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Research Article

Strength of Hollow Compressed Stabilized Earth-Block Masonry Prisms

Xinlei Yang [1,2] and Hailiang Wang [1,2]

[1] *School of Civil Engineering, Tianjin Chengjian University, No. 26, Jinjing Road, Xiqing District, Tianjin 300384, China*
[2] *Tianjin Key Laboratory of Civil Buildings Protection and Reinforcement, No. 26, Jinjing Road, Xiqing District, Tianjin 300384, China*

Correspondence should be addressed to Xinlei Yang; yxl@tcu.edu.cn

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Earth represents an ecological building material that is thought to reduce the carbon footprint at a point in its life cycle. However, it is very important to eliminate the undesirable properties of soil in an environmentally friendly way. Cement-stabilized rammed earth, as a building material, has gradually gained popularity due to its higher and faster strength gain, durability, and availability with a low percentage of cement. This paper covers a detailed study of hollow compressed cement-stabilized earth-block masonry prisms to establish the strength properties of hollow compressed cement-stabilized earth-block masonry. The test results for masonry prisms constructed with hollow compressed cement-stabilized blocks with two different strength grades and two earth mortars with different strengths are discussed.

1. Introduction

Earth has been widely utilized as a building material since ancient times [1]. As a natural and sustainable construction material, earth has the advantages of low embodied energy, natural moisture buffering [2], low CO_2 emission, high recyclability, and good thermal inertia [3]. At present, there are many earth buildings in many countries, including Yemen, Iran, India, and China. It is reported that approximately one-fourth of the world's population lives in dwellings built from raw earth [4], which shows that the importance of earth construction remains very high worldwide. Earth can be used a building material for walls in many ways, such as earth blocks, rammed earth, and cob [5]. However, there are a few undesirable properties, such as poor dimensional stability, low strength, brittle behaviour, erosion due to wind or rain, and especially, low resistance to dynamic actions [6–10]. These drawbacks can be reduced or eliminated by stabilizing the soil with stabilizing additives such as cement and lime [11–14]. Among these stabilizing additives, cement is cost-effective and environment friendly. Generally, cement-stabilized soil is used to make compressed cement-stabilized earth blocks compacted either manually or by hydraulically operated machines. Compressed cement-stabilized earth blocks are the most-used earth building technique and represent a modern evolution of the moulded earth block [15].

Compressed cement-stabilized earth-block construction is currently a popular topic, with growing interest due to its high levels of sustainability and thermal and acoustic performance, the low energy required for production and transport, the decrease in landfill waste, its fire resistance, and the cost of the raw material [15, 16]. Compressed cement-stabilized earth-block construction is a feasible solution for sustainable buildings in many developed and developing countries because cement-stabilized earth blocks offer a number of advantages, such as simple construction methods and maximal utilization of local materials [17]. Much research has been undertaken to investigate the mechanical properties of compressed cement-stabilized earth blocks [18–20]. The test results show that the effect of adding cement on the compressive stress is quite noticeable. However, most of the research on the mechanical properties of compressed cement-stabilized earth blocks has focused on solid blocks.

In remote mountainous areas and Loess Plateau region in western China, due to the lack of high-performance building materials, a large number of houses have to be built using local earth as building materials, and the local earth is often used to make adobe bricks. However, the strength of these locally made adobe bricks is low, whose raw materials are free and locally available. The seismic behaviour of these buildings built with locally made adobe bricks is poor. In order to use locally made adobe bricks for wide application, it is necessary to develop high-strength adobe bricks to improve the seismic performance of adobe brick structures.

At present, the environmental pollution in China is very serious, and green building materials are increasingly attracting everyone's attention. There are very large market demands for ecological building materials. Earth, as a natural and sustainable construction material, has gradually attracted people's attention and captured the interest of many researchers in recent years due to its low embodied energies and low life cycle cost.

In order to make full use of locally available natural soil resources and minimize environmental impact, decrease the weight of adobe structures, and improve the construction efficiency, an extensive research program has been carried out at Tianjin Chengjian University. The aim of this project is to develop a type of hollow compressed cement-stabilized earth block (HCCSEB). The results of this investigation could enrich the data available, documenting the behaviour of hollow compressed cement-stabilized earth-block masonry, and contributed to enlarge the application of hollow compressed cement-stabilized earth blocks when constructing rural houses in remote mountainous areas and Loess Plateau region in western China.

Hollow compressed cement-stabilized earth blocks investigated in the manuscript are intended primarily for the construction of single-storey or two-storey rural houses and were successfully used to build a two-storey building in Tianjin, China, as shown in Figure 1.

This paper presents experiments on the mechanical behaviour of HCCSEB masonry prisms. The HCCSEBs were manufactured from soil taken from Gongyi County in Henan Province, China, and ordinary Portland cement. A single HCCSEB was tested under compression and three-point bending, and the HCCSEB masonry prisms were tested for compression behaviour and shear behaviour.

2. Experimental Program

2.1. Geometry of the HCCSEBs and the Masonry System. The general dimensions of the HCCSEBs used in this study are 390 mm (length), 190 mm (height), and 190 mm (width). The face and web shell thickness is 50 mm. These physical dimensions are the same as those of the hollow concrete blocks used in China, which allows single- and double-layer walls to be built. Two mortars specially designed for HCCSEBs are used in this study, i.e., M5 and M7.5. The

Figure 1: A two-storey hollow compressed cement-stabilized earth-block masonry structure in China.

details of the mixture proportions for M5 and M7.5 are given in Table 1. Three cubes of $70.7 \times 70.7 \times 70.7\ \mathrm{mm}^3$ were cast and tested at 28 days of curing time to determine the compressive strength of each mortar. The average compressive strength of the three mortar specimens was $6.2\ \mathrm{N/mm}^2$ for mortar M5 and $9.5\ \mathrm{N/mm}^2$ for mortar M7.5.

2.2. Materials and Manufacturing of the HCCSEBs. The used soil was taken from Gongyi County in Henan Province, China, which is located in the East Loess Plateau. The properties of the soil were determined according to Chinese standard GB/T 50123 [21] and are presented in Table 2. The optimum moisture content (OMC) and the maximum dry density (MDD) were 16.5% and $1710\ \mathrm{kg/m}^3$, respectively, as determined by the standard Proctor test. Ordinary Portland cement of grade 42.5 conforming to GB 175 [22] was selected as a stabilizer, and 5~10% cement by dry mass of soil was used for the production of the HCCSEBs.

The optimum moisture content (OMC) is an important physical index of soils. The OMC was first determined by the standard Proctor test, and it served as a reference value. When manufacturing the HCCSEBs, cement was added for enhancing the strength of blocks, and it was found that the OMC could not meet the requirements of production process. Therefore, the water content was adjusted according to the production process of vibration forming through a large number of trial production.

The HCCSEBs were manufactured by using a Tiger D-Series Concrete Products Machine (Figure 2), which has synchronized vibrators and counter-rotating shafts and provided programmable variable vibration as well as dual-layer product capability. The machine has a vibration system, which provides a more uniform wave amplitude from the front to the rear of the mould and creates denser and more homogeneous products. The strength of the HCCSEBs was controlled by adjusting the amount of cement and the moulding pressure. Trial production of two compressive-strength-grade HCCSEBs, i.e., MU5 and MU7.5, was performed by Tianjin Yuchuan Building Materials Co., Ltd.

2.3. Testing Procedure

2.3.1. Methods. There are currently no code provisions applicable to HCCSEBs. Therefore, the evaluation of

Table 1: The mixture proportions of two mortars.

Proportions	Cement (%)	Slag powder (%)	Earth (%)	Sand (%)	Water (%)
M5	10	7.5	62.5	20	31.7
M7.5	12.5	10	67.5	10	33.6

Table 2: Summary of the soil properties.

Property	Parameter	Percentage
Grain size distribution	Gravel fraction	28%
	Sand fraction	44%
	Silt fraction	13%
	Clay fraction	15%
Atterberg limit	Liquid limit	27.8%
	Plastic limit	17.7%
	Plastic index	10.1%
Proctor test	Optimum moisture content	16.5%
	Maximum dry density (kg/m^3)	1710

Figure 2: Machine used for manufacturing the HCCSEBs.

HCCSEBs is performed according to the requirements specified in the test methods section for concrete blocks and bricks (GB/T 4111-2013) [23] and the standard for testing the basic mechanical properties of masonry (GB/T 20129-2011) [24]. The HCCSEBs were tested individually for compression and flexural strength (three-point bending test), and the masonry prisms were tested under compression and shear loading (triplet test). The HCCSEBs' characteristics are sensitive to their dry density and moisture content. The dry density of the blocks under dry conditions varied within the range from 1243 to 1369 kg/m^3, and the moisture content ranged from 2.5 to 3.3% in air dry at the time of testing.

2.3.2. Compression Tests of the HCCSEBs. The compression tests of single HCCSEBs were conducted according to Chinese code GB/T 4111-2013 [23], and the load was applied under load control at a rate of approximately 4 kN/s~6 kN/s. Six specimen groups were tested, and each group consisted of five HCCSEBs in each strength grade. The top and bottom platens were used as testing platens to avoid cutting and capping the specimens, as shown in Figure 3(a). These platens have the same shape as the HCCSEBs, which means that they are able to distribute the load uniformly on the top and bottom surfaces of the specimens.

2.3.3. Three-Point Bending Tests of the HCCSEBs. The three-point bending tests were performed according to Chinese code GB/T 4111-2013 [23]. The specimens were supported by cylindrical metallic rollers featuring a 350 mm span. The load was applied at midspan under load control at a rate of approximately 100 N/s~1000 N/s, as shown in Figure 3(b). Six specimen groups were tested, and each group consisted of five HCCSEBs in each strength grade.

2.3.4. Compression Tests of Masonry Prisms. The compression behaviour of the HCCSEB masonry was assessed by means of compression tests on masonry prisms with dimensions of 590 mm (length), 190 mm (width), and 990 mm (height), as shown in Figure 4(a). The masonry prisms were constructed with five courses in a running bond pattern. All the prisms were moist cured for 28 days before testing.

Three sets of HCCSEB prisms were designed. One set of prisms was designated A (MU5 HCCSEBs and M5 mortar), another set of prisms was designated B (MU7.5 HCCSEBs and M5 mortar), and the last set of prisms was designated C (MU7.5 HCCSEBs and M7.5 mortar); there were 9 prisms in each set. The axial strain between the top and bottom blocks and lateral strain were measured by means of two dial indicators attached to each face of the masonry prism, respectively. Compression tests of the masonry prisms were performed according to the procedure specified by Chinese code GB/T 50129-2011 [24].

2.3.5. Shear Tests of the Masonry Prisms. The shear behaviour of the HCCSEB masonry was assessed by means of shear tests on masonry prisms made from three HCCSEBs with average dimensions of approximately $390 \times 590 \times 190\ mm^3$ (width × height × thickness) (Figure 4(b)). The tests were conducted in accordance with Chinese code GB/T 50129-2011 [24]. The shear load was applied by means of an actuator parallel to the joints under load control at a rate of approximately 0.2 N/mm^2 per minute.

Three sets of HCCSEB prisms were designed. One set of prisms was designated D (MU5 HCCSEBs and M5 mortar), another set of prisms was designated E (MU7.5 HCCSEBs and M5 mortar), and the last set of prisms was designated F (MU7.5 HCCSEBs and M7.5 mortar). There were six prisms in each group. Six prisms were tested for each mixture, giving a total of eighteen specimens.

3. Results

3.1. Compression Tests of the HCCSEBs. The test results for single HCCSEBs with strength grade MU5 are presented in Table 3, and the test results for single HCCSEBs with strength grade MU7.5 are presented in Table 4. The

(a) (b)

Figure 3: Testing of the individual HCCSEBs under (a) compression and (b) three-point bending.

(a) (b)

Figure 4: Testing HCCSEB masonry prisms under (a) compression and (b) shearing.

Table 3: Compression test results for HCCSEBs with strength grade MU5.

Number	Compressive strength (MPa)	Mean compressive strength value (MPa)	Mean coefficient of variation (%)
Group 5C-1	3.2~4.5	4.17	10.57
Group 5C-2	3.5~4.6		
Group 5C-3	3.8~4.7		
Group 5C-4	3.4~4.1		
Group 5C-5	3.8~4.8		
Group 5C-6	4.3~5.4		

Table 4: Compression tests results for HCCSEBs with strength grade MU7.5.

Number	Compressive strength (MPa)	Mean compressive strength value (MPa)	Mean coefficient of variation
Group 7.5C-1	5.4~6.4	5.92	8.63
Group 7.5C-2	5.5~6.5		
Group 7.5C-3	4.7~6.2		
Group 7.5C-4	5.0~6.6		
Group 7.5C-5	6.4~7.0		
Group 7.5C-6	5.2~6.4		

nomenclature for the tests of single HCCSEBs under compression was as follows: the first and second characters refer to "MU5 under compression" or "MU7.5 under compression," the third character is the group number, and the fourth character is the specimen number. A typical failure mode of a single HCCSEB tested under compression is shown in Figure 5.

According to the requirements of the Chinese code, when compressing blocks to obtain their compressive strength, it is necessary to carry out six groups of compression tests and each group has five test specimens. Each group of tests corresponds to a coefficient of variation. It could be seen that the mean coefficient of variation of HCCSEBs with strength grade MU5 is 10.57%, and the mean

Figure 5: Typical failure mode of a single HCCSEB tested under compression.

coefficient of variation of HCCSEBs with strength grade MU7.5 is 8.63%. Thus, it is considered that the little variation in strength was observed when the strength of HCCSEBs was higher.

3.2. Three-Point Bending Tests of HCCSEBs. In masonry structures, due to the fact that the surface of the block itself is not flat, the thickness of the laying mortar is not uniform, or the horizontal joint is not full, the single block is not evenly pressed in the masonry and may be in a bent state as shown in Figure 6. In Chinese code "Test methods for the concrete block and brick (GB/T 4111-2013)," there is a clear requirement for the three-point bending test. Therefore, the results are presented herein.

Tables 5 and 6 present the results of the three-point bending tests of single HCCSEB with strength grades MU5 and MU7.5, respectively. The nomenclature for the three-point bending tests of single HCCSEBs was similar to that for the single HCCSEBs under compression except that "T" stands for "three-point bending test." The flexural strength of the specimens was tested in air dry state. The failure of all specimens occurred at the midspan cross section. It can be seen that the mean flexural strength is 0.52 MPa for HCCSEBs with strength grade MU5 and 0.58 MPa for HCCSEBs with strength grade MU7.5. The mean coefficient of variation of the flexural strength exhibited features similar to that of the compressive strength of single HCCSEBs, i.e., the mean coefficient of variation for HCCSEBs with strength grade MU5 is greater than that for HCCSEBs with strength grade MU7.5. The typical failure mode of a single HCCSEB subjected to a three-point bending test is shown in Figure 7.

3.3. Compression Tests of HCCSEB Masonry Prisms. The responses of HCCSEB masonry prisms to compression were roughly divided into three phases. In the first phase (before the first crack was initiated), no obvious damage was found, and the test specimen was in the elastic state. In the second phase, the cracks initiated, gradually propagated, and tended to merge with increasing loading, and the test specimen was in an elastic-plastic state. In the third phase, vertical cracks propagated quickly, crossing mortar bed joints and blocks, and the bearing capacity of the specimen suddenly decreased and brittle failure occurred. The typical failure mode for the HCCSEB masonry prisms is shown in Figure 8. On the whole, the failure mode of the HCCSEB masonry prisms due to compression is similar to that of ordinary hollow-block concrete masonry prisms. Failures of masonry prisms under

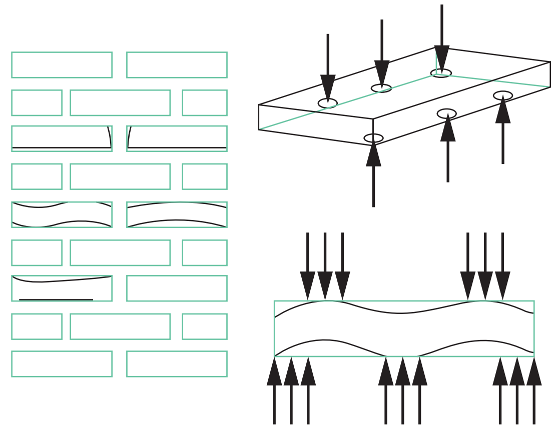

Figure 6: Complex stress state of blocks in masonry structures.

Table 5: Flexural strength tests results for HCCSEBs with strength grade MU5.

Number	Flexural strength (MPa)	Mean value (MPa)	Mean coefficient of variation (%)
Group 5T-1	0.4~0.6		
Group 5T-2	0.4~0.6		
Group 5T-3	0.4~0.6		
Group 5T-4	0.4~0.6	0.52	14.28
Group 5T-5	0.6		
Group 5T-6	0.4~0.6		

Table 6: Flexural strength tests results for HCCSEBs with strength grade MU7.5.

Number	Flexural strength (MPa)	Mean value (MPa)	Mean coefficient of variation (%)
Group 7.5T-1	0.5~0.6		
Group 7.5T-2	0.5~0.6		
Group 7.5T-3	0.5~0.6		
Group 7.5T-4	0.5~0.6	0.58	8.63
Group 7.5T-5	0.5~0.7		
Group 7.5T-6	0.5~0.7		

Figure 7: Typical failure mode for a single HCCSEB tested under three-point bending.

(a) (b) (c)

Figure 8: Typical failure mode for the HCCSEB masonry prisms tested under compression.

compression are usually caused by a tension crack that propagates through the blocks and mortar in the direction of the applied force.

Table 7 presents the results of the compression tests of the HCCSEB masonry prisms. It can be seen that the compressive strength of the HCCSEB masonry prisms could be enhanced by increasing the strength of the mortar or the units. The coefficient of variation for the strength of the three groups of HCCSEB masonry prisms varied between 13.9% and 19.7%, showing that the strength exhibited relatively high scattering.

Relative to Group A, Group B exhibited a 5% increase in the compressive strength, and Group C exhibited a 9% increase in compressive strength compared with Group B, which shows that the effect of the mortar's strength on the mechanical properties of HCCSEB masonry is stronger than those of the HCCSEB's strength.

A predictive model with high prediction accuracy for predicting the compressive strength of HCCSEB masonry is proposed based on multiple regression analysis. The compressive strength f_m of the HCCSEB masonry can be calculated using the following equation:

$$f_m = 0.568 f_1^{0.5} \left(1 + 0.07 f_2\right), \quad (1)$$

where f_m is the mean compressive strength of HCCSEB masonry (MPa), f_1 is the mean compressive strength of HCCSEB (MPa), and f_2 is the mean compressive strength of the mortar (MPa).

A comparison of the calculated and measured values for HCCSEB masonry is presented in Table 8. It can be seen that the calculated results are in remarkably good agreement with the measured values.

The stress-strain relationship of masonry is essential for predicting the strength and deformation of masonry structures in analytic modelling. The stress-strain curves for HCCSEB masonry prisms under compression are presented in Figure 9.

Table 7: The results of the compression tests of HCCSEB masonry prisms.

Number	Compressive strength (MPa)	Mean value (MPa)	Standard deviation	Coefficient of variation
Group A	1.44~2.31	1.84	0.26	13.9%
Group B	1.54~2.58	1.94	0.33	16.9%
Group C	1.75~2.48	2.12	0.42	19.7%

Table 8: The comparison of the calculated and measured values for HCCSEB masonry.

Group	Group A	Group B	Group C
Calculated value	1.72	2.15	2.06
Measured value	1.84	1.94	2.12
Correlation coefficient		0.632	

The experimental results show that if the compressive stress and strain are normalized with respect to the compressive strength and the peak strain, respectively, the resulting normalized stress-strain curves are close to each other. Normalized stress-strain curves are obtained by using the maximum compressive stress to normalize the compressive stress and the reference strain to normalize compressive strain. The reference strain is defined by the strain corresponding to the maximum compressive stress.

Equations to represent the relationship between the normalized compressive stress and strain were derived using parabolic regression. The best-fit curves are highlighted in red in Figure 9.

The best-fit equations are as follows:

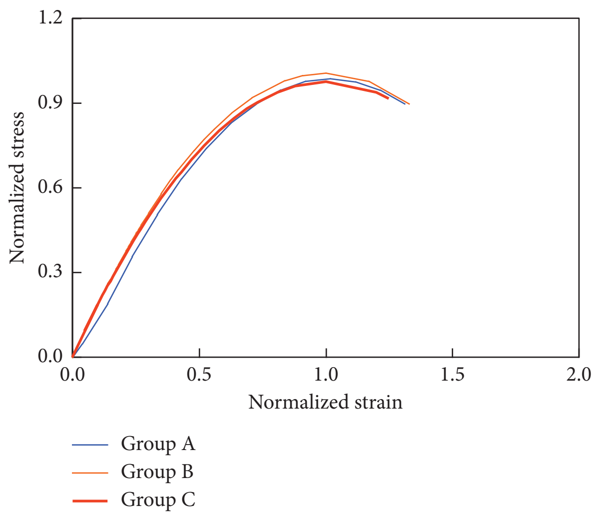

Figure 9: Stress-strain curves of masonry prisms in compression.

$$\text{Group A}: \frac{\sigma}{\sigma_{max}} = 1.8412\left(\frac{\varepsilon}{\varepsilon_0}\right) - 0.8819\left(\frac{\varepsilon}{\varepsilon_0}\right)^2,$$

$$\text{Group B}: \frac{\sigma}{\sigma_{max}} = 1.9435\left(\frac{\varepsilon}{\varepsilon_0}\right) - 0.9689\left(\frac{\varepsilon}{\varepsilon_0}\right)^2, \quad (2)$$

$$\text{Group C}: \frac{\sigma}{\sigma_{max}} = 2.0072\left(\frac{\varepsilon}{\varepsilon_0}\right) - 1.0016\left(\frac{\varepsilon}{\varepsilon_0}\right)^2.$$

It can be seen from Figure 9 that the best-fit curve using the proposed equation is in good agreement with the normalized curve for each specimen; therefore, the parabolic constitutive relation is reasonable.

3.4. Shear Tests of HCCSEB Masonry Prisms. Table 9 presents the results of the shear tests of HCCSEB masonry prisms. It can be seen that the shear strength of the HCCSEB masonry prisms can be improved by increasing the strength of the mortar. The coefficient of variation in strength for the three groups of HCCSEB masonry prisms varied between 3.52% and 5.19%, which shows that the strength exhibited relatively low scattering.

The failure of all the specimens experienced shear bond failures at block mortar interface, and the typical failure mode for the prisms is shown in Figure 10, where the middle block slides relative to the left and right blocks. The shear failure of HCCSEB masonry prisms occurs by brittle fracture. When shear bond failure occurred, the bearing capacity was immediately lost, and the blocks themselves remain intact without any damage.

Table 9: The results of the shear tests of HCCSEB masonry prisms.

Number	Shear strength (MPa)	Mean value (MPa)	Coefficient of variation (%)
Group D	0.069~0.079	0.074	5.19
Group E	0.074~0.081	0.078	3.52
Group F	0.087~0.097	0.092	4.46

Figure 10: Typical failure mode of the masonry prisms tested under shear loading.

4. Conclusions

This paper presents an experimental program in which the mechanical behaviour of hollow compressed cement-stabilized earth blocks and masonry prisms is assessed. The mechanical tests performed on single HCCSEBs showed that the mean compressive strength reaches approximately 4.2 MPa for HCCSEBs with strength grade MU5 and 6 MPa for HCCSEBs with strength grade MU7.5; the mean flexural strength reached 0.52 MPa for HCCSEBs with strength grade MU5 and 0.58 MPa for HCCSEBs with strength grade MU7.5. These measured mechanical properties were slightly lower than the corresponding design values, which show that the manufacturing technology and the mixtures should be further optimized and improved.

The failure mode of the HCCSEB masonry prisms under compression is similar to that of hollow-block masonry prisms made from ordinary concrete. Failure of masonry prisms under compression is usually caused by a tension crack that propagates through the blocks and mortar in the direction of the applied force.

Triplicate tests showed that the stronger the mortar was, the greater the shear strength was. The failure of HCCSEB triplicate-test specimens occurred at the bed joint where the middle block slides relative to the left and right blocks.

Data Availability

Experimental data and experimental photographs could be downloaded from https://pan.baidu.com/s/17uk3T2Oanodw0Um_fbpXgg.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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