Towards a simple compressive strength test for earth bricks?

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J.E. Aubert[a*], P. Maillard[b], J.C. Morel[c,d], M. Al Rafii[a]

[a] Université de Toulouse; UPS, INSA; LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135 avenue de Rangueil, F-31 077 Toulouse cedex 4, France

[b] Centre Technique de Matériaux Naturels de Construction (CTMNC), Service Céramique R&D, Ester Technopole, 87069 Limoges Cedex, France

[c] Laboratoire de Tribologie et Dynamique des Systèmes, UMR 5513CNRS, Ecole Nationale des Travaux Publics de l'Etat, Université de Lyon, Rue Maurice Audin, 69518 Vaulx en Velin cedex, France

[d] Laboratoire de Génie Civil et Bâtiment, Ecole Nationale des Travaux Publics de l'Etat, Université de Lyon, Rue Maurice Audin, 69518 Vaulx en Velin cedex, France

Abstract

There is an increasing demand for earth construction in the world today but there is no consensus on the procedure to be used to measure the compressive strength of earth bricks. The study presented in this paper aims to propose a test procedure specific to earth bricks that would give the most realistic value of compressive strength while remaining as simple as possible. This study focused on four different bricks and consisted of measuring the compressive strength of these specimens by varying several parameters: specimen size, orientation, use of Teflon capping or not, and tests on dry sawn specimens, on half-bricks or on entire bricks. The results of the study show that the best compromise to achieve a simple and representative compressive strength test for earth bricks is to transform the bricks as little as possible before the test and thus to test entire bricks.

Keywords: earth bricks; compressive strength; procedures; standards; aspect ratio; confinement.

*Corresponding author. Tel. 0033 (0)5 61 55 66 97 Fax: 0033 (0)5 61 55 99 49;
e-mail: jean-emmanuel.aubert@univ-tlse3.fr

1. Introduction

Compressive strength is often considered as the most important mechanical characteristic of construction materials but its measurement has always been a subject of controversy. Regardless of the type of material tested (concrete, stone, fired bricks or earth bricks), the experimental measurement of the compressive strength depends strongly on the dimensions of the specimens, because of the confinement produced by the friction of the steel plates on the loaded surfaces of the specimen during the test. This confinement is intended to prevent the specimen from expanding radially and has the effect of delaying the destruction of the specimen, thus artificially increasing the Apparent Compressive Strength (ACS) of the material. This lateral confinement at the top and the bottom of the sample relates to the reduction of the lateral strain, which is at the origin of the fracture of the material. This artificial confinement changes the uniaxial compression test into a test closer to a triaxial compression test.

For cement-based materials (concrete or mortar), this problem is easily solved by standardizing the size of the test specimens. For example, the European standard for concrete (EN 206-1) authorizes measurement of the compressive strength of concrete on cubes or on cylinders with an aspect ratio equal to 2 (European Standard 2004). To take the effects of confinement into account, the standard gives a table of proportionality between the compressive strength values measured using these two shapes of specimens.
For masonry blocks, the British Standard considers the effects of the geometry of the blocks in the determination of the compressive strength of masonry (British Standard 1992). In the European Standard (EN 772-1) for methods of test for masonry units (European Standard 2000), the compressive strength of the blocks is standardized using a geometrical correction factor to take account of the effects of the aspect ratio (the aspect ratio is defined as the ratio between the thickness of a specimen and the smallest characteristic length of its surface). This is also the case in Australia, where the geometric variations of fired bricks or concrete blocks are also allowed for by the application of a geometrical correction factor. The empirical correction factor of Krefeld aimed to eliminate the effects of geometry by converting the values of ACS into Unconfined Compressive Strength (UCS) i.e. that obtained on a specimen having an aspect ratio of 5 (Krefeld 1938).

In the last 20 years, earth, which is certainly one of the oldest building materials, has come to be reconsidered as a pertinent material for construction in advanced economies. There are several reasons for this new attraction but the most important are the low impact of this material on the environment and its regulation of the hydrothermal conditions of the indoor climate. With the recent keen interest in sustainable development, earthen constructions have become very attractive. The consequence of this has been the appearance of scientific studies on earthen building materials and especially on their mechanical properties.

Numerous studies have dealt with the compressive strength of earth bricks (Walker 1995; Olivier et al. 1997; Morel and Pkla 2002; Venkatarama et al. 2003), usually by following the procedures developed for fired bricks or concrete blocks (Walker 1996). As with other materials, but perhaps even more for earth bricks, which cannot be considered as a brittle material, the phenomenon of confinement is significant during compressive strength testing (Morel et al. 2013). This is much more noticeable for adobes, which were traditionally manufactured in the form of plates to facilitate natural sun drying. The test procedure used to measure the compressive strength of earth bricks therefore has a very marked effect on the value found and can lead to aberrations in some cases (> 45 MPa) (Aubert et al. 2013).

The aim of this paper is to propose a test procedure specific to earth brick that will give the most realistic value of compressive strength (unconfined compressive strength) while being as simple as possible. A literature review of international standards on earth bricks will be presented to establish the state of the art on existing procedures for compressive strength testing. Then, the experimental results will be presented and analysed to propose a simple compressive strength test for earth brick. This study focuses on four different bricks and measures the compressive strength of these specimens by varying several parameters: specimen size, orientation, and use or not of Teflon capping to prevent confinement. The tests were performed on dry sawn specimens, half-bricks or entire bricks.

2. Normative review of compressive strength tests for earth bricks

The literature showed that research to find suitable procedures for measuring the compressive strength of earth bricks was oriented in three directions:

- cutting specimens of standard shape in bricks or preparing specimens of standard shape of the same composition as the brick under test (procedure similar to that used for cement-based materials),
- testing the bricks directly,
- cutting bricks in two halves and superposing the two half-bricks to increase the aspect ratio and thus reduce the effects of confinement.

Several studies in the literature report tests performed on specimens of standard shape to characterize the compressive strength of earth bricks. Venkatarama et al. (2003) cut cubes in earth brick blocks and tested them in direct compression. However, comparison of tests carried out on bricks or on cubes of the same material showed poor correlation concerning the compressive strength. More recently, Silveria et al. (2013) have studied the influence of the testing procedures in the mechanical characterization of adobe bricks. These authors studied adobe bricks collected from three houses in different locations of the Aveiro District (Portugal). The sizes of the adobe bricks were: 0.41x0.28x0.13 m^3, 0.46x0.32x0.12 m^3 and 0.44x0.24x0.12 m^3. Cylindrical specimens were extracted from adobe bricks by rotary core drilling for simple compression tests and for splitting tests, and cubic specimens were cut from the same bricks. Cylindrical and cubic adobe specimens were subjected to simple compression tests, adobe bricks to flexural tests, and cylindrical adobe specimens to splitting tests. No test was carried out directly on the adobe bricks, which meant that the compressive strength measured on "standard" specimens (cubic or cylindrical specimens) could not be compared to that of the bricks.

The literature showed that many international standards specified the use of procedures drawn up for fired bricks or concrete blocks for the measurement of the compressive strength of earth brick (Walker 1996). The bricks were tested directly between the platens of a press. The surfaces of the bricks were often sufficiently flat and parallel for only a thin sheet of plywood to be needed to cap them. The bricks were usually tested in the direction in which they were manufactured, which is also the direction in which they are generally used in walls. From 5 to 10 bricks were usually tested for the compressive strength measurement.

The effects of geometry on the compressive strength of the bricks were usually studied in two ways. In some cases, the authors did not seek to correct the results and did not take the effects of confinement into account (Vilane 2010).
In another approach, applied in Australia (2002) and New Zealand (1998), the effects of confinement were taken into account by reducing the compressive strength by a correction factor depending on the aspect ratio of the bricks. The correction factors used in these studies

were usually the same as those used for fired bricks. Other studies have suggested other correction factors more suited to Compressed Earth Blocks (CEB) (Heathcote and Jankulovski 1992). These correction factors are presented in Table 1.

Table 1: Aspect ratio correction factors

Aspect ratio	0	0.4	0.7	1.0	3.0	≥5.0
Krefeld's correction factor (using linear interpolation) (1938)	0	0.50	0.60	0.70	0.85	1.00
Heathcote and Jankulovski's correction factor (non-linear) (1992)	0	0.25	0.40	0.58	0.90	1.00

Finally, in an attempt to directly measure unconfined compressive strength, CEB RILEM Technical Committee 164 has proposed the test set-up shown in Fig. 1 (Olivier et al. 1997). To double the aspect ratio of the test specimens, bricks were halved, stacked and bonded using an earth mortar bed joint. The earth mortar joint replicated masonry construction and enabled even, uniform stress transfer between stacked blocks.
However, the presence of this joint has consequences on the overall behaviour of the system as the mortar joint, even if it is composed of the same material as the bricks, is less rigid than the bricks because of its high initial water content and the lack of compaction. In addition, the quality of the mortar joint (and thus its properties) depends strongly on the experimenter, which will add another variable parameter during the test.
To enable even transfer of stress between platens and blocks, the specimens were capped with a layer of neoprene. A sheet of Teflon was also placed between the platen and the specimen at each end to minimize friction. Half blocks were prepared as in a splitting strength test, an indirect tensile strength test similar to the Brazilian test performed on concrete cylinders.

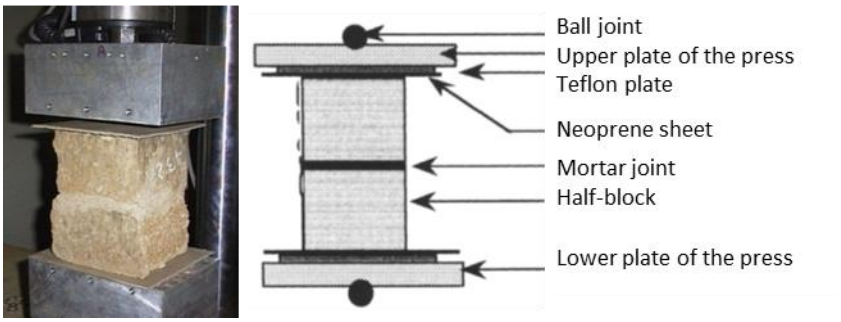


Figure 1: Experimental device developed by Olivier et al. (1997) and adopted by RILEM TC 164.

Some tests were carried out using the Rilem procedure on CEB and the results were compared with those obtained using tests carried out on cylindrical specimens manufactured by double compaction or on half-bricks composed of the same materials as the bricks. These validation tests were performed independently in three international research laboratories (Hakimi et al. 1996; Olivier et al. 1997; Pkla 2002) and the results are shown in Figure 2.

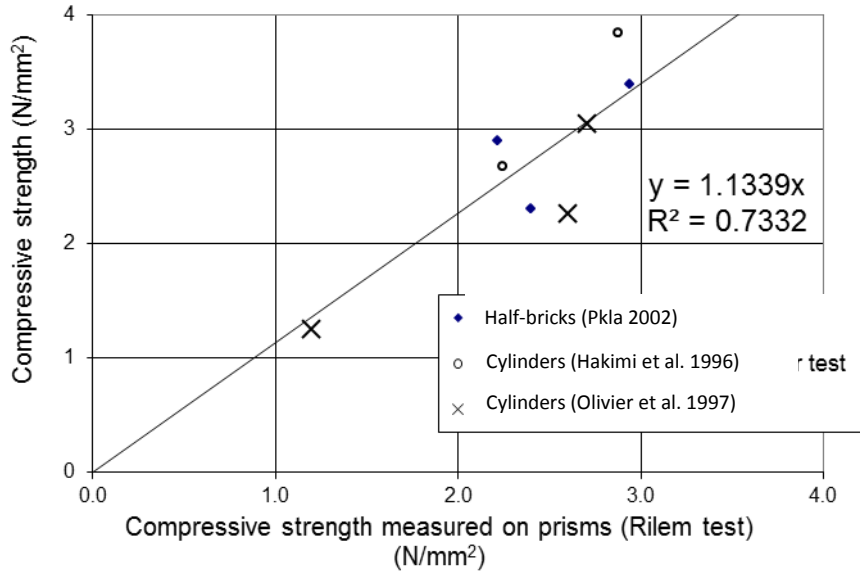


Figure 2: Comparison between tests carried out on cylinders or half-bricks and the Rilem test

Each point of the graph corresponds to the mean value of 2 to 13 repeated tests. On average, the RILEM test underestimates the compressive strength of the earth bricks (by approximately 15%). The authors of this study concluded that this difference was small enough to justify the use of this test for the measurement of earth bricks' compressive strength (Morel et al. 2007).

There are few international standards on earth bricks and the majority of them are on CEB. In France, an experimental standard, XP P13-901 (2001), deals with the characterization of stabilized or non-stabilized CEB (French Standard 2001). For the measurement of compressive strength, the procedure of stacked half-bricks (Rilem test) presented above is used. The only difference between this standard and the Rilem test is the nature of the mortar used for the joint, which is a traditional cement mortar (sand and cement) here rather than an earth mortar.

In 2013, Germany produced a standard for earth bricks (DIN 18945 (German Standard 2013)). This standard deals only with earth brick without binder whatever the mode of production (compressed, extruded or moulded). For the measurement of the compressive strength, this standard proposes two different procedures depending on the geometry of the bricks. For bricks having a thickness greater than 71 mm, it is possible to test the compressive strength directly on the entire brick loaded according to its direction of laying. But for the others, the German standard recommends the use of the Rilem procedure (tests on half- blocks bonded with cement mortar or plaster).

As mentioned above, Australia and New Zealand use the same procedure for earth bricks as that used for fired bricks, with the same aspect ratio correction factors. The Spanish Standard on earth bricks, UNE 41410, uses the same approach (Spanish Standard 2008). The test recommended for the measurement of compressive strength of earth bricks is that used for masonry units (concrete blocks and fired bricks) presented in EN 772-1 (European Standard 2000). In this standard, aspect ratio correction factors are presented (Table 2). Table 2 shows that these correction factors depend on the aspect ratio but vary depending on the width of the brick. A brick with a smaller width results in a reduced correction factor for the same aspect ratio.

Table 2: Aspect ratio correction factors for masonry units according to EN 772-1 (European Standard 2000)

Width (mm) Height (mm)	50	100	150	200	≥250
40	0.80	0.70	-	-	-
50	0.85	0.75	0.70	-	-
65	0.95	0.85	0.75	0.70	0.65
100	1.15	1.00	0.90	0.80	0.75
159	1.30	1.20	1.10	1.00	0.95
200	1.45	1.35	1.25	1.15	1.10
≥250	1.55	1.45	1.35	1.25	1.15

Maskell et al. (2013) compared the values of the standard EN 772-1 with experimental results of compression tests on extruded earth bricks having various aspect ratios, by changing the thickness of the brick. The experimental results obtained by the authors on earth bricks did not fit the values of the standard for aspect ratios higher than 1 and the authors explained that these values were developed for fired bricks, which have a significantly higher compressive strength and may therefore be less susceptible to crushing.

This brief literature review of tests used for measuring the compressive strength of earth bricks shows that there is no consensus on the procedure to be used. The standards consider the effect of confinement in two ways: by artificially increasing the height of the bricks by cutting them in half and stacking the two resulting pieces or by using aspect ratio correction factors originally intended for other materials. These two solutions have limits and further studies on procedures suitable for the measurement of compressive strength on earth bricks, e.g. that presented in this paper, seem to be necessary.

2. Materials and methods

2.1 Materials

The tests were carried out on four types of earth bricks produced in France. These bricks were manufactured by extrusion in four different brickworks. The objective of this study was not to analyse the characteristics of the bricks and link them to their compressive strength but to have several different bricks (if possible having different compressive strengths) to validate the procedures used on various specimens.

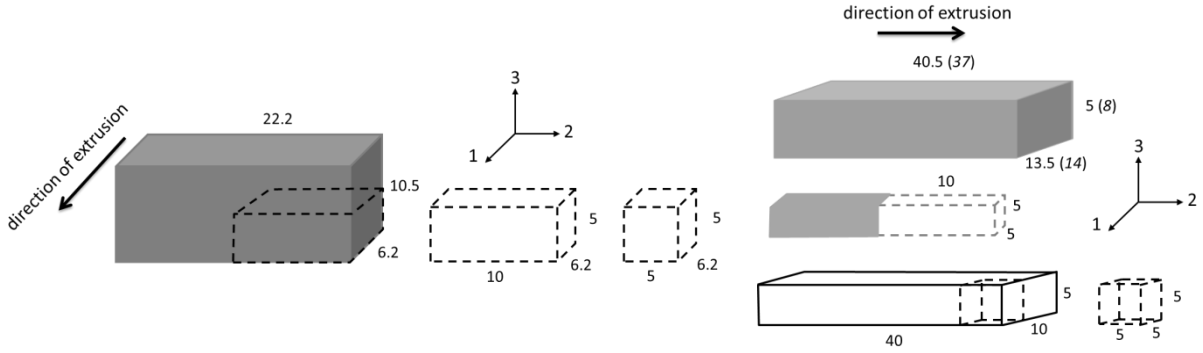
The four bricks studied had the sizes and densities (measured on bricks cured in an air-conditioned room at 20°C and 50% relative humidity until their mass was constant) shown in Table 3 and Figure 3.

Table 3: Dimensions and densities of the bricks

Brick	h (mm)	l (mm)	L (mm)	ρ (g.cm^{-3})
Brick 1	62	105	222	2110 ± 20
Brick 2	62	105	222	1680 ± 20
Brick 3	50	135	405	2220 ± 20
Brick 4	80	140	370	2210 ± 20

The extrusion direction for bricks 1 and 2 was different from that of bricks 3 and 4 as shown in Figure 3. Moreover, the preparation of the 5x5x10 cm^3 and the 5x5x5 cm^3 specimens was also different:

- For bricks 1 and 2, the 5x5x10 cm^3 specimens (real dimensions were 5x6.2x10.5 cm^3) were sawn from bricks as shown in Fig 3. Then, the specimens were cut in half to obtain two cubic specimens,
- For bricks 3 and 4, the 5x5x10 cm^3 specimens were prepared in the brickworks at the outlet of the extruder according to the orientation shown in Fig. 3. The 5x5x10 cm^3 specimens of bricks 3 and 4 had the same densities as the bricks. The 5x5x5 cm^3 specimens were cut from 40x10x5 cm^3 plates manufactured specifically for this study as presented in Fig. 3.



a) Brick 1 and brick 2 b) Brick 3 (*brick 4*)

Figure 3: Extrusion of bricks and preparation of specimens

2.2 Procedures

The compression tests were carried out using two types of hydraulic press depending on the size of the specimens: one press with a capacity of 50 kN for the smallest specimens (5x5x10 cm^3 and the 5x5x5 cm^3) and another with a capacity of 2500 kN for the tests on complete bricks. In both cases, the tests were run at a constant rate of 0.08 $MPa.s^{-1}$. Before the tests, the specimens were cured in an air-conditioned room at 20°C and 50% relative humidity until their mass was constant, because the moisture content of soil blocks is considered to have a strong effect on their compressive strength (Morel et al. 2007; Jaquin et al. 2009; Bui et al. 2014). In this study, bricks and specimens were prepared industrially and they were thus sufficiently flat and parallel for no specific capping to be necessary to correct them (except for the tests on the effects of capping with Teflon (plates 2 mm thick) to avoid confinement).

Table 4 describes the various tests. For each test, the size of the specimens and the orientation are detailed. The properties of earthen construction materials (and in particular their homogeneity and anisotropy) depend strongly on the technique used for their manufacture. In the case of extrusion, there is potential for particle alignment during the process, due to friction and the tapering of the extrusion, as has already been observed for fired bricks (Kornmann 2007). It is thus possible that extruded unfired earth bricks are anisotropic, so it is important, initially, to take the orientation of the specimens into account: the two directions "parallel" and "perpendicular" to the plane of extrusion were considered (Fig. 3).

The half-bricks were prepared according to French standard XP P13-901 (French Standard 2001), in which half-bricks are bonded using a cement mortar bed joint. In this study, two different tests were carried out to study the effect of this joint on the compressive strength of

the material: half the specimens were joined with a cement mortar as recommended by the French standard XP P13-901 and the other half were simply stacked without any jointing material.

Table 4: Orientations relative to the plane of extrusion of the specimens during the compressive tests

Test	Specimen size (cm)	Bricks 1 and 2	Bricks 3 and 4
Aspect ratio	5x5x10	2 (parallel)	1 (parallel)
	5x5x5	2 (parallel)	2 (parallel)
Capping with Teflon	5x5x5	2 (parallel)	3 (perpendicular)
Anisotropy	5x5x5	3 (perpendicular)	3 (perpendicular)
Horizontal bricks and stacked half-bricks	-	1 (parallel)	3 (perpendicular)
Vertical brick	-	2 (parallel)	1 (parallel)

3. Results

3.1 Aspect ratio effects

Table 5 shows the compressive strength of 5x5x10 cm^3 and 5x5x5 cm^3 specimens for the four bricks. In this part of the study, no capping was used and the specimens were directly tested between the platens of the press. For each series of results, the minimum (f_{cmin}), maximum (f_{cmax}) and average ($\overline{f_c}$) values are presented and the variability of the results is taken into account by considering the standard deviation (σ_{fc}) expressed in %.

Table 5: Compressive strength of 5x5x10 cm^3 and 5x5x5 cm^3 specimens

Specimens	Brick 1		Brick 2		Brick 3		Brick 4	
Size (cm^3)	5x5x10	5x5x5	5x5x10	5x5x5	5x5x10	5x5x5	5x5x10	5x5x5
1	7.5	7.1	1.7	1.9	5.5	6.2	5.0	3.1
2	6.8	8.7	2.3	1.9	5.5	6.0	5.0	3.7
3	5.0	8.8	2.5	1.5	5.8	5.2	5.6	4.1
4	5.9	6.0	2.1	1.5	5.5	2.9	5.1	4.0
5	6.1	7.2	2.1	1.8	3.9	4.5	4.6	3.7
6	3.0	7.1	1.7	2.1	4.4	6.8	4.8	3.9
f_{cmin} (MPa)	**3.0**	**6.0**	**1.7**	**1.5**	**3.9**	**2.9**	**4.6**	**3.1**
f_{cmax} (MPa)	**7.5**	**8.8**	**2.5**	**2.1**	**5.8**	**6.8**	**5.6**	**4.1**
$\overline{f_c}$ (MPa)	**5.7**	**7.5**	**2.1**	**1.8**	**5.1**	**5.3**	**5.0**	**3.8**
σ_{fc} (%)	**27**	**14**	**16**	**14**	**15**	**27**	**7**	**10**
$\overline{f_c}_{5x5x5} / \overline{f_c}_{5x5x10}$	**1.3**		**0.9**		**1.0**		**0.8**	

The results obtained on the 5x5x10 cm^3 specimens show that the average compressive strength of the bricks ranged from 2.1 MPa (brick 2) to 5.7 MPa (brick 1). Table 5 also shows that the variability of the results was very high (standard deviation of 7% to 27%), since, in the worst cases (brick 1), the results of the 6 specimens ranged between 3.0 MPa and 7.5 MPa. This problem of significant variability, highlighted by the high values of the standard deviations, was observed in the cases of 5x5x5 cm^3 cubic specimens too: the example of brick 3 illustrates this problem since, on six tests, five results were in the 4.5 to 6.8 MPa range and one specimen had a very low compressive strength of 2.9 MPa. This large variability on the mechanical strength of earthen materials has often been observed and can be partly explained by problems of homogeneity in the materials. In addition, the specimen preparation by dry

sawing using a grinder generates strong vibrations that could produce microcracking in such small samples and thus affect their compressive strength. This will have to be verified in further work but, for this study, it is possible to consider that the tests results were comparable, the various specimens being cut following the same procedure.
The effect of reducing the aspect ratio from 2 (5x5x10 cm^3) to 1 (5x5x5 cm^3) varied depending on the brick considered: for the strongest brick (brick 1), an increase of 30% was observed but, for the brick 3, the compressive strength was unchanged and, for bricks for 2 and 4, it decreased. The experimental results were contrary to those expected. A decrease in the aspect ratio should theoretically lead to an increase in compressive strength due to the confinement phenomenon. As noted before, the potential damage when a specimen is dry sawn could be an explanation for this. For bricks 3 and 4, 5x5x10 cm^3 specimens were not sawn using a grinder but were cut directly at the outlet of the extruder in samples of bricks still in their plastic state before drying. If the dry sawing partially damaged specimens, the 5x5x10 cm^3 specimens would not be affected by it, unlike the 5x5x5 cm^3 specimens that were sawn in dry bricks. For bricks 1 and 2, both types of specimens were dry sawn but brick 1 had much higher resistance than brick 2. Brick 1 probably resisted dry sawing better and this could explain why it was the only brick for which an increase in compressive strength was observed when the aspect ratio increased.

3.2 Effects of capping with Teflon

A solution for avoiding or, at least, limiting confinement is to decrease the friction between the specimens and the platens of the press. For this, it is possible, for example, to insert a plate of Teflon between the two surfaces in contact. Tests were performed on specimens having the lowest aspect ratio (5x5x5 cm^3), for which confinement should be the most significant. Table 6 shows the results of compressive strength measured when the specimen was capped with Teflon (plate 2 mm thick) compared with when it was left uncapped.

Table 6: Comparison of compressive strength of 5x5x5 cm^3 specimens with or without Teflon capping

5x5x5 cm^3 specimens	Brick 1		Brick 2		Brick 3		Brick 4	
With or without Teflon	Without	With	Without	With	Without	With	Without	With
1	7.1	9.6	1.9	2.3	6.1	6.1	3.6	4.4
2	8.7	6.1	1.9	1.8	7.1	5.0	4.9	4.0
3	8.8	7.1	1.5	1.3	6.2	6.3	4.3	3.4
4	6.0	6.4	1.5	2.0	7.3	7.5	4.8	4.7
5	7.2	8.6	1.8	2.0	6.3	7.5	4.1	4.5
6	7.1	5.4	2.1	1.6	7.4	5.4	4.9	3.8
f_{cmin} (MPa)	**6.0**	**5.4**	**1.5**	**1.3**	**6.1**	**5.0**	**3.6**	**3.4**
f_{cmax} (MPa)	**8.8**	**9.6**	**2.1**	**2.3**	**7.4**	**7.5**	**4.9**	**4.7**
$\overline{f_c}$ (MPa)	**7.5**	**7.2**	**1.8**	**1.8**	**6.7**	**6.3**	**4.4**	**4.1**
σ_{fc} (%)	**14.4**	**22.2**	**13.5**	**19.1**	**8.8**	**16.5**	**11.9**	**11.8**
$\overline{f_c}_{\text{ with}} / \overline{f_c}_{\text{ without}}$	**1.0**		**1.0**		**0.9**		**0.9**	

The ratios of the average values obtained on specimens without Teflon capping compared to those with Teflon capping ranged between 0.9 and 1.0. The effects of the capping with such a procedure (using only a 2 mm thickness of Teflon) were very small: a slight decrease of compressive strength (10% on average) could be observed when the Teflon was used. That is

consistent with the decrease of friction and consequently the effects of confinement, because confinement leads to an artificial increase in compressive strength. Moreover, Table 6 shows that capping with Teflon did not reduce the high variability of results. In fact, for bricks 1, 2 and 3, the standard deviations of compressive strength measured with Teflon capping were higher.

3.3 Effects of anisotropy

Table 7 shows the compressive strength of 5x5x5 cm^3 specimens for the four bricks measured in two perpendicular load directions (parallel (paral.) and perpendicular (perp.) to the extrusion plane, see Table 4). In this part of the study, no capping was used and the specimens were tested directly between the platens of the press.

Table 7: Comparison of compressive strength of 5x5x5 cm^3 specimens depending on the load direction

5x5x5 cm^3 specimens	Brick 1		Brick 2		Brick 3		Brick 4	
Direction	Paral. (2)	Perp. (3)	Paral. (2)	Perp. (3)	Paral. (2)	Perp. (3)	Paral. (2)	Perp. (3)
1	7.1	8.4	1.9	2.3	6.2	6.1	3.1	3.6
2	8.7	8.6	1.9	3.4	6.0	7.1	3.7	4.9
3	8.8	9.1	1.5	2.5	5.2	6.2	4.1	4.3
4	6.0	8.4	1.5	2.3	2.9	7.3	4.0	4.8
5	7.2	8.2	1.8	3.1	4.5	6.3	3.7	4.1
6	7.1	9.1	2.1	2.3	6.8	7.4	3.9	4.9
f_{cmin} (MPa)	**6.0**	**8.2**	**1.5**	**2.3**	**2.9**	**6.1**	**3.1**	**3.6**
f_{cmax} (MPa)	**8.8**	**9.1**	**2.1**	**3.4**	**6.8**	**7.4**	**4.1**	**4.9**
$\overline{f_c}$ (MPa)	**7.5**	**8.6**	**1.8**	**2.7**	**5.3**	**6.7**	**3.8**	**4.4**
σ_{fc} (%)	**14**	**4**	**14**	**18**	**27**	**9**	**10**	**12**
$\overline{f_c}$ (3) / $\overline{f_c}$ (2)	**1.2**		**1.5**		**1.3**		**1.2**	

The results show that the compressive strength seems to depend on the loading direction: the values obtained for a loading direction perpendicular to the extrusion plane ("perpendicular", direction 3) were always higher than the values obtained when the loading direction was parallel to the extrusion plane ("parallel", direction 2). The anisotropy factor (ratio between compressive strength measured in the perpendicular direction to that measured in the parallel direction) ranged between 1.2 and 1.5 for the four bricks. This large anisotropy of extruded earth brick has already been observed by Maillard and Aubert (2014) on the hygrothermal properties of these materials. The authors showed that the thermal conductivity and the water vapour permeability depended strongly on the direction in which these properties were measured. Although the bricks studied in the two works were different, it is interesting to compare the values of anisotropy factors: for thermal conductivity, the anisotropy factors ranged from 1.2 to 1.8 and, for the water vapour permeability, the range was from 1.3 to 1.9. For hygrothermal properties, anisotropy also seems to be slightly greater than for mechanical properties but, in both cases, the properties of extruded earth bricks were anisotropic.

As explained by Maillard and Aubert (2014), this anisotropic behaviour of the extruded earth bricks is due to the extrusion process: during this process, the clay platelets orientate themselves in the direction of extrusion due to the effect of the parallel sides of the extruder outlet. This preferred orientation depends on the width of the extruder outlet (i.e. the width of the extruded bricks) because the vertical sides of the extruder outlet orientate the clay platelets

vertically. The majority of extruded bricks (and, in particular, the bricks studied in this paper) are much wider than they are high and, thus, the clay platelets are globally orientated in the direction of extrusion. This phenomenon, little studied in the literature, is well known by brick manufacturers in fired clay bricks (Kornmann 2007; Jacqus et al. 2011). Jacqus et al. (2011) considered this anisotropic behaviour for the prediction and the physical understanding of sound transmission through fired clay masonry. Bourret (2012) provided XRD and SEM evidence that clay platelets are oriented in the direction of extrusion on extruded kaolin-based foams.

3.4 Direct tests on entire bricks

Table 8 shows the compressive strength measured directly on entire bricks in two orientations: horizontal or vertical ("horizontal" means that brick is laid so that its largest dimension is in the horizontal plane). For each test, the direction in comparison with the plane of extrusion is recalled. The results obtained on 5x5x10 cm^3 specimens in the same direction were added to facilitate comparison with the previous results of this study. In this part of the study, no capping was used and the bricks were directly between the platens of the press during testing.

Table 8: Compressive strength measured directly on entire bricks in two orientations (horizontal or vertical)

Specimens	Brick 1		Brick 2		Brick 3		Brick 4	
Orientation	horiz.	vert.	horiz.	vert.	horiz.	vert.	horiz.	vert.
Direction	paral.	paral.	paral.	paral.	perp.	paral.	perp.	paral.
Aspect ratio	0.6	3.6	0.6	3.6	0.4	8.1	0.6	4.6
1	10.2	8.4	3.1	2.5	not possible	3.2	4.6	3.5
2	9.7	7.6	2.8	2.7		4.3	4.5	3.8
3	10.3	7.8	3.2	2.3		3.8	4.7	3.4
4	11.4	6.9	3.0	2.6		3.9	4.4	3.4
5	10.4	7.3	3.3	2.3		4.1	4.8	3.9
6	12.0	6.2	3.5	2.2		3.7	5.1	4.5
f_{cmin} (MPa)	**9.7**	**6.2**	**2.8**	**2.2**		**3.2**	**4.4**	**3.4**
f_{cmax} (MPa)	**12.0**	**8.4**	**3.5**	**2.7**		**4.3**	**5.1**	**4.5**
$\overline{f_c}$ (MPa)	**10.7**	**7.4**	**3.2**	**2.4**		**3.8**	**4.7**	**3.8**
σ_{fc} (%)	**8**	**10**	**8**	**8**		**10**	**5**	**11**
$\overline{f_c}$ horiz/ $\overline{f_c}$ vert	**1.4**		**1.3**		**not possible**		**1.2**	

It is interesting to distinguish bricks 1-2 and bricks 3-4 for the analysis of the results presented in Table 8. For bricks 1 and 2, the change in the orientation of the brick changed the aspect ratio but the load direction compared to the extrusion plane was the same. That was not the case for bricks 3 and 4, however, because the change in orientation of the bricks for the test changed the direction compared to the extrusion plane. The tests carried out on these bricks cumulated the effects due to the change in aspect ratio and those linked to the anisotropy highlighted in section 3.3.

The results obtained on bricks 1 and 2 were similar: the compressive strength was very different depending on the orientation of the brick (horizontal or vertical) and that could be directly linked to the change in aspect ratio from 0.6 (brick 1) to 3.6 (brick 2). The ratios of compressive strength measured in the two orientations were quite similar: 1.4 for brick 1 and 1.3 for brick 2.

The case of brick 3 was very interesting since it was impossible to break this brick when it was placed horizontally. This result has been published by Aubert et al. (2013) and can be explained by the fact that the specific dimensions of the brick (small height and large area (h=5 cm, l=13.5 cm and L=40.5 cm)) led to such a significant increase in the confinement (corresponding to artificial lateral forces due to the friction between the specimens and the platens of the press) that this test became more comparable to an oedometric test, which led to settlement but did not permit the rupture point of the specimen to be reached. It is important to note that the size of this brick seemed unusual compared to other industrial bricks but was similar to many from heritage adobe buildings. The special shape of adobes from heritage was essentially linked to how they were manufactured (plastic earth moulded in a wooden mould and sun dried) because their small height (generally 5 cm) compared to a significant laying surface facilitated their sun drying. Thus, this experimental "problem" related to the inability to measure compressive strength on samples with small height relative to their surface would also occur if the majority of adobes from the heritage were tested.

The results obtained on brick 4 are difficult to analyse because the effects of the aspect ratio and the anisotropy accumulate for this brick. The $\overline{f_c}_{\text{ horiz}}/\ \overline{f_c}_{\text{ vert}}$ ratio was equal to the anisotropy ratio (Table 7), meaning that the value of the aspect ratio had no effect on the value of the compressive strength in this case but it is difficult to draw conclusions when the interactions of several phenomena have various effects on the compressive strength.

Finally, Table 8 shows that, in all cases, the variability of results was significantly lower when the tests were carried out directly on the bricks rather than on sawn specimens. This last point is a strong argument in favour of performing mechanical tests directly on bricks.

3.5 Tests on half-bricks

Table 9 shows the compressive strength measured directly on half bricks with two different procedures. Half the specimens were joined with a cement mortar as recommended by the French standard and the other half were simply stacked without any joint. In this part of the study, no capping was used and the bricks were tested directly between the platens of the press.

Table 9: Compressive strength measured directly on half-bricks with or without cement mortar joint

Specimens	Brick 1		Brick 2		Brick 3		Brick 4	
Direction	paral.		paral.		perp.		perp.	
Aspect ratio	1.2		1.2		0.7		1.1	
Joint	without mortar	with mortar	without mortar	with mortar	without mortar	with mortar	without mortar	with mortar
1	6.9	5.8	1.6	1.8	7.3	4.9	3.6	3.8
2	6.7	5.6	1.3	1.6	7.2	5.1	3.8	3.9
3	6.2	5.3	1.4	1.6	7.5	5.7	4.1	3.9
4	4.8	6.6	1.4	1.7	6.1	5.5	3.6	3.6
5	5.2	5.4	1.6	1.8	6.4	5.5	3.9	3.4
6	5.6	4.7	1.6	1.7	6.9	5.5	3.5	2.7
f_{cmin} (MPa)	**4.8**	**4.7**	**1.3**	**1.7**	**6.1**	**4.9**	**3.5**	**2.7**
f_{cmax} (MPa)	**6.9**	**6.6**	**1.6**	**1.8**	**7.5**	**5.7**	**4.1**	**3.9**
$\overline{f_c}$ (MPa)	**5.9**	**5.6**	**1.5**	**1.7**	**6.9**	**5.4**	**3.8**	**3.6**
σ_{fc} (%)	**14**	**11**	**9**	**5**	**8**	**6**	**6**	**13**

The results in Table 9 confirm that the procedure significantly increased the aspect ratio, the values of which ranged from 0.7 to 1.2 compared to values ranging from 0.4 to 0.6 when the tests were carried out directly on the bricks laid horizontally (the main objective of this procedure). This led to a decrease in compressive strength for the four bricks: from 10.7 MPa to 5.9 MPa for brick 1, from 3.2 MPa to 1.7 MPa for brick 2 and from 4.7 MPa to 4.1 MPa for brick 4. The specific case of brick 3 is very interesting because the test on stacked half-bricks made the measurement of compressive strength possible, which was not the case for the test carried out on entire bricks laid horizontally.

Moreover, the comparison of the compressive strengths measured on the stacked half-bricks with or without a cement mortar joint shows that the presence of a joint had hardly any effect for bricks 1, 2 and 4. However, in the case of brick 3, the use of cement mortar to join the two stacked half-bricks led to a significant decrease of the compressive strength, from 6.9 MPa to 5.4 MPa. This result could be explained by a greater sensitivity of this brick to moisture: applying wet cement mortar would lead to a significant drop in the compressive strength of the brick. This is sometimes observed on extruded earth bricks that contain too much clay. They are too sensitive to water and thus impossible to use in masonry. This result is interesting because it shows that this test procedure (cutting bricks into two halves and joining them with wet mortar) measures not only the compressive strength of a brick but also its sensitivity to the application of a wet mortar joint and consequently the possibility of using it in masonry. So, this corresponds more to a technological test of use than to a simple, relevant and reproducible test for measuring the compressive strength of earth bricks, because too many parameters are involved. The results show that stacking without mortar could be an alternative that would artificially increase the aspect ratio without changing the intrinsic behaviour of the brick by using a wet mortar. In addition, it has the advantage of greatly simplifying the use of this procedure. This procedure is applicable only to industrial bricks, such as those tested in this work, because their surfaces are sufficiently flat and parallel, but it would be impossible with traditional adobe from heritage buildings, where the laying surfaces are too irregular.

Table 9 shows that, as in the test on entire bricks, the variability of the results was relatively low compared to that of the tests on sawn specimens.

4. Discussion

Table 10 shows a synthesis of the compressive strength of the four bricks measured on various types of specimens. These results were obtained without any capping and all in the "parallel" direction: for tests on bricks (horizontal) and half-bricks in the cases of bricks 3 and 4, the results were divided by the anisotropy ratio determined in Table 7 (results marked * in Table 10; the numbers in brackets are the results obtained without the correction by the anisotropy ratio). These results are reported in Figure 4.

Table 10: Synthesis of the compressive strength measured on various specimens of the four bricks

Specimens	Brick 1		Brick 2		Brick 3		Brick 4	
	Aspect ratio	$\overline{f_c}$ (MPa)	Aspect ratio	$\overline{f_c}$ (MPa)	Aspect ratio	$\overline{f_c}$ (MPa)	Aspect ratio	$\overline{f_c}$ (MPa)
Bricks (horiz.)	0.6	10.7	0.6	3.2	0.4	-	0.6	3.8* (4.7)
5x5x5 cm^3	1	7.5	1	1.8	1	5.3	1	3.8
Half-bricks (without mortar)	1.2	5.9	1.2	1.5	0.7	5.3* (6.9)	1.1	3.1* (3.8)
5x5x10 cm^3	2	5.7	2	2.1	2	5.1	2	5.0
Bricks (vert.)	3.6	7.4	3.6	2.4	8.1	3.7	4.6	3.8

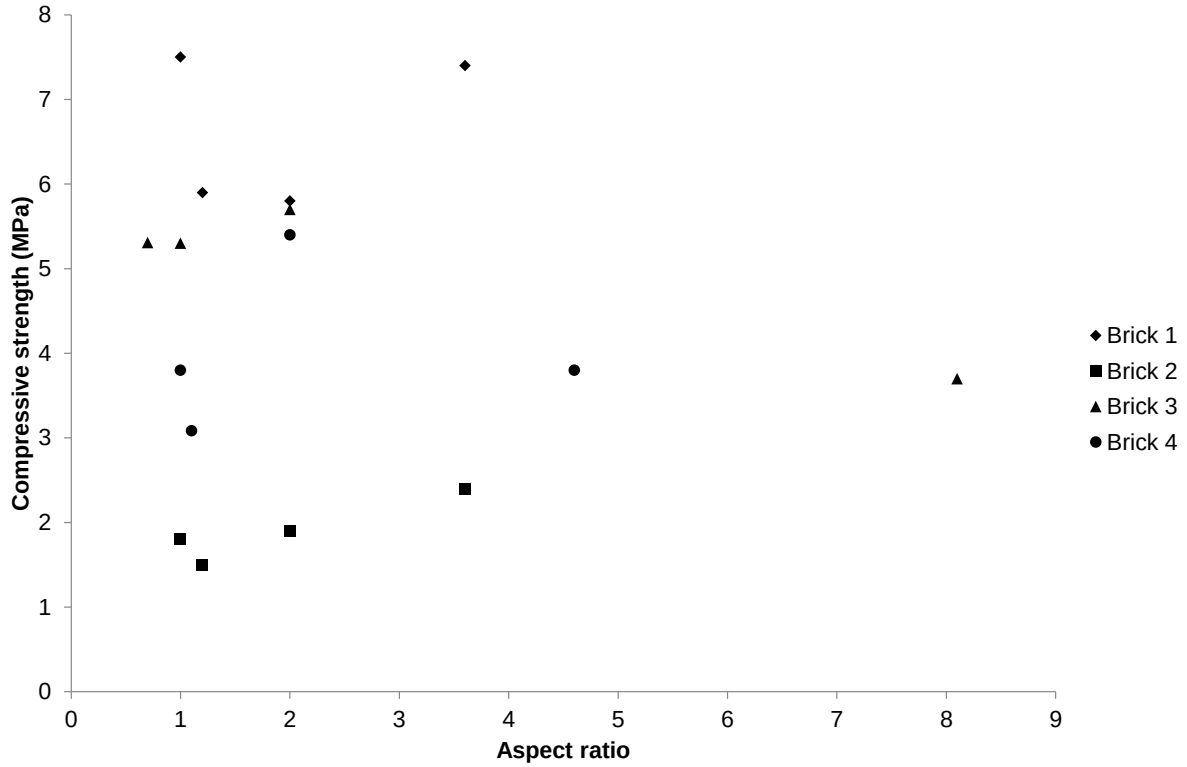


Figure 4: Compressive strength versus aspect ratio for the four bricks

Figure 4 does not show a general trend for the evolution of compressive strengths versus aspect ratio. According to the effects of confinement, the compressive strengths should decrease with the aspect ratio but that is not always the case.

When comparing the results presented in Table 10 for each brick, some significant comments could be made and it seems possible to reach an average "representative" strength value for each brick.

First, for all the bricks, the test performed directly on entire bricks laid horizontally gave aberrant results or was impossible to carry out (case of brick 3). It is true that the bricks studied in this paper were thin (6.2 cm for bricks 1 and 2, and 5 cm for brick 3). So, it seems that this direct test on bricks laid horizontally should not be recommended, especially for bricks with small thicknesses. This confirms the German standard recommendation that this

procedure should be used only for bricks having a thickness greater than 71 mm (German Standard 2013). Brick 4 falls into this category and it is true that the compressive strength measured using this procedure seems consistent with the measurements made on other specimens but it was necessary to correct the measured strength by the anisotropy factor, the measured strength being to 4.7 MPa otherwise.

The results of Table 10 show that, for brick 1, the compressive strengths ranged from 5.7 to 7.5 MPa (rejecting the test where bricks were laid horizontally). For brick 2, which had the same dimensions as brick 1 but much lower resistance, the difference between the various results ranged from 1.5 to 2.4 MPa. For these two bricks, the simplest test that gave the results closest to the UCS was the test on entire bricks set vertically.
The compressive strengths of brick 3 ranged from 3.7 to 5.3 MPa. In this case, the direct test on entire bricks set vertically gave the lowest results. This was probably because the large height (40 cm) of this brick compared to its other dimensions could lead to weakening of the brick by buckling. However, the compressive strength measured with this procedure remained consistent and favoured safety by providing a low value of compressive strength, which was not the case for the tests on half-bricks. If the correction due to the anisotropy was not made for the latter test, the compressive strength measured was high (6.9 MPa) compared to the other values of compressive strength (3.7 to 5.3 MPa). It is true that when a mortar was applied as recommended in the French and German standards (French Standard 2001; German Standard 2013), the strength decreased (5.4 MPa) to reach a value closer to the other values of compressive strength (3.7 to 5.3 MPa). But this was probably just a coincidence because many effects from various origins cumulated in various ways (anisotropy and sensitivity of the brick to the moisture).
Finally, for brick 4, the values ranged from 3.1 to 5 MPa. Once again, the direct test on entire bricks set vertically gave correct results that were more safety oriented than results measured on entire bricks laid horizontally which indicated higher compressive strength (4.7 MPa) if the correction due to the anisotropy was not made.

5. Conclusion

The objective of this work was to propose a procedure for the measurement of the compressive strength of earth bricks that was as simple as possible and as representative as possible of the "real" strength of the material. The results presented in this paper lead to several significant conclusions that should help in the future choice of such a procedure.

1- The measurement of compressive strength on small specimens dry sawn from bricks is not a good solution for at least two reasons. Firstly, the practical implementation of these tests is rather difficult: it poses health (dust) and safety problems or needs heavy specific equipment (saw equipped with a powerful vacuum system to evacuate the dust). Secondly, some of the results presented in this paper raise the question of the integrity of small specimens sawn using this procedure: it seemed that the vibrations generated by the dry sawing damaged the specimens. This last point should be confirmed by further experiments.

2- There is anisotropy in extruded bricks but its effects on the compressive strength are limited (the error was close to 20-30% if anisotropy was not taken into account).

3- The tests on half-bricks provided interesting results, especially for bricks of small height. But the use of a cement mortar joint could have significant effects for some bricks, certainly due to their high sensitivity to water. This could have the advantage of showing that the use of such bricks for masonry could lead to problems but this type of test then corresponds more to

a technological test of use than to a simple, relevant and reproducible test for measuring the compressive strength of earth bricks because too many parameters are involved. Moreover, the procedure using a joint between the two half-bricks is cumbersome and also depends strongly on a the experimenter: the test on half-bricks without mortar would be easier to use but would only be possible if the surfaces of the bricks were of sufficient quality (parallel and flat), which is not the case for adobes from heritage buildings, for example.

4- The tests on entire bricks clearly show that the effect of confinement could lead to aberrations in the cases of bricks having small thicknesses. However, when the tests were carried out on surfaces other than the laying surface, the values of compressive strength became consistent. Such a procedure was significantly the simplest even though, for these tests, the loaded surfaces must be flat and parallel.

In conclusion, it seems that the best compromise to achieve a simple, representative compressive strength test for earth bricks is to transform the bricks as little as possible before the test and thus to test entire bricks. The best solution would be to impose a standard shape of brick for the compressive strength test as is the case for concrete. In practice, this would be difficult because of the variety of techniques (moulded adobe, compressed bricks or extruded bricks) and the shapes and sizes that exist. Furthermore, one of the advantages of earth bricks is that they can be produced in a traditional way on the building site, using local earth. In this case, it would be difficult to have units of standard shape. In addition, for direct tests on bricks of different sizes, it appears that the error made by ignoring the anisotropy seems acceptable in comparison to the much greater error related to confinement when bricks with small thickness are tested horizontally. In the case of CEB, and probably in the case of heritage adobes, anisotropy should be smaller than in extruded bricks.
In this study, only two load directions were tested. A further study should concern an extensive series of tests on entire bricks manufactured using various techniques (moulded, compressed and extruded), in which the entire bricks would be tested in three directions. This should help provide geometric criteria for choosing the direction in which the compressive strength test should be performed to decrease the error made in the value of the compressive strength of these bricks.

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