experimental investigation in characterizing the properties of cement-stabilized masonry using cement-soil mortars. However, the experimental data were only compared with prediction equation recommended by Eurocode. This emphasizes the requirement of conducting tests on the compressive behavior of stabilized earth block masonry and further developing a simple expression to determine the masonry compressive strength in function of the compressive strength of stabilized earth block and mortar.

3. Materials and Methods

3.1. Material Used. Ordinary Portland cement (OPC) was used for the preparation of stabilized earth blocks and joint

Table 1: Summary of the predicted equation for the estimation of masonry strength.

Reference	Masonry unit type	Block strength (MPa)	Mortar type	Mortar strength (MPa)	Equations
Eurocode 6 [17]	Clay bricks	<75	General purpose	<20 and $<2f_b$	$f_m = K\ (f_b)^{0.7}\ (f_j)^{0.3}$
Brocker [4]	Clay bricks				$f_m = 0.68\ (f_b)^{0.5}\ (f_j)^{0.33}$
Mann [5]	Concrete blocks, lime sand stones and bricks	—	—	—	$f_m = 0.83\ (f_b)^{0.66}\ (f_j)^{0.18}$
Hendry and Malek [6]	—	—	—	—	$f_m = 0.317\ (f_b)^{0.531}\ (f_j)^{0.208}$
Dayaratnam [7]	—	—	—	—	$f_m = 0.275\ (f_b)^{0.5}\ (f_j)^{0.5}$
Bennett et al. [8]	Clay bricks	2.3–35.6	Cement-sand	13.2–16.7	$f_m = 0.3 f_b$
Dymiotis and Gutlederer [9]	Clay bricks	10–174	—	0.5–49	$f_m = 0.3266 f_b\ (1-0.0027 f_b + 0.0147 f_j)$
Gumaste et al. [10]	Bricks (table mouled and wire-cut)	3–23	Cement-soil-sand	0.8–16	$f_m = 0.317\ (f_b)^{0.866}\ (f_j)^{0.134}$
Kaushik et al. [11]	Clay bricks	16.1–28.9	Cement-lime-sand	3.1–20.6	$f_m = 0.63\ (f_b)^{0.49}\ (f_j)^{0.32}$
Christy et al. [12]	Clay bricks & flyash bricks	—	Cement-sand	—	$f_m = 0.35\ (f_b)^{0.65}\ (f_j)^{0.25}$
Lumantarna et al. [13]	Vintage clay bricks	8.5–43.4	Cement-lime-sand	0.69–23.2	$f_m = 0.75\ (f_b)^{0.75}\ (f_j)^{0.31}$
Sarhat and Sherwood [14]	Hollow cement blocks	8.9–45.6	Cement-lime-sand	3.65–26.9	$f_m = 0.886\ (f_b)^{0.75}\ (f_j)^{0.18}$
Adrain et al. [15]	Clay bricks	12.75	Cement-lime-sand	0.6–13.3	$f_m = 0.56\ (f_b)^{0.53}\ (f_j)^{0.5}$
Kumavat [16]	Clay bricks	4.61–5.54	Cement-sand	24.98–28.67	$f_m = 0.69\ (f_b)^{0.6}\ (f_j)^{0.35}$

mortar. The locally available soil was used as aggregates for stabilized earth blocks. For the preparation of joint mortar, in addition to local soil, natural river sand was used. The soil was collected from closer to laboratory, which is located in Kilinochchi promises, University of Jaffna, Ariviyal Nager, Kilinochchi. River sand from quaternary sediments at Kandawalai, traditionally used in the past to manufacture cement blocks, was used in this study. Properties of the material used for this experimental program are given in Table 2.

Table 2: Physical properties of cement, sand, and soil.

Properties	Cement	River sand	Soil
Specific gravity	3.15	2.67	2.37
Bulk density (kg/m^3)	1362	1667	1348
Fineness modulus	0.67	2.95	1.09
Clay + silt (%)		1.5	45.8
Sand (%)		69.2	50.2
Gravel (%)		29.3	4.0
Liquid limit LL (%)		—	16
Plastic limit PL (%)		—	15
Plastic Index PI (%)		—	1.07

3.2. Details of Specimens

3.2.1. Blocks. Solid blocks having size $205 \times 105 \times 65\ \text{mm}^3$ were cast for the experimental program. Blocks were prepared using 1 : 4, 1 : 6, 1 : 8, and 1 : 10 cement-soil mortar by volume. For the preparation of mortar mix, ordinary Portland cement and local soil were used.

3.2.2. Mortar. For the manufacturing of the joint mortar, three kinds of binders were selected in a volume ratio based on mortar designation (ii), (iii), and (iv) according to BS EN 1996 [17]. For each mortar designation, two types of mortars, cement-river sand and cement-local soil, were used. Mortars were prepared in a mixer with a 1 : 5, 1 : 7, and 1 : 9 cement: sand or soil ratio of bulk volume.

3.2.3. Masonry Prism. Table 3 summarized the specimen dimensions and a number of specimens used for the experimental program. Hundred and forty-four masonry specimens using a combination of four different strengths stabilized earth blocks and six types of mortar (three each for cement-soil and cement-sand mix mortar) have been prepared. Prisms using different types of blocks have been cast using mortar mixes like as 1 : 5, 1 : 7, and 1 : 9 volume ratio of the cement-soil mix as well as 1 : 5, 1 : 7, and 1 : 9 volume ratio of the cement-sand mix.

For the prisms, block units $205 \times 105 \times 65\ \text{mm}^3$ in size were used and blocks are kept in normal environmental condition before preparation of specimens. Each prism consisted of three stabilized earth blocks and two 10 mm thick mortar joints. Specimens were kept in an indoor lab environment for curing up to a period of 28 days before testing.

3.3. Testing

3.3.1. Tests on Blocks. The compressive strength of the stabilized earth block was determined through displacement-controlled method, according to the procedure adopted from

Table 3: Materials used in blocks, mortar, and masonry.

Specimen	Size (mm^3)	Designation	Cement: sand/soil (by volume ratio)	Material used (kg)				No. of samples
				Cement	River sand	Soil	Water	
Blocks	$205 \times 105 \times 65$	SB1	1 : 4	1.00	—	4.73	1.10	6
		SB2	1 : 6	1.00	—	7.09	1.25	6
		SB3	1 : 8	1.00	—	9.45	1.40	6
		SB4	1 : 10	1.00	—	11.81	1.60	6
Mortar (cement-local soil)	$150 \times 150 \times 150$	MSo5	1 : 5	1.00	—	5.91	1.18	6
		MSo7	1 : 7	1.00	—	8.27	1.32	6
		MSo9	1 : 9	1.00	—	10.63	1.50	6
Mortar (cement-river sand)	$150 \times 150 \times 150$	MSa5	1 : 5	1.00	7.30	—	1.30	6
		MSa7	1 : 7	1.00	10.23	—	1.55	6
		MSa9	1 : 9	1.00	13.15	—	1.80	6
Masonry prism (with three types of local soil mortar as a joint layer)	$205 \times 105 \times 215$		4 types of blocks and 3 types of joint mortar					72 (6 each for one block type and one mortar type)
Masonry prism (with three types of river sand mortar as a joint layer)	$205 \times 105 \times 215$		4 types of blocks and 3 types of joint mortar					72 (6 each for one block type and one mortar type)

EN 772-1 [20] as shown in Figure 1(a). The applied load was increased at a rate of 2 mm/min until failure occurred. Compressive strength was calculated by

$$\text{compressive strength} = \frac{\text{ultimate load}}{\text{area of bed face}}. \tag{2}$$

The flexural strength of stabilized earth blocks was determined using three-point flexural tests in accordance with EN 1015-11 [21]. Flexural tensile strength was calculated by

$$\text{flexural tensile strength} = \frac{1.5Pl}{(bd^2)}, \tag{3}$$

where P is the load applied to the middle of the block at failure, l is the distance between supports, b and d are the width and depth of the midspan section respectively.

For the water absorption test, the stabilized earth blocks were dried in an oven at 105°C for 24 hrs. Then, the blocks were merged in water at the indoor laboratory environmental condition for 24 hrs. Oven-dry and wet state weights of the blocks were measured and recorded. By using the equation (4), the water absorption rate is determined according to ASTM C642 [22]:

$$\text{water absorption} = \frac{(W_s - W_d)}{V}, \tag{4}$$

where W_d is the weight of cement blocks in a dry condition, W_s is the weight of cement blocks in wet condition, and V is the volume of the cement block.

3.3.2. Tests on Mortar Cubes. The compressive strength of the mortar cube was evaluated according to European standards EN 1015–11 [21] as shown in Figure 1(b). The mortar cube was $150 \times 150 \times 150\,mm^3$ in size placed in the universal axial testing machine and the load was applied under displacement controlled at a rate of 2 mm/min until failure occurred. The testing criteria and strength calculation were similar to the compression test on the blocks.

3.3.3. Tests on Masonry Prisms. In order to obtain the compressive strength, compression tests were performed according to EN 1052-1 [23] as shown in Figure 1(c). The testing criteria and loading displacement rate were similar to the compression test on the blocks. The compressive strength was calculated using

$$\text{compressive strength} = \frac{\text{failure load}}{\text{area of prism bed face}}. \tag{5}$$

4. Compression Behavior

4.1. Properties of Blocks and Mortars. Density, water absorption rate, compressive strength, and flexural strength of the stabilized earth blocks have been obtained for blocks with different combinations of cement and soil fractions. Table 4 gives details of the blocks, its density, water absorption rate, and mean strength values. The results presented in Table 4 indicate that increasing the cement content in the blocks provides a density increase and water absorption rate decrease. However, all the cases, water absorption rate showed a value below the minimum that recommended by the ASTM standard for medium weight cement blocks. For the blocks produced with 17.5% of cement content, the SB1 blocks reached a mean value of 12.19 MPa at 28 days, while the blocks with 7.8% of cement content reached 4.61 MPa. All mean compressive strength values of the blocks were above the minimum stipulated (4.12 MPa) by ASTM standard C129 [24].

Table 5 gives the details of the cement-soil and cement-sand mortar, its density, water absorption rate and compressive strength. Water absorption rate lies in the range of 165–177 kg/m^3 for cement-soil mortar and 261–275 kg/m^3 for cement-sand mortar. Water absorption rate increases

(a) (b) (c)

Figure 1: Compressive test setup (a) block, (b) mortar cube, and (c) masonry prism.

Table 4: Properties of stabilized earth blocks.

Property	No of specimens tested	Block type			
		SB1	SB2	SB3	SB4
Cement content (%)	—	17.5	12.4	9.6	7.8
Water/cement ratio	—	1.10	1.25	1.40	1.60
Density (kg/m^3)	12	1974	1967	1957	1944
Dry density (kg/m^3)	12	1921	1911	1897	1877
Water absorption rate (kg/m^3)	6	164	167	173	182
Compressive strength (MPa)	6	12.19 (3.6%)	7.42 (6.3%)	5.81 (5.5%)	4.61 (5.2%)
Flexural tensile strength (MPa)	6	1.12 (6.0%)	1.04 (6.9%)	0.97 (9.6%)	0.83 (9.2%)

Note: numbers in parenthesis indicates COV values.

Table 5: Properties of cement-soil and cement-sand mortar cubes.

Mortar composition C : So : Sa	W/c ratio	Designation	Density (kg/m^3)	Water absorption rate (kg/m^3)	Compressive strength (MPa)
1 : 5 : 0	1.18	MSo5	1973	165	6.90 (4.8%)
1 : 7 : 0	1.32	MSo7	1962	170	5.32 (2.6%)
1 : 9 : 0	1.50	MSo9	1949	177	4.19 (6.0%)
1 : 0 : 5	1.30	MSa5	1846	261	4.77 (6.1%)
1 : 0 : 7	1.55	MSa7	1808	267	2.89 (3.7%)
1 : 0 : 9	1.80	MSa9	1784	275	1.64 (6.3%)

C, cement; So, local soil; Sa, river sand. Numbers in parenthesis indicates COV values.

with a decrease in cement content in the mortar and cement-soil mortar have a lower water absorption rate than cement-sand mortar. As the soil is finer than sand, the higher fine percentage in the cement-soil mortar could lead to lower surface porosity when compared to the surface porosity of cement-sand mortar. The lower water absorption value for cement-soil mortar could be attributed to low surface porosity. As expected, the compressive strength of mortar decreases with increases in soil or sand fraction of the mortar. The compressive strengths lie in the range of 4.19–6.90 MPa for cement-soil mortar and 1.64–4.77 MPa for cement-sand mortar.

4.2. Compressive Strength of Prisms. The behavior of the stabilized earth block masonry in compression was similar to that of fired clay brick and concrete block masonry. The masonry prisms were failed by splitting with vertical crack or failed by block crushing as shown in Figure 2. The failure of masonry mainly based on strain compatibility at masonry units—mortar interface [10]. If the block is stronger than mortar, the failure of masonry was initiated by the tensile splitting of the mortar in the joint and it extends to the block causing a vertical crack in the masonry. Also, if the block-mortar interface failed in shear due loss of bonds, blocks were failed in tensile splitting. On other hand, if the block was weaker than mortar, the block was failed by crushing ahead of the splitting failure.

The compressive strengths of masonry prisms are summarized in Figures 3 and 4. Results show that masonry strength increases with block strength and mortar strength

(a) (b)

Figure 2: Failure pattern of masonry prisms.

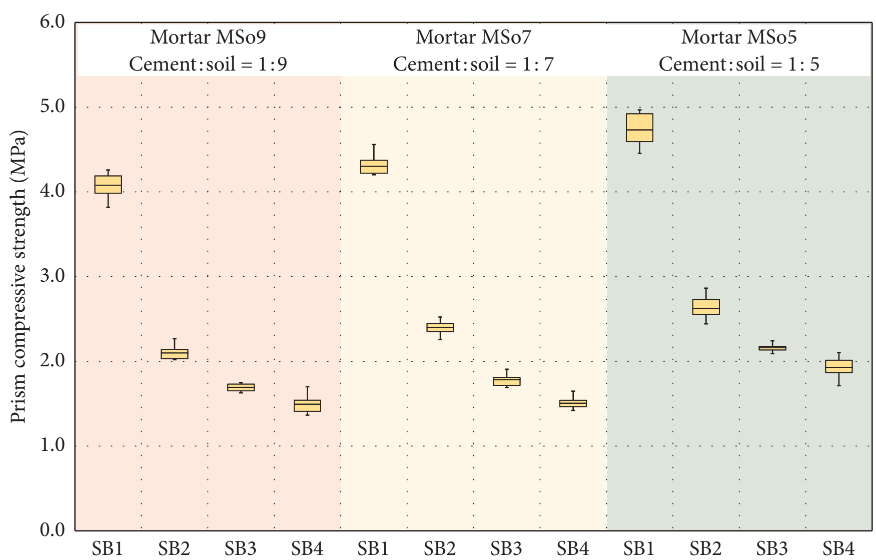

Figure 3: Compressive strength variation of masonry prisms with different blocks and cement-soil mortar combination.

for all the block types and all the mortar types. However, the increase is more prominent when the block type is changing in masonry prism. For stronger blocks (SB1 and SB2), masonry prisms with cement-soil mortar joints show greater compressive strength then prisms with cement-sand mortar joints. However, for weaker blocks (SB3 and SB4), prisms with both mortar types show closer compressive strength.

5. Estimation of Masonry Compressive Strength

The normalized compressive strength of the stabilized earth blocks (f_b), the mortars (f_j) and the masonry prisms (f_m) are included in Table 6. The normalized mean compressive strength of blocks (f_b) is determined according to EN 772-1 [20]. A shape factor is multiplied by the mean strength of the blocks (f_{uc}) as shown in equation (6) to get f_b:

$$f_b = \text{shape factor} \times f_{uc}. \quad (6)$$

The normalized mean compressive strength of masonry (f_m) is determined according to ASTM C1314 [25]. A correction factor for the height/thickness of prisms is multiplied by the mean strength of the masonry prism (f_{mc}) as shown in equation (7) to get f_m.

$$f_m = \text{correction factor} \times f_{mc}. \quad (7)$$

The empirical expression for masonry compressive strength using "least squares" regression analysis is summarized in Table 7. Due to the different aggregate mortar

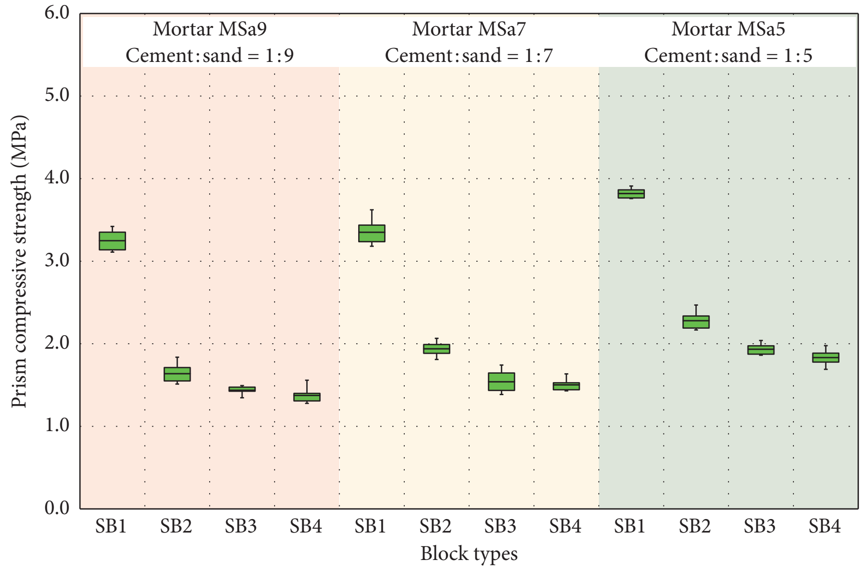

Figure 4: Compressive strength variation of masonry prisms with different blocks and cement-sand mortar combination.

Table 6: Mechanical properties of the blocks, mortars, and masonry prisms.

Block type	Block strength (f_{uc}) (MPa)	Block-normalized strength (f_b) (MPa)	Mortar mix proportion	Mortar strength (f_j) (MPa)	Masonry strength (f_m) (MPa)
SB1	12.19	9.76	1 : 9 cement-sand	1.64	3.25
			1 : 7 cement-sand	2.89	3.35
			1 : 5 cement-sand	4.77	3.82
SB2	7.42	5.94	1 : 9 cement-sand	1.64	1.64
			1 : 7 cement-sand	2.89	1.94
			1 : 5 cement-sand	4.77	2.28
SB3	5.81	4.65	1 : 9 cement-sand	1.64	1.44
			1 : 7 cement-sand	2.89	1.54
			1 : 5 cement-sand	4.77	1.93
SB4	4.61	3.69	1 : 9 cement-sand	1.64	1.37
			1 : 7 cement-sand	2.89	1.50
			1 : 5 cement-sand	4.77	1.83
SB1	12.19	9.76	1 : 9 cement-soil	4.19	4.08
			1 : 7 cement-soil	5.32	4.30
			1 : 5 cement-soil	6.90	4.73
BS2	7.42	5.94	1 : 9 cement-soil	4.19	2.10
			1 : 7 cement-soil	5.32	2.40
			1 : 5 cement-soil	6.90	2.63
SB3	5.81	4.65	1 : 9 cement-soil	4.19	1.69
			1 : 7 cement-soil	5.32	1.78
			1 : 5 cement-soil	6.90	2.16
SB4	4.61	3.69	1 : 9 cement-soil	4.19	1.49
			1 : 7 cement-soil	5.32	1.51
			1 : 5 cement-soil	6.90	1.93

used for joint mortar, further regression analysis was undertaken, treating prisms with cement-soil mortars and cement-sand mortars separately.

The fitness of the models was evaluated by means of the coefficient of determination (R^2) and standard error of estimate (σ) between the experimentally obtained values and values obtained by regression analysis as given by equations (8) and (9), respectively.

$$R^2 = 1 - \sqrt{\frac{\sum\left(f_i - f_{R_i}\right)^2}{\sum\left(f_i - f_{\text{mean}}\right)^2}}, \tag{8}$$

$$\sigma = \sqrt{\frac{\sum\left(f_i - f_{Ri}\right)^2}{n-3}}, \tag{9}$$

Table 7: Equation proposed for the estimation of stabilized earth block masonry compressive strength.

Mortar used for masonry prisms	Regression model for compressive strength	R^2	σ (MPa)
All	$f_k = 0.25 \times f_b^{1.03} \times f_m^{0.28}$	0.97	0.19
Cement-river sand	$f_k = 0.32 \times f_b^{0.93} \times f_m^{0.22}$	0.96	0.20
Cement-soil	$f_k = 0.19 \times f_b^{1.09} \times f_m^{0.37}$	0.98	0.16

where f_i is the i^{th} experimental masonry prism strength, f_{R_i} is the i^{th} regression estimate of masonry prism strength, f_{mean} is the average of experimental masonry prism strength, and n represents the number of experimental data points investigated.

When the Eurocode 6 equation is applied with $K = 0.55$ (Group 1 clay brick as per the code) to the data of the present study, $f_{m,p}/f_{m,e}$ ratio, R^2, and σ come out to be 1.27, 0.64, and 0.63 MPa, respectively. Table 8 summarizes the $f_{m,p}/f_{m,e}$ ratio, coefficient of determination (R^2), and standard error of estimate (σ) for present experimental data with an empirical expression derived by previous researchers. The value of $f_{m,p}/f_{m,e}$ ratio closer to unity shows that the empirical expression prediction value is closer to experimental data. The ratio being more than one indicates that the predicted value overestimates the strength and less than one indicates that the predicted value underestimates the strength value. A value of R^2 close to unity indicates a good fit and that closer to zero or negative values indicate a poor fit. Also, least σ implying that the scatter in data about the estimated value is a minimum. Table 8 shows that the only empirical relation recommended by Kaushik et al. [11] gives a reasonable match with $f_{m,p}/f_{m,e}$ ratio of 1.05 and R^2 closer to 0.71.

To predict the compressive strength of stabilized earth block masonry, statistical regression analysis was carried out using 24 data sets and the details of the data are given in Table 6. A prediction equation developed based on regression analysis on 24 experimental data is given in Table 7. The R^2 value corresponding to the equation for compressive strength of stabilized earth block is 0.97 which means that the proposed expression is able to predict 96% of the variation in masonry strength.

Table 8: Comparison of present experimental data with analytical predication.

Reference	$f_{m,p}/f_{m,e}$ Mean	$f_{m,p}/f_{m,e}$ COV	R^2	σ
Eurocode 6 [17]	1.27	0.12	0.93	0.63
Brocker [4]	1.17	0.18	0.84	0.57
Mann [5]	1.52	0.14	0.95	1.16
Hendry and Malek [6]	0.49	0.17	0.93	1.60
Dayaratnam [7]	0.60	0.20	0.71	1.32
Bennett et al. [8]	0.78	0.16	0.86	0.75
Dymiotis and Gutlederer [9]	0.88	0.14	0.90	0.50
Gumaste et al. [10]	0.79	0.11	0.94	0.75
Kaushik et al. [11]	1.05	0.18	0.84	0.57
Christy et al. [12]	0.69	0.13	0.94	1.06
Lumantarna et al. [13]	1.91	0.11	0.94	2.21
Sarhat and Sherwood [14]	1.90	0.12	0.95	2.11
Costigan et al. [15]	1.28	0.20	0.73	0.78
Kumavat [16]	1.44	0.15	0.88	1.01

6. Comparison of Past Experimental Results with Prediction Models

The proposed empirical expression for the compressive strength of stabilized earth block masonry is examined for its fitness by comparing it with experimental data obtained in eleven different studies published [4, 18, 26–34]. The details of the data are given in Table 9.

The predicted strength of masonry is compared with the experimental data. The masonry prism strength prediction models proposed by 14 researchers and present study are given in Tables 1 and 7, respectively. The comparison of predicted masonry strength ($f_{m,p}$) to experimental data ($f_{m,e}$) is given in Figure 5. The data points closer to the $f_{m,p} = f_{m,e}$ lines indicates that the predicted values are in a good fit with the experimental data. Results show that the empirical expression proposed in the present study is a fairly good fit and consistently better than the other empirical expression. The data point below the line indicates that prediction value underestimates than the actual strength and the data point above the line indicates that prediction value overestimates than the actual strength.

The mean and coefficient of variance of the ratio between the predicted masonry strength to experimental data and standard error of estimate between predicted and experimental data are given in Table 10. The mean ratio of the predicted strength to experimental strength is found to be closer to 1.00 for the present study predicted equation and the equation proposed by Gumaste et al. [10]. However, the present study proposed equation gives a lesser standard error of estimate when compared to other proposed equations. This indicates that the variation of predicted strength from experimental data is lower for the expression proposed in the present study compared to other proposed equations.

7. Conclusion

The compressive strength and the modulus of elasticity were determined for 144 masonry prisms using 24 different blocks and mortar combinations. Experimental results were used to develop an expression for the compressive strength of stabilized earth block masonry, using block and mortar compressive strengths. The main conclusions from this study may be summarized as follows:

(i) Based on the regression analysis, a simple relationship has been identified for obtaining the compressive strength of stabilized earth block masonry from their corresponding block and mortar compressive strength. A predicted expression

Table 9: Experimental data from published in literature.

References	Block size (mm)	Block strength (f_{uc})[1] (MPa)	Mortar mix proportion	Mortar strength (MPa)	Masonry prism size (mm)	Masonry prism strength (f_{mc})[2] (MPa)
Venkatarama Reddy and Jagadish [26]	305 × 146 × 82	2.51	1 : 6 cement mortar	3.38	305 × 146 × 368	1.52
Shrinivasa Rao et al. [27]	305 × 146 × 100	4.94	1 : 6 cement mortar	6.07	305 × 146 × 345	2.14
Walker [28]	305 × 70 × 23	8.80	1 : 20 cement-soil mortar	0.73	140 × 70 × 380	0.75
	305 × 70 × 47	4.00		0.73	140 × 70 × 339	0.68
	305 × 70 × 77	3.00		0.73	140 × 70 × 347	0.66
	305 × 70 × 113	1.40		0.73	140 × 70 × 347	0.43
	305 × 70 × 23	8.80	1 : 3 : 12 cement-lime mortar	1.46	140 × 70 × 368	0.77
	305 × 70 × 47	4.00		1.46	140 × 70 × 339	0.65
	305 × 70 × 77	3.00		1.46	140 × 70 × 347	0.63
	305 × 70 × 113	1.40		1.46	140 × 70 × 371	0.42
	295 × 140 × 120	3.30	1 : 25 cement-soil mortar	0.75	295 × 140 × 640	1.70
Venkatarama Reddy and Gupta [18][3]	305 × 143 × 100	3.13	Cement-soil mortar	1.92	305 × 143 × 460	1.25
		3.13	1 : 4 cement mortar	2.70		1.37
		3.13		5.40		1.23
		3.13		5.94		1.33
		5.63		1.92		2.07
		5.63		2.70		2.50
		5.63		5.40		1.76
		5.63		5.74		2.32
		7.19		3.42		4.56
		7.19		2.70		4.84
		7.19		1.92		4.43
		7.19		6.76		5.60
		7.19		5.40		5.50
		7.19		2.70		5.25
		7.19		5.40		4.55
		7.19	1 : 1 : 4 cement-lime mortar	5.94		5.27
Venkatarama Reddy et al., [29]	305 × 143 × 100	10.43	1 : 2 : 5 cement-soil mortar	3.45	305 × 143 × 460	3.54
		10.43	1 : 1 : 6 cement-lime mortar	2.93		3.58
Venkatarama Reddy and Uday Vyas [30]	255 × 122 × 80	5.09	1 : 1 : 6 cement-lime mortar	3.42	255 × 122 × 440	2.65
		5.09	1 : 0.5 : 4 cement-lime mortar	9.40		2.39
		11.46	1 : 1 : 6 cement-lime mortar	3.42		6.16
Venkatarama Reddy and Gupta [31]	305 × 143 × 100	7.19	1 : 6 cement mortar	5.40	305 × 143 × 436	4.55
		7.19	1 : 1 : 6 cement-lime mortar	5.94		5.27
Wu et al. [32]	200 × 90 × 50	1.66	1 : 0.8 soil-sand mortar	1.70	290 × 200 × 530	0.88
		1.66	1 : 1 soil-sand mortar	1.60		0.98
		1.66	1 : 1.2 soil-sand mortar	1.39		0.95

Table 9: Continued.

References	Block size (mm)	Block strength (f_{uc})[1] (MPa)	Mortar mix proportion	Mortar strength (MPa)	Masonry prism size (mm)	Masonry prism strength (f_{mc})[2] (MPa)
Vimala and Kumarasamy [33]	240 × 240 × 90	8.20	1 : 4 cement mortar	9.43	240 × 240 × 510	3.20
		8.20	1 : 6 cement mortar	3.63		3.05
		8.20	1 : 8 cement mortar	2.02		2.87
		8.20	1 : 10 cement mortar	1.24		2.60
		8.20	1 : 12 cement mortar	0.60		2.12
Divya et al. [34]	210 × 100 × 100	7.20	1 : 3 cement mortar	10.00	350 × 225 × 440	5.27
	100 × 100 × 100	7.20	1 : 5 cement mortar	5.00		3.10
Thaickavil and Thomas [3]	190 × 113 × 100	4.56	1 : 6 cement mortar	13.60	190 × 113 × 210	1.27
		4.56	1 : 5 cement mortar	14.20		1.46
		4.56	1 : 4 cement mortar	17.50		1.56
		4.56	1 : 3 cement mortar	35.50		1.69

[1]Table provides the mean strength of blocks (f_{uc}). To get normalized block strengths (f_b), these values are multiplied by shape factor as shown in equation (6). [2]Table provides the mean strength of masonry wallet (f_{mc}). To get normalized masonry strengths (f_m), these values are multiplied by h/t ratio correction factors as shown in equation (7). [3]Values provided are wet compressive strengths. However, same block type used in Venkatarama Reddy et al.[29] and dry compressive strength obtained from that before calculated the normalized compressive strength.

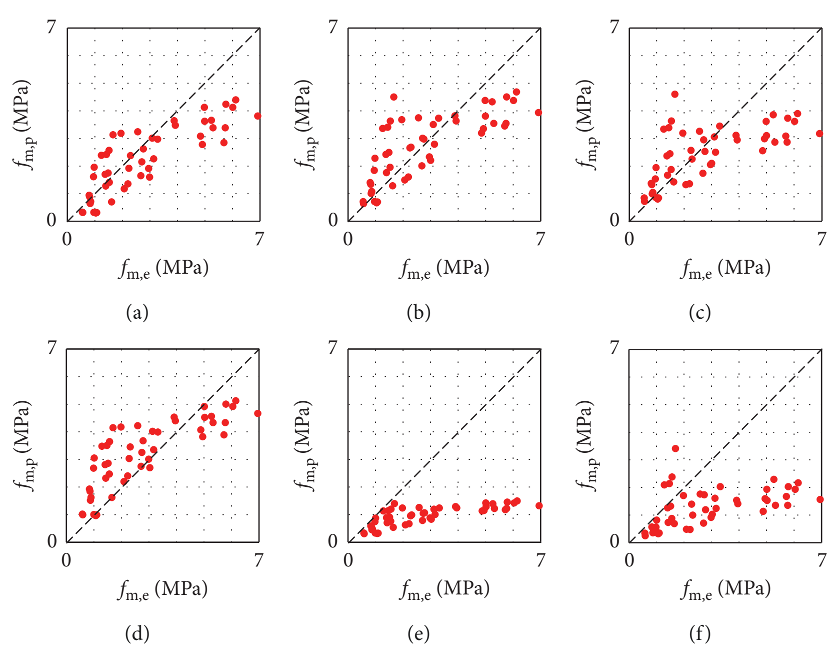

Figure 5: Continued.

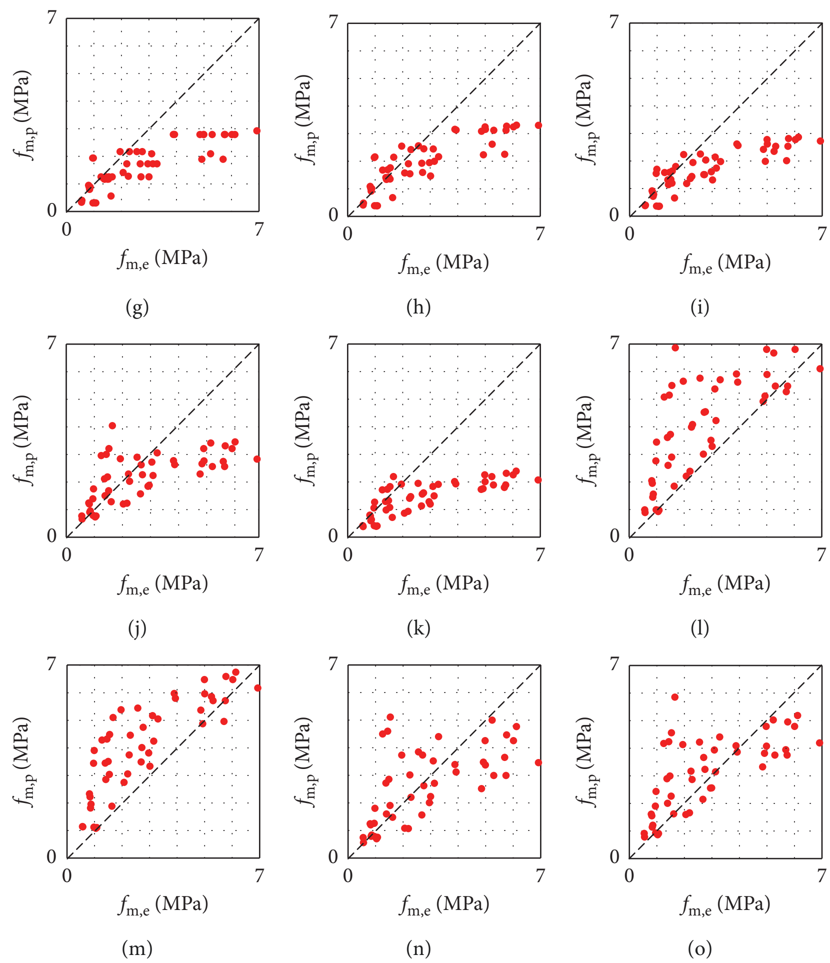

Figure 5: Compression of predicted compressive strength of the masonry prisms with experimental data from the literature: (a) present study, (b) Eurocode [17], (c) Brocker [4], (d) Mann [5], (e) Hendry and Malek [6], Dayaratnam [7], (g) Bennett et al. [8], (h) Dymiotis and Gutlederer [9], (i) Gumaste et al. [10], (j) Kaushik et al. [11], (k) Christy et al. [12], (l) Lumantarna et al. [13], (m) Sarhat and Sherwood [14], (n) Costigan et al. [15], and (o) Kumavat [16].

Table 10: Comparison of past experimental data with analytical predication.

Reference	$f_{m,p}/f_{m,e}$ Mean	COV	σ
Present study	0.95	0.47	1.19
Eurocode 6 [17]	1.24	0.49	1.25
Brocker [4]	1.17	0.53	1.47
Mann [5]	1.52	0.46	1.25
Hendry and Malek [6]	0.49	0.48	2.41
Dayaratnam [7]	0.60	0.68	2.22
Bennett et al. [8]	0.77	0.50	1.64
Dymiotis and Gutlederer [9]	0.89	0.49	1.44
Gumaste et al. [10]	1.05	0.53	1.56
Kaushik et al. [11]	0.77	0.45	1.67
Christy et al. [12]	0.69	0.48	1.96
Lumantarna et al. [13]	1.85	0.50	1.99
Sarhat and Sherwood [14]	1.86	0.45	1.77
Costigan et al. [15]	1.28	0.68	1.70
Kumavat [16]	1.42	0.53	1.43

relating f_b, f_j, and f_m in the form of the Eurocode 6 expression was derived, and constants K, α, and β were found to be 0.25, 1.03, and 0.28 using the normalized mean material compressive strengths.

(ii) A comparison of past experimental results on the compressive strength of stabilized earth block masonry prisms with present study analytical predictions, which show a close fit between the analytical and experimental data compared with other proposed analytical predictions for brick or cement block masonry. Except for the present study and Gumaste et al. [10], prediction expressions significantly underestimate or overestimate the compressive strength.

The results of the present study were obtained using only four types of stabilized earth blocks and six types of mortar; hence, a widening of the kinds of materials considered will be necessary for a better understanding of the compressive behavior of stabilized earth block masonry. Furthermore, only a limited amount of published data is available for the compressive behavior of stabilized earth block masonry, unlike brick or cement block masonry. Compressive strength masonry not only influenced by block and mortar strength, but also other parameters such as the height-to-thickness ratio of prisms, the volume fraction of bed joints to block volume. Yet, for the practical purpose of using this empirical expression, it is recommended to conduct the further study on the effect of other parameters on the compressive strength of stabilized earth blocks.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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