An earth block with a compressive strength higher than 45MPa!

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Abstract

This paper presents the results of a compressive strength test carried out on an extruded earth block of dimensions 40.7x13.6x4.8 [cm^3]. The failure of the block was not detected by the press used, which reached its highest load (2500 kN). This would correspond to a compressive strength of the block greater than 45 MPa! This value is obviously an aberration and the discussion developed in the paper, based on results from the literature, aims to explain this result and propose solutions for measuring the compressive strength of such products.

Highlights (3 to 5 bullet points (maximum 85 characters, including spaces, per bullet point)

The compressive strength measured for an earth block was higher than 45 MPa.
The direct measurement of the compressive strength on adobe plates is aberrant.
Compressive strength tests on adobe plates are comparable to oedometric tests.
A 3 point bending test could be a solution for measuring the UCS of adobe plates.

Keywords: adobe, earth construction, compressive strength test, aspect ratio, earth block.

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1. Introduction

For millennia, human beings have used earth in various forms for construction: compacted in formworks (rammed earth); mixed with straw and put in place by hand, either alone or as filling in timber structures (cob); or as masonry blocks, generally molded (adobes) and dried in the sun. The mechanical strength and durability of this material was recognized long ago, as highlighted by the significant heritage of earth constructions all around the world. In terms of resistance, the example of the city of Shibam in Yemen is often quoted as a reference: in this city, buildings with more than 8 stories reaching heights of 30 meters were built with earth blocks. Shibam is a UNESCO world heritage site and is known as the most ancient skyscraper city in the world [1].

The main weakness of earth used as a construction material is its sensitivity to water. To protect earth constructions, Man has developed a variety of strategies: orientation of the building and of its earth walls with respect to the dominant rain direction, advanced roof, impermeable foundations or, in some cases, protective lime coating.

The compressive strength of construction materials is a modern notion and is recent in the case of earth construction materials. Until the beginning of the 20th century, empiricism prevailed: earth in its various forms allowed loadbearing walls that did not show too much deformation over time to be built in a sustainable way. In terms of building materials, the 20th century can be considered as the century of concrete. This new material has replaced almost all others in construction for many reasons, including its exceptional compressive strength: 20 MPa for traditional concrete and over 100 MPa since the development of superplasticizers in the 1980s. With concrete, the notion of compressive strength has become the most important characteristic for building materials: this parameter is often considered as a criterion of quality (the higher the compressive strength, the better the concrete) and it is very useful for the sizing of structures because it is one of the main parameters in the majority of computation models.

Thus, when researchers' interest in the use of earth as a construction material began to revive a little more than 20 years ago, essentially for environmental and heritage reasons, measuring the compressive strength of earthen materials became a priority. The first idea was to apply the same procedures to earth blocks as those used for modern materials like concrete or fired bricks. However, earth blocks are more comparable to compacted soil and the analogy with brittle materials is showing its limits. Shedding light on these limits is one of the aims of this paper, in which a compressive strength higher than 45 MPa will be presented for an earth block.

2. Experimental procedure and results

The soil used for this study came from the quarry of a brickworks in southern France. This brickworks produces both fired bricks and soil blocks but with different compositions, in particular for the proportions of clay and sand in the mixtures. The blocks, whether fired or not, are manufactured in the same way: the clay is crushed and mixed with sand and then mixed with 16-18% water. The fresh mixture is extruded to form a long cable of material that is cut into bricks of the desired length. The bricks are then hardened by drying for nearly four days at a temperature increasing progressively from 25°C to 100°C. Several dimensions of bricks exist but the specimens used for this study were 40.7x13.6x 4.8 [cm^3].

The compression test was carried out using a hydraulic press. The test was run at a constant rate of 0.08 $MPa.s^{-1}$. The press had a capacity of 2500 kN and the dimensions of the platen were 42x42 [cm^2]. Before the test, the samples 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 [2, 3]. The water content of the sample, measured by its loss of water at 105°C, was equal to 2.4%.

In this study, blocks were tested in the direction in which they are generally laid (horizontally). The surface area in contact with the platens was thus very large and the aspect ratio was very small (the aspect ratio is defined as the ratio between the thickness of a sample and the smallest characteristic length of its surface). In this case of study, the aspect ratio was equal to 0.35. Block surfaces were usually sufficiently flat and parallel and no specific capping was necessary to correct them. The blocks were tested directly between the platens of the press, which maximized the plate restraint effects.

During the test, the force continued to grow linearly until the maximum capacity of the press (250 tons) was reached. Theoretically, this should mean that the earth block tested had a compressive strength greater than 45 MPa, which was extremely improbable. Tests were performed on samples cut from these blocks and cured in the same way. Six samples of 5x5x10 [cm^3], tested vertically (aspect ratio of 2) gave the usual compressive strength for earth blocks, ranging from 4.4 to 6.3 MPa (with an average value of 5.5 MPa).

During the test, cracks appeared around the edges of the sample (approximately 1 cm from the edge) as shown in Figure 1. Despite the appearance of these cracks, the press did not detect a fall in force and continued to load the sample. At the end of the test, the height of the sample had decreased from 48 mm to 38 mm as shown in Figure 1. In addition, initially rough brick surfaces had become smooth and it could be seen that the density of the central part of the block had increased considerably. The block, which can be considered as a sample of clayey soil, had thus undergone settling without actual failure in extension.

700kN

1000kN

Figure 1: a) Cracking on the block b) Block before and after the test

3. Discussion

Before developing the discussion, it is necessary to define the differences between UCS, "Unconfined Compressive Strength", which is calculated using the maximum force (divided by the surface area of the sample) that a material can withstand in an unconfined compression test, and the stress called "Apparent Compressive Stress", ACS. UCS is a characteristic of the material and must therefore be independent of the means and methods used to measure it. In contrast, the influence of the geometry of samples of earth blocks on the result of compressive strength tests has already been observed by many authors (e.g. [2, 4, 18]). All these results

tend to show an increase of the ACS as the aspect ratio decreases. The reason typically given to explain this is the phenomenon of friction between the sample and the press.
For example, Piattoni et al. [4] carried out compressive strength tests on two geometries of samples (46x31x13 [cm^3], aspect ratio = 0.42; and 23x15x13 [cm^3], aspect ratio = 0.87) and compared the results with those obtained on a wall of similar composition (aspect ratio = 2.55). They observed a significant increase in the compressive strength with decreasing aspect ratio: from 6.56 MPa for the sample of aspect ratio = 0.42 to 1 MPa for the walls. In fact, different experimental studies seem to indicate that, depending on the type of material, the ACS tends to the UCS for aspect ratios ranging from 2 (e.g. standard ASTM 1314 [5]) to 5 [6-7].

(i) Limits of the use of correction factor in the case of adobe plates

The conventional way to account for the effect of the aspect ratio on the value of the compressive strength is to modify the ACS of bricks by a correction factor depending on the aspect ratio [6, 8]. However, this approach has reached its limits in the study of the adobes of heritage buildings or in the cases of some modern extruded bricks (themselves inspired by the heritage bricks). In such cases, the material is often in the form of plates with a very low aspect ratio (close to 0.3) to facilitate the drying of the brick. With such dimensions, the problem becomes more delicate and the application of a single correction factor does not appear to be sufficient for several reasons.
First, the geometry strongly influences the characteristics of the material during its manufacture and curing (kinetics of drying, modifications of the homogeneity and the arrangement of earth) [9]. Thus, applying a correction factor to the ACS of plates in order to obtain a compressive strength comparable to those measured on blocks does not really have any sense since it would compare two different materials and would therefore lose the intrinsic character of the UCS.

In addition, the use of a single correction factor implies that the impact of the means and methods does not have greater influence on the ACS values than the intrinsic characteristic of the sample tested. In other words, the difference between the ACS and the UCS should remain moderate, which is often not the case for thin plate samples. In addition to the results presented in this study, there are several publications ([10-11]) that refer to compressive strengths higher than 10 MPa - far above conventional values for the UCS of earthen brick (less than 5 MPa). For example, the results presented in this paper can be compared to those reported by Eslami et al. [12] on plates of adobe (190x190x47 [mm^3], aspect ratio = 0.25). In that study, the authors observed a continuing increase in the axial stress with deformation, up to values close to 12 MPa for axial deformations of 20%. For the determination of the compressive strength, the authors proposed the use of a kind of elastic yield stress that would be characterized by a slight slope change as highlighted on Figure 2. One can wonder about the validity of the approach proposed by Eslami et al. [12]. Although this value can give some information on the first yield of the tested material, we can hardly link it to the strength since the tested material seems to show an elasto-plastic hardening behavior.

(ii) Influence of the sample's geometry on its real load

Considering the observed differences of behavior, it would first be relevant to think about the influence of the sample's geometry on its real load and thus on the nature of the information obtained during the analysis of the results. This point is illustrated in Figure 2, which presents typical stress-strain curves obtained on plates (aspect ratio = 0.25), bricks (aspect ratio = 2) and adobe walls. In order to compare the curves obtained on adobes having various compositions and cures, the stress values were normalized by a reference stress. This was equal to the UCS for the "adobe block" and "adobe wall" curves, and to the yield stress for the "adobe plate" curve.

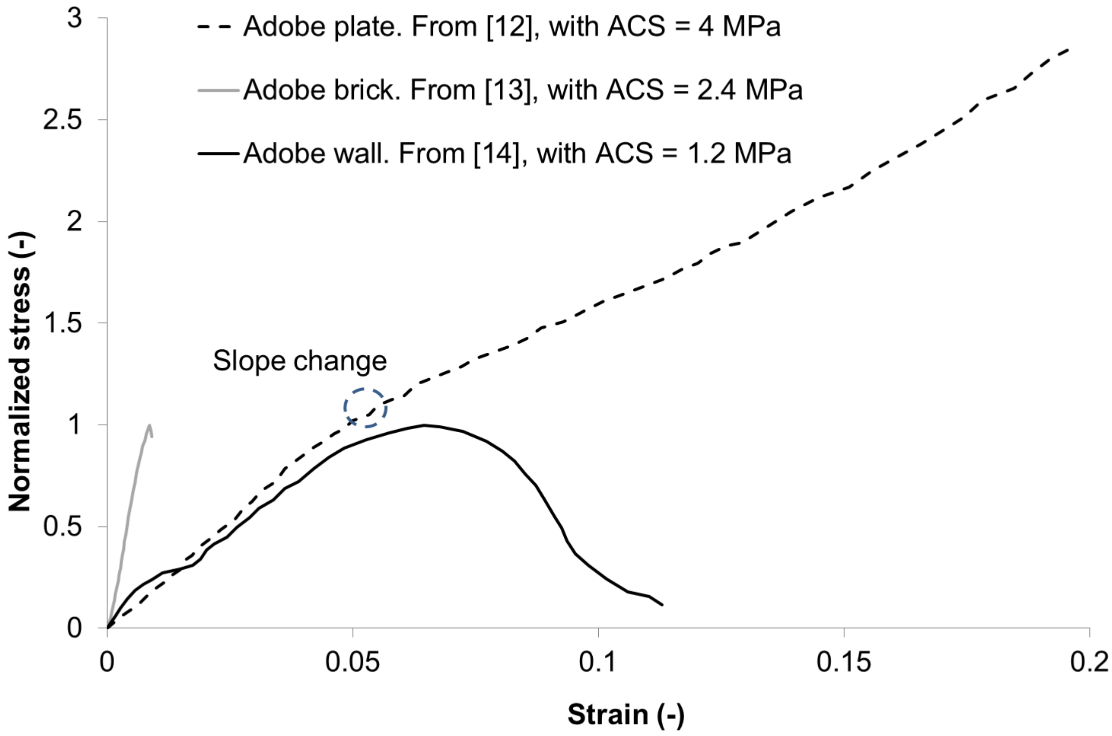

Figure 2: Typical shape of axial stress versus axial strain for adobe plates, bricks and walls.

The behavior of the adobe bricks having an aspect ratio of 2 corresponded to that expected for an unconfined compression test: a quasi linear increase in stress with deformation up to the maximum strength, followed by a sharp fall in stress corresponding to the failure of the sample (case of brittle failure in extension). The values plotted on the graph were taken from [13] but comparable results have been reported by many authors (e.g. [4, 15]).

In contrast, the behavior of adobe plates (aspect ratio = 0.35 in our case or aspect ratio = 0.25 in Eslami et al. [12]) seemed closer to that classically observed during an oedometer test. This seems reasonable because, in compression strength tests such as these, the friction between the press and the sample impacts the lateral displacements throughout the height of the sample. The conditions were thus comparable to those of the oedometer, in which lateral displacement is prevented. It appears, therefore, that the sample was subjected to a complex load path somewhere between the compressive strength test and the oedometer test, which depended on the nature of the material, and the type of bond between the test sample and the press. Accordingly, the interpretation of the data thus obtained became particularly difficult and the observed values of compressive strength were not, from a purely mechanical point of view, the UCS. The link between these values and the UCS may be only indirectly established using a rheological model for the behavior of the soil on condition that the real load path is known.

(iii) Possible solutions for measuring UCS on adobe plates

Considering the previous discussion, it is possible to ask what tests should be carried out in order to correctly characterize the mechanical behavior of adobe plates.

One possible method could be to test a stack of several adobe plates in order to increase the apparent aspect ratio of the specimen. However, in such a case, the value obtained would be related to a structure made of this assemblage rather than to an intrinsic property of the material.

To conserve information on the material, 3 point bending tests could be a good alternative. The usual interpretation of this type of test, as proposed by Walker [16], leads to the calculation of the tensile strength through the equations of Strength of Materials theory. The compressive strength is then obtained by using a coefficient of proportionality but, in the case of earth blocks, the results are inconclusive, essentially because three of the principal assumptions of the Strength of Materials theory are not respected (aspect ratio greater than 10, St Venant's principle and linear elasticity). To solve this problem, Morel and Pkla [17] proposed a methodology that consisted in modeling the earth block sample by a lattice composed of two struts and a tie, and assuming a failure in the compressed struts (Figure 3). The results obtained using this methodology were very close to those published by Walker [18], which were measured by a conventional compressive strength test on the same materials with samples having an aspect ratio equal to 1.4.

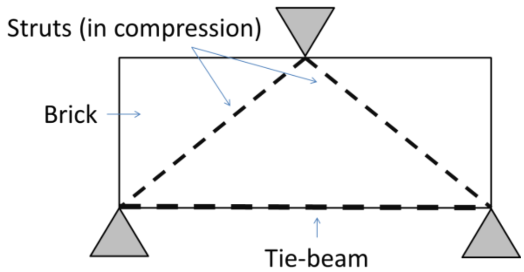

Figure 3: Representation of the earth block sample by a lattice, composed of two struts and a tie, for the analysis of the 3 point bending test.

Another approach would be to measure the intrinsic rheological characteristics of the material using an oedometer test. With this type of testing (and unlike the compressive strength testing situation), the load path remains fully controlled even in the case of samples with low aspect ratios.

Finally, it would be relevant to question the representativeness of the UCS to quantify the mechanical resistance of earth blocks. Here, it could be interesting to consider the real mechanical behavior of the material on site. As illustrated in Figure 2, the study by Quagliarini et al. [14] suggests that adobe walls have an elastoplastic behavior closer to that of thin compacted soils than to that of conventional building materials (concrete, fired bricks, etc.). Thus, it would seem pertinent to explore other ways of characterizing the resistance of such material, e.g. based on the cohesion and the angle of friction, which would be better suited to the behavior of compacted soil. It should be noted that this analysis could be extended to other earthen construction materials, such as rammed earth, where constructions would certainly have rheological behavior similar to that of adobe constructions.

4. Conclusion

The title of this article is deliberately provocative. Obviously, the earth block tested did not have a real compressive strength (or UCS) greater than 45 MPa but the fact that the brick did not break up to this value was due to the specific environment of the unconfined compression test coupled with the specific characteristics of the sample (especially its geometry). For a long time, researchers have sought to apply procedures developed for other construction materials (concrete, fired bricks, stone, etc.) to earth construction materials. However, this study, supported by many others, shows that such practices are not possible or, at least, not always. It is important for the scientific community, which is increasingly working on these earth construction materials, to be aware of these difficulties. Although this material seems quite simple and basic at first sight, especially from the mechanical point of view, in reality it is much more complex.

With this type of material, we think that it would be better not to use the habitual models of failure mechanics of brittle materials as has been done so far. Instead, we think that these materials should be considered as samples of soil and that the theories of soil mechanics should thus be employed. Finally, as has been done in Europe for other elements of masonry [8], it would be interesting to study how the strength measured on earth blocks can be used to obtain the real strength of the walls built using these blocks bonded with laying mortars. Then, the nature and the characteristics of the laying mortars would certainly have a significant effect on the overall mechanical behavior of the wall, which would greatly multiply the number of parameters to be studied.

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