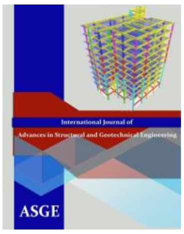
ASGE Vol. 03 (02), pp. 1-13, 2022

Egyptian Knowledge Bank

International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/

Print ISSN 2785-9509 Online ISSN 2812-5142



Stress-strain curves of Cellular Light Weight Concrete Brick and masonry

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1. ABSTRACT

Masonry panels are commonly used in buildings construction in most parts of the world. Brick's characteristics, such as strength, thermal insulation and sound insulation, determine the uses of bricks in buildings. Therefore, brick industry is always seeking for enhancing brick's characteristics and producing new types. Accordingly, several types of bricks were developed, such as cellular lightweight concrete (CLC) bricks. CLC bricks proved promising benefits in various applications in buildings construction. In this regard, this study investigates CLC brick's mechanical properties. An experimental program was conducted according to ASTM and British standards to obtain the essential in-plane mechanical properties of CLC bricks and masonry panels, such as compressive strength, tensile strength, modulus of elasticity, Poisson's ratio and bond strength between brick and mortar. The object of this study is to provide the needed mechanical properties for numerical modelling used in analysing the behaviour of different elements (i.e., constructed from CLC bricks). This study shows that CLC bricks give a good performance regarding loads resistance because of its ductile behaviour. Consequently, it enhances the flexibility and ductility of buildings, which allows the absorption of most of the loads' energy. Moreover, it is a light type of bricks.

Keywords: Cellular lightweight concrete, Masonry, mechanical properties, Compressive strength

2. INTRODUCTION

Masonry is one of the oldest building materials, it has been used for different construction purposes. Brick industry are now developing [1-5]. New types of bricks have been developed to enhance the behavior of masonry panels in different buildings, such as foamed concrete or cellular light weight concrete (CLC) bricks. CLC is a lightweight construction material that can be produced as building block unites of different dimensions as well as different densities as required. In addition, it is a ductile material. This material is composed of a solid part as well as an air void part. The void part is composed of small bubbles generated using foaming agent material and it occupies about 70% of the volume. Moreover, the solid part constitutes about 30% of the volume. The solid part is composed of Portland cement: filler: water as 2:1:1 by weight. The mixture is reinforced with 0.5 kg/m3 polypropylene fibers. This lightweight material has a weight of 700 kg/m3 as a dry density. Similar to common burnt clay bricks, it can be widely used in all buildings construction activities. The CLC bricks are comparatively lighter in weight and more ductile than common clay bricks. The demand for CLC Bricks has picked up in view of the superior quality and light weight.

Article history: Received March 2022 & Accepted April 2022
DOI: 10.21608/asge.2022.152695.1004

Determination of mechanical properties of bricks and brick masonry are very important as the mechanical properties like compressive strength, modulus of elasticity, poisson's ratio, stress-strain curves, dissipation energy, tensile strength and shear strength are widely used in design, retrofitting and analysis of masonry structures and are considered an essential input for finite element analysis. By evaluating 84 masonry prisms, 40 brick specimens from 4 different manufacturers and 27 mortar cube specimens of three different grades, Kaushik and Rai [6] reported the compressive stress-strain curve behavior for local hand molded burnt clay solid bricks, mortar, and unreinforced masonry prisms. The findings showed that the modulus of elasticity (MOE) of bricks varied between 150 and 500 times the strength of the brick on the basis of experimental observations with an average value of 300 times the individual brick strength. The MOE of mortar was found to vary between 100 and 400 times with an average value of 300 times the mortar strength. Finally, the MOE of masonry was found to vary between 250 and 1100 times the strength of the prism of masonry with an average value of 550 times the prism strength. Gumaste and Rao [7] indicated that the compressive strength of brick masonry varies from 25% - 50% of brick's compressive strength. Tests were proposed to estimate the compressive strength and elasticity modulus of brick masonry prisms and wallets under compression using table moulded bricks and wire-cut bricks of India with various types of mortars. On the other hand, Eurocode 6 [8] determine the characteristic compressive strength of masonry $(\boldsymbol{f_m})$ from the following Equation (1) :

$$\boldsymbol{f_m = K f_b^{\alpha} f_{mo}^{\beta}} \quad (1)$$

where $\boldsymbol{K}$, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are constants, $\boldsymbol{f_b}$ is the compressive strength of units in the direction of applied action effort in (N/mm^2) and $\boldsymbol{f_{mo}}$ is the compressive strength of mortar in (N/mm^2).

Furtado and Rodrigues [9] conducted Four different types of experimental tests on masonry walls made with three different types of masonry units: lightweight vertical hollow concrete blocks and hollow clay bricks. The objective of the study was to present an extensive experimental campaign of mechanical characterization tests of different types of infill masonry walls and compare their mechanical properties. Reddy and Gupta [10] Conducted an experimental investigation to characterize the properties of Stabilized Mud Block (SMB) masonry using cement-soil mortar. In their investigations, it has been found that SMB masonry strength and the masonry modulus increase as block strength increases. The cement-soil mortars can be beneficially used for SMB masonry which is cheaper than conventional mortars.. Penava and Radic [11] determined the basic mechanical properties for masonry panels of hollow-clay blocks in Croatia through several tests using Croatian/European norms and guidelines. The findings of their study could form the basis for any further numerical analysis of masonry walls and masonry infill panels of hollow-clay blocks. Radovanović and Grebović [12] examined the compressive strength and the modulus of elasticity of masonry panels of hollow clay, clay and concrete blocks in Montenegro. The characteristic compressive strengths of the walls obtained from the experiments are lower than those in European and American regulations and accordingly, the elasticity modulus values of the tested walls are higher than those provided in these regulations. Phaiju and Pradhan [13] investigated the mechanical properties of locally available handmade bricks of Kathmandu, such as compressive strength, modulus of elasticity and the modulus of rigidity of bricks and masonry walls. Their study uses ASTM for the experimental work. Narayanan and Sirajuddin [14] conducted an experimental work to determine the characteristic properties of wire cut and country burnt bricks used for construction in Kollam, Kerala. These properties are widely used in finite element analysis. Nollet and Guizani [15] conducted a three phase experimental program to determine the mechanical properties and parameters of unreinforced brick (manufactured moulded brick units) and stone masonry traditionally used in old existing buildings in Eastern Canada. The tested properties fell within the range of the corresponding properties and models reported in the literature for old traditional brick masonry buildings. Nwofor [16] conducted compressive strength test on the solid burnt Clay bricks and brick masonry to obtain basic mechanical properties which are considered as basic input parameters for numerical modeling of masonry and infilled frame structure.

To the author knowledge, the characteristics properties of CLC bricks and its masonry walls and their behavior in resisting vertical and lateral loads haven't been studied. This study investigates the behavior and mechanical properties of CLC bricks. Simple experiments are done to determine basic mechanical properties of anisotropic masonry walls. The current study presents tests on the masonry made of CLC blocks according to ASTM and British standards [17-22]. The mechanical properties, such as vertical and horizontal compressive strength, modulus of elasticity, tensile strength, stress-strain curves and dissipation energy form the basis for numerical analysis of masonry walls and masonry infill panels. The outcomes of this study represent a good reference for designers, brick industry and masonry builders.

3. Experimental program

A set of tests was prepared according to ASTM and British standards [17-22] to obtain the essential mechanical properties of bricks and masonry panels consisting of CLC bricks. The tests examine the flexure strength, tensile strength, the compressive strength, poisson's ratio and modulus of elasticity of individual brick and brick masonry. Also the bond strength between brick and mortar in masonry panels is tested. The materials (tested specimens) used in experimental program are bricks and masonry panels. **Error! Reference source not found.**a shows CLC b ricks used in this study with density of 700 kg/m3. The CLC bricks consist of cement (representing the solid part 30%), foams (forming the void part 70%) and polypropylene fibers. The cement mortar is used in making the masonry panels. The mortar consists of 1 part cement, 3 parts sand and 0.5 part water by weight. Finally, bricks and mortar are used together for making the masonry samples as shown in **Error! Reference source not found.**b. **Error! Reference source not found.** shows the dimensions, used specification and the number of samples for all the tests performed on the materials used in this study.


(a)


(b)

Fig.1: CLC specimens: (a) CLC bricks and (b) CLC masonry

Table 1. Test specimens' details

Material	Type of Test	Specification number	Dimensions of specimens *l***h***b*(mm)	No. of specimens
Bricks	Compressive strength test (V&H)	ASTM C67-14	300*120*200	10
	Flexure strength test	ASTM C67-14	300*120*200	5
	Tension strength test	ASTM C1006	300*120*200	5
Masonry Panels	Compressive strength test (V&H)	BS EN 1052-1:1999	820*810*120	6
	Diagonal tension test	ASTM E519/E519M-10	1230*1250*110	3
	Bond strength test	BS EN 1052-3:2004	390*300*200	3

3.1 *Bricks*

Experimental tests were conducted on individual bricks of CLC, such as compressive strength, flexure strength and tensile strength tests. The results of tests are used to determine the mechanical properties of bricks, such as compressive strength (***f**b*), tensile strength (***f**tb*), Modulus of Rupture (f_{rb}), stress strain curves, modulus of elasticity (***E**b*) and poisson's ratio (***υ**b*). the tests are conducted according to ASTM standards [21, 22].

Ten specimens of CLC bricks (Density = 700 kg/m3 and dimensions 300 x 200 x 120 mm) were tested to determine the compressive strength according to ASTM.C67-14 [22]. Compressive strength was determined in vertical and horizontal directions. For this purpose, five specimens of each type are positioned in testing machine as shown in **Error! Reference source not found.**a to get the vertical compressive strength of brick units (f_{bv}) and the other five are positioned as in **Error! Reference source not found.**b to get the horizontal compressive strength of bricks (f_{bh}). Load was applied axially till failure then maximum load was recorded and compressive strength was determined as (maximum load / Area of surface of loading) for each specimen. Strain values were recorded using pi gauges and data logger system for specimens in vertical loading test only. Strain devices were connected to each brick; one in longitudinal and one along lateral direction of the bricks in order to obtain the stress-strain curves which enables the determination of the modulus of elasticity. Also transversal values of strains were used to determine the poisson's ratio as the ratio between transversal strain to the longitudinal strain.

ASTM.C1006-07 [21] tests the tensile strength of a masonry unit by applying compressive forces through two rods to the top and bottom of each specimen as shown in **Error! Reference source not found.**a. The rods' essential role is to distribute the applied load along the top and bottom of the specimen. The load was applied and was increased continuously till the specimen cracked. The maximum load was recorded and the tensile strength can be determined from the following formula:

$$f_{tb} = 2P_{max}/\pi LH \quad (2)$$

where f_{tb} is the splitting tensile strength of brick unit in (MPa), P_{max} is the maximum applied load indicated by the testing machine in (Newton), L is split length in (mm) and calculated as gross length minus the length of any voids along the failure plane of the bearing rods and H is the distance between rods in (mm).

Bricks were tested in Universal Testing Machine (UTM) like beams in flexure according to ASTM.C67-14 [22]. Five specimens of CLC bricks were supported by rollers at the edges in the position as shown in **Error! Reference source not found.**b. The load was applied by UTM on a third roller at the center and was increased till the specimen failure. The Modulus of Rupture which represents the flexure strength was calculated by registering the failure load using the following formula:

$$f_{rb} = \frac{1.5 * P_{max} * l}{b * t^2} \quad (3)$$

where f_{rb} is the modulus of rupture of brick unit, P_{max} is the maximum load taken by specimen, l is the span of member, b is the width of specimen and t is the thickness of specimen.

(a) (b)

Fig.2: compressive strength test: (a) Vertical configuration and (b) horizontal configuration


(a) (b)

Fig.3: Tests for bricks: (a) tensile strength test and (b) flexure strength test

3.2 *Brick masonry panels*

Nine unreinforced masonry panels of CLC bricks (see **Error! Reference source not found.**b) were tested to determine vertical compressive strength (***f_{mv}***), horizontal compressive strength (***f_{mh}***), tensile (shear) strength (***f_{tm}***), stress strain curves, vertical modulus of elasticity (***E_{mv}***), horizontal modulus of elasticity (***E_{mh}***) and poisson's ratio (***υ_m***). The mortar was evenly applied to the bed and head faces of masonry units.

According to the norm BS.EN.1052-1 [17], three specimens of CLC masonry panels with dimensions 820 x 810 x 120 mm were tested vertically to determine ***f_{mv}***, ***E_{mv}***, ***υ_m*** and stress strain curves. Furthermore, additional three specimens were tested horizontally to determine ***f_{mh}***, ***E_{mh}*** and stress strain curves to investigate the masonry behavior in the other direction. The specimens were subjected to a uniform compression load distributed by rigid steel loading beam. Strain sensors (LVTDs) were used to measure strains in longitudinal and transversal directions to determine the stress-strain curves and accordingly the Elasticity modulus and Poisson's ratio. For vertical configuration, four LVDT-deformation sensors were placed in vertical direction (**V_{a1}**, **V_{b1}**, **V_{a2}** and **V_{b2}**) and two in horizontal direction (**H_{a1}** and **H_{b1}**). The scheme of the tested specimen is shown in **Error! Reference source not found.**. For horizontal configuration, Four LVDT-deformation sensors were placed in vertical direction (**V_{a1}**, **V_{b1}**, **V_{a2}** and **V_{b2}**) as shown in **Error! Reference source not found.**. The testing criteria were similar to the compression test on the blocks. The compressive strength was calculated as (maximum load / Area of surface of loading) for each panel.

Three specimens of CLC masonry panels with dimensions 1230*1250*110 mm were tested to determine the diagonal tensile or shear strength of masonry specimens according to ASTM.E519/E519M [19]. The specimens were placed diagonally at an angle of 45 degrees towards horizontal with a special support as shown in **Error! Reference source not found.**. The specimens were subjected to a compression load along the diagonal direction. A total of four LVDT-deformation transducers were used to measure the deformations. Two LVDT deformation sensors were placed in vertical direction (**V_{a1}** and **V_{b1}**) for the longitudinal deformations and two in horizontal direction (**H_{a1}** and **H_{b1}**) for the transversal deformations. The strains' measurements are used to determine the stress-strain curve of the specimen. The failure load of each specimen was recorded and the tensile strength of masonry ($\boldsymbol{f_{tm}}$) were calculated according to ASTM.E519/E519M [19] from the following relationship:

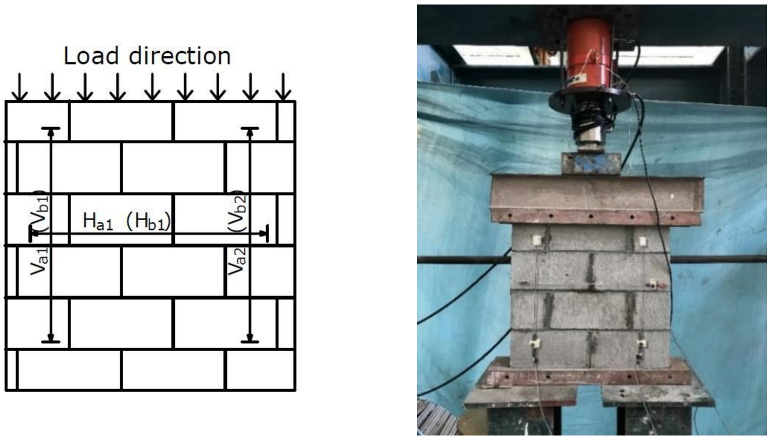
$$\boldsymbol{f_{tm}} = \frac{\boldsymbol{0.707 P_{max}}}{\boldsymbol{A_n}} \qquad (4)$$

Where $\boldsymbol{f_{tm}}$ is the Tensile strength or shear stress of masonry on net area in (MPa), $\boldsymbol{P_{max}}$ is the maximum applied load in (Newton) and $\boldsymbol{A_n}$ is the net area of the specimen in (mm^2).

Testing of triplet specimens in UTM has experimentally determined the bond shear strength retained by the joint between the brick and the mortar according to the norm BS.EN.1052-3 [18]. The specimens were composed of three bricks combined together with dimensions 390*300*200 mm as shown in **Error! Reference source not found.**. Under the two end bricks two supports were provided, and loading was applied to the center brick. This procedure made the middle brick sheared till failure and the fault load was recorded when the middle brick detached from the masonry. The bond strength is determined by dividing the load by twice the brick surface area as follows:

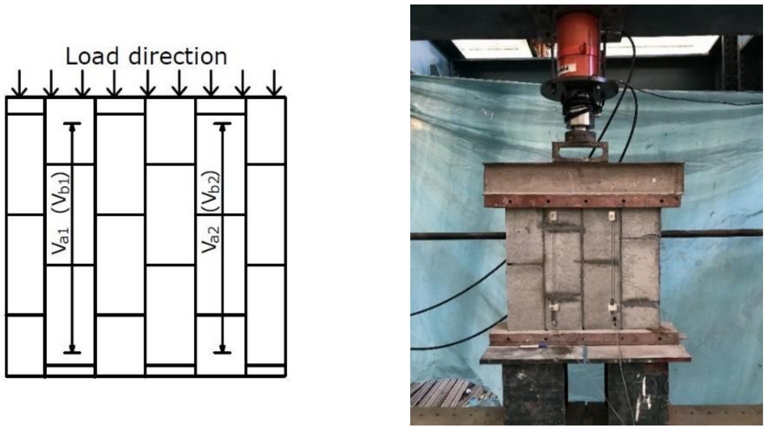
$$\tau_b = P_v / 2A \qquad (5)$$

where $\boldsymbol{\tau_b}$ is the bond stress in (MPa), $\boldsymbol{P_v}$ is the Vertical compressive load in (Newton) and $\boldsymbol{A}$ is the cross section area of the triplet prism in (mm^2).



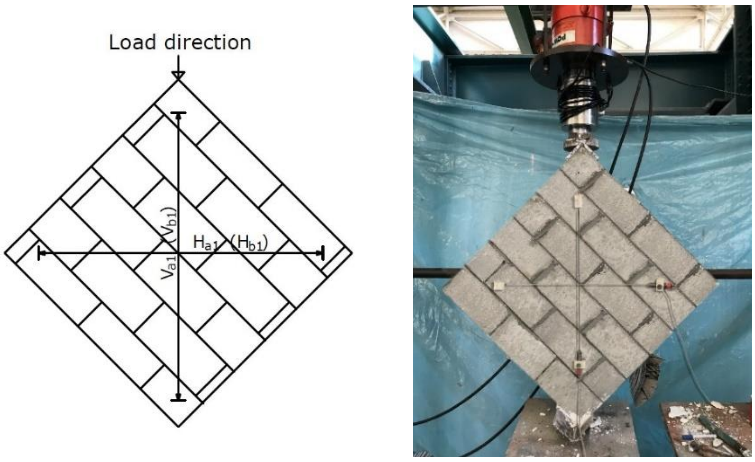
(a) **(b)**

Fig.4: Vertical configuration of compression test: (a) test layout and (b) CLC specimen



(a) **(b)**

Fig.5: Horizontal configuration of compression test: (a) test layout and (b) CLC specimen



(a) **(b)**

Fig.6: Diagonal Tension test: (a) test layout and (b) CLC specimen

Fig.7: Arrangement of the triplet test

4. Experimental results and discussions

4.1 Bricks

Error! Reference source not found. shows the characteristic properties of CLC bricks calculated from tests results illustrated in the previous section. Furthermore, stress- strain curve is determined from the relation between normal stress and normal strain in compression test due to vertical loads. Beside brick behavior clarification, it also helps in determining elasticity modulus ***(E$_b$***) of brick. **Error! Reference source not found.** shows the mean Stress-strain curves of CLC bricks.

Table 2: Results of bricks' tests

S.NO.	Compressive strength Vertical loading[a]			Horizontal loading[b]			Tensile strength[c]			Flexure strength[d]		
	P_{max} (kN)	f_{bv} (MPa)	$f_{bv\ (mean)}$ (MPa)	P_{max} (kN)	f_{bh} (MPa)	$f_{bh(mean)}$ (MPa)	P_{max} (kN)	f_{tb} (MPa)	$f_{tb(mean)}$ (MPa)	P_{max} (kN)	f_{rb} (MPa)	$f_{rb\ (mean)}$ (MPa)
1	86.5	2.4		47.52	1.98		29.7	0.789		15.2	1.19	
2	84.1	2.34		51.12	2.13		34.3	0.91		17.8	1.39	
3	81.4	2.26	**2.33**	50.16	2.09	**2.13**	25.4	0.674	**0.78**	16.4	1.28	**1.33**
4	87.1	2.42		54	2.25		28.4	0.754		18.3	1.43	
5	80.2	2.23		52.56	2.19		29.5	0.782		17.4	1.36	

Notes:
[a]area used for vertical loading in compression test are 120*300, [b]area used for horizontal loading in compression test are 120*200, [c]***L*** and ***H*** used for Tensile test are 200,120 and [d]***L***, ***b*** and ***t*** used for Flexure test are 250,120,200.

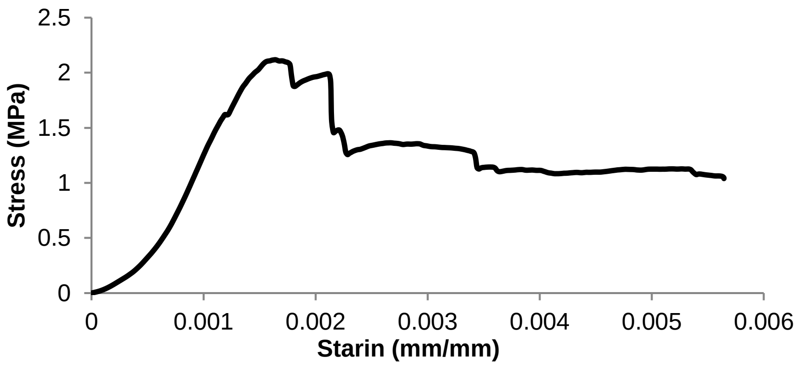
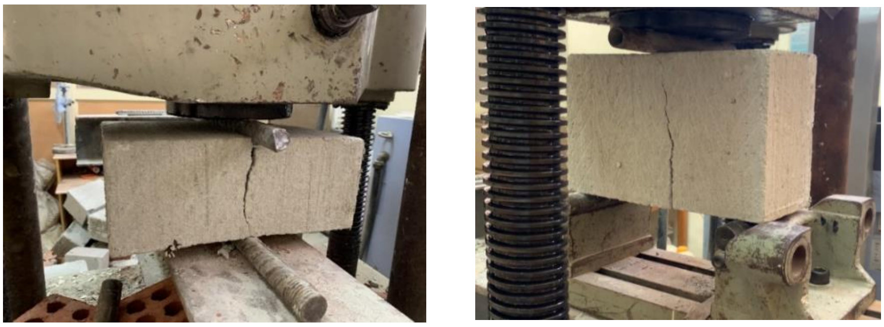


Fig.8: Stress-strain curves of bricks in compression strength test

Error! Reference source not found. shows that the behavior of CLC bricks is ductile. In addition, t he post-failure phase shows that the failure happens gradually. Stress-strain curves also helps in determination of modulus of Elasticity of brick unit (E_b) which considered an important property in finite element analysis for masonry members. The elasticity modulus (E_b) was determined from stress-strain curve as the secant slope of (30% - 60%) of the maximum estimated stress as done by some other researchers [23-25]. In this study, the secant modulus was taken at 45% of the maximum strength. The average value of elasticity modulus is determined as 2110 N/mm^2. In addition, Poisson's ratio of brick unit (υ_b) is determined from compression test due to vertical loads. It is estimated as the ratio between transversal strain to the longitudinal strain. The values of (υ_b) of the five tested samples for CLC are ranged from 0.2 to 0.27 with average 0.25. **Error! R eference source not found.** and **Error! Reference source not found.** show the failure of bricks in different tests. In compression test (vertical loading), the cracks propagated in the specimen till failure (**Error! Reference source not found.**a). While, the failure in horizontal loading is occurred due to a vertical crack extended from top to bottom (see **Error! Reference source not found.**b). In tensile test, the failure is recognized as a vertical crack initiated from the top to the bottom of the sample as shown in **Error! Reference source not found.**a causing the specimen to split into two parts. Finally, in flexure test, the failure is recognized as a vertical crack initiating at the bottom and propagating to the top of the sample as shown in **Error! Reference source not found.**b. It has been noticed that the failure of CLC bricks are ductile and happens gradually. The ductile failure of CLC refers to the polypropylene fibers it contains. In addition, the gradually failure happening in CLC brick is clearly observed in its behavior in Stress-strain curves especially in the post-failure phase.

(a) (b)

Fig.9: Failure of bricks in compression test (vertical loading): (a) vertical configuration and (b) horizontal configuration



(a) (b)

Fig.10: Failure of bricks in Tensile and flexure test: (a) tensile strength test and (b) flexure strength test

4.2 *Brick Masonry panels*

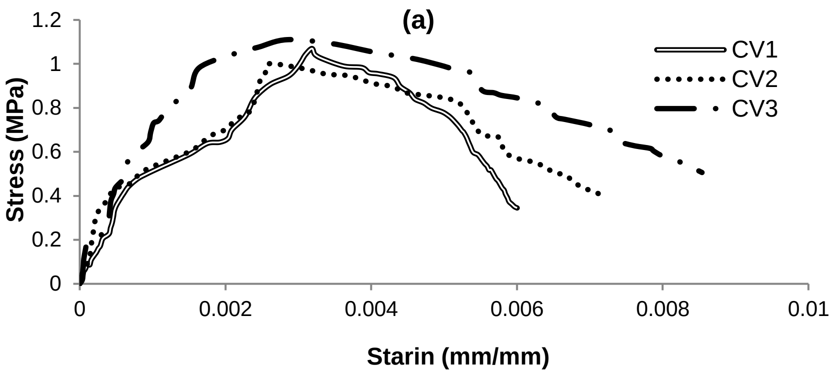
Properties of masonry depends on the properties of bricks. **Error! Reference source not found.** p resents the results of the experimental tests conducted on CLC masonry specimens illustrated in the previous section. Using the recorded loads and the corresponding displacement, stress-strain curves were determined for CLC panels as shown in **Error! Reference source not found.** and **Error! Reference source not found.**. The stress-strain curves show that the behavior of CLC panels is ductile because of its polypropylene fibers component which plays an important role in providing ductility of bricks. From compression stress-strain curves, the elasticity modulus E_m of each sample is calculated as the ratio between stress (to be one-third of the maximum force) and the mean strain value for all four measuring devices (LVDT) at a force equal to one-third of the maximum force as in the following expression:

$$E_m = \frac{P_{max}}{3\varepsilon A} \qquad (6)$$

where P_{max} is the maximum force, ε is the mean strain measured on all four LVDTs at the force equal to one third of the fracture force and A is the leaning area of the wall.
Error! Reference source not found. shows the calculated modulus of elasticity (E_m). The values o f elasticity modulus indicate that the horizontal test values are about half of their counterparts in vertical configuration. Another property calculated from vertical configuration of compression test is the Poisson's ratio of masonry (υ_m). It is calculated as the ratio between lateral strain evaluated in the perpendicular direction to the loading strain and the normal strain in vertical configuration test. The strain was determined vertically and horizontally by LVTDs attached to the specimen, then the Poisson's ratio was estimated. **Error! Reference source not found.** displays the values o f Poisson's ratio for different specimens of CLC masonry panels and the average value.

Table 3. Experimental results of brick masonry

S.NO.	Compressive strength test – Vertical configuration				Horizontal configuration			Diagonal tension test		Bond strength test	
	P_{max} (kN)	f_{mv} (MPa)	E_{mv} (MPa)	υ_m	P_{max} (kN)	f_{mh} (MPa)	E_{mh} (MPa)	P_{max} (kN)	f_{tm} (MPa)	P_{vmax} (kN)	τ_b (MPa)
1	105.3	1.07	709	0.24	128.5	1.32	410	17.54	0.127	12.93	0.107
2	98.5	1	1280	0.25	141.5	1.45	495	18.68	0.135	13.36	0.111
3	109.2	1.11	883	0.21	133.8	1.38	620	19.81	0.143	13.41	0.112
Mean	**104.3**	**1.06**	**957**	**0.23**	**134.6**	**1.38**	**508**	**18.68**	**0.135**	**13.23**	**0.11**



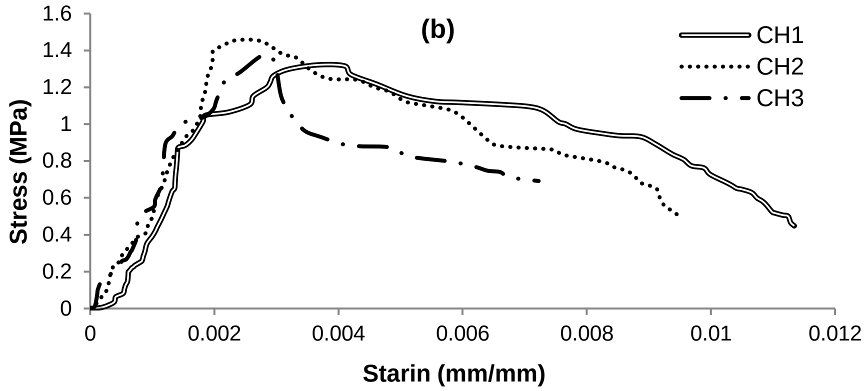


Fig.11: Stress-strain curves for different samples: (a) vertical configuration and (b) horizontal configuration

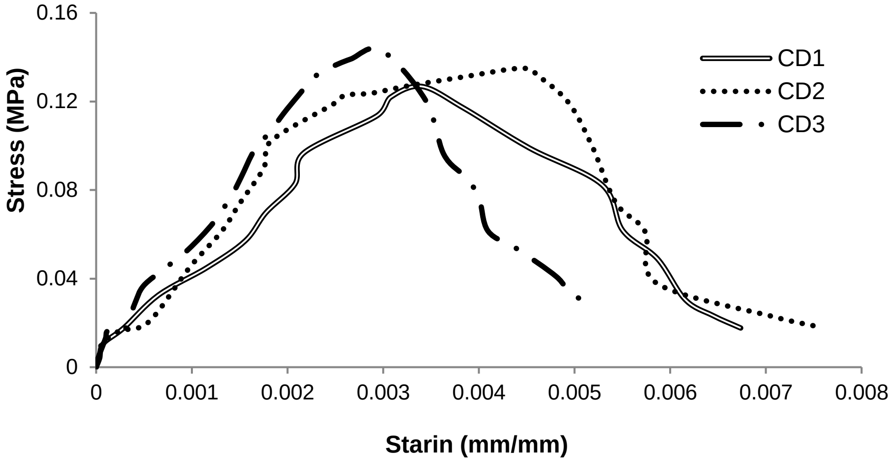


Fig.12: Stress-strain curves for diagonal tension test

The failure of specimens is shown in **Error! Reference source not found.** and **Error! Reference source not found.**. In vertical load configuration test, the failure was characterized by vertical cracks initiated at the brick unit then propagated to include the mortar and bricks as shown in **Error! Reference source not found.**a. For the horizontal configuration, the CLC masonry failure can be seen as random cracks in brick units almost diagonally then propagates in both bricks and mortar causing complete failure as shown in **Error! Reference source not found.**b. In addition, the failure degradation happens gradually in CLC panels as seen in stress-strain curves (Fig.11 and Fig.12). In diagonal tension test, the failure starting with a crack initiated in the diagonal direction of the specimen, then propagated towards the top and bottom. The crack propagated through the brick units and the mortar causing a split in the specimens into two parts almost symmetrically as shown in **Error! Reference source not found.**a. The specimens failed in triplet test as shear failure in the unit/mortar bond area on one face (see **Error! Reference source not found.**b) which was described in BS.EN.1052-3 [18].

(a) **(b)**

Fig.13: Failure of masonry's compression test: (a) vertical configuration and (b) horizontal configuration.

(a) **(b)**

Fig.14: Failure of masonry specimens: (a) diagonal tension test and (b) triplet test

5. Conclusions

This study investigates the in plane mechanical properties of bricks and masonry for CLC bricks, such as compressive strength, tensile strength, flexure strength, modulus of elasticity and Poisson's ratio. An experimental program was proposed to fulfill this scope. In this program, several tests were conducted, such as compressive strength, flexure strength, tensile strength, diagonal tension and bond strength tests. The tests were conducted according to ASTM and British standards. The findings of this study show that the average compressive strength for CLC individual brick (f_b) is 2.33 and 2.13 MPa for vertical and horizontal loading, respectively, and for masonry panels (f_m) is 1.06 and 1.38 MPa for vertical and horizontal loading, respectively. Furthermore, the average tensile strength for CLC individual brick (f_{tb}) is 0.78 MPa and for masonry panels (f_{tm}) is 0.135 MPa. The average elasticity modulus for bricks (E_b) is 2110 MPa and for masonry panels (E_m) is 957 and 508 MPa for vertical and horizontal configuration, respectively. The bond strength test showed that the strength (τ_b) for CLC bricks was 0.11 MPa. The tested properties represent the initial inputs needed to conduct nonlinear numerical analysis of the masonry.

From results, the CLC bricks have a higher performance in resisting loads because the behavior is ductile and the failure happens gradually. The high ductility of CLC bricks comes from their ability to absorb a lot of energy before complete failure and the high deformation that occurs to the CLC specimens in all tests. Based on the finding of this study, it is recommended to use CLC bricks to give the structure more flexibility and ductility especially in seismic and high wind areas. In addition, CLC bricks are a light weight material as well.

6. References

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