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EXTRUDED EARTH BRICKS: MECHANICAL AND HYGROTHERMAL PROPERTIES, AN ANISOTROPIC BEHAVIOUR

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Abstract

The study focuses on the mechanical, thermal and hydric properties of extruded earth bricks. The bricks used for testing were produced following an extrusion process in various French brickworks located in the north, the centre and the west of France. Different types of bricks, all solid blocks without perforation, were studied. The compressive strength, the thermal conductivity and the water vapour permeability tests highlight an anisotropic behaviour of the bricks depending on the extrusion direction during the production process. The results confirm that the extrusion process has a major influence on the orientation of clay layers and has an impact on the mechanical and physical properties (perpendicular or parallel to the direction of extrusion). This feature is an opportunity for the brick manufacturers to improve the characteristics of the bricks for wall construction by adapting the laying direction of the brick to the geometry of their bricks and the direction of their extrusion during the process.

Keywords:

Earth construction, earth brick, compressive strength, thermal conductivity, water vapour permeability, anisotropy

1 INTRODUCTION

Earth is one of the oldest building materials still use [Minke 2006]. Earthen forms of construction as rammed earth, adobe or compressed earth bricks, have been used for thousands of years and there is a renewed interest due to its low embodied impact and its good capacity for the hygrothermal regulation inside a building. This interest in traditional earth constructions has grown in Europe since a few years with the recent keen interest in sustainable development, earthen constructions have become attractive and French brick manufacturers produce more and more extruded earth bricks widening their product range. One of the advantages of the extrusion process is that it enables fast production of large quantities of homogeneous bricks that are similar in shape and size. As it was observed for fired clay bricks, an alignment of the clay platelets occurs during this process because of the frictions and the pressure with the die [Kornmann 2007, Aubert 2013, Maskell 2013, Aouba 2015]. Relatively few publications focus on extruded earth bricks and a majority of them deals with their mechanical properties [Heath 2009, Aubert 2012, Aubert 2013, Maskell 2013, Cagnon 2014, Maillard 2014, Aubert 2015]. This article focuses on the hygrothermal and mechanical properties of extruded earth bricks by measuring their thermal conductivity, their water vapor permeability, their water vapor sorption and their compressive strength.

2 MATERIALS AND PROCEDURE

2.1 Materials

For this study, the five bricks tested (referenced B1 to B5) are used for interior partition walls and were produced by different French brickworks (*Fig 1*). In the case of extruded earth bricks, the soil mixed with water to approximately the plastic limit of the soil is extruded under a vacuum through a machined die. This produces a stiff column of clay, then cut into single bricks. The dimensions, the dry densities and the clay content are summarized in the *Tab.1*.

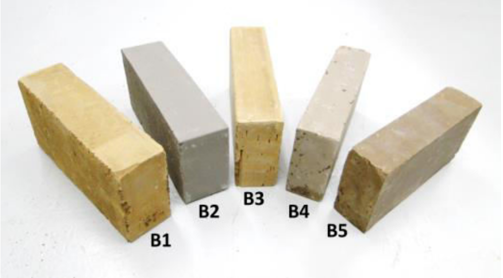

Fig. 1: The five bricks tested.

Tab. 1: Dimensions, dry density and clay content of the unfired clay bricks.

Unit code	Length (cm)	Width (cm)	Height (cm)	ρ (kg/m³)	<2,5 µm (%)
B1	22.7	11.0	6.0	1680	28.8
B2	22.5	10.5	6.0	1940	39.8
B3	22.5	11.3	5.4	2020	55.2
B4	21.6	10.6	5.0	2050	58.3
B5	21.5	10.5	5.0	2020	47.7

For these five bricks, the directions of extrusion were not the same: B1 and B2 were extruded heightwise; B3, B4 and B5 were extruded in lengthwise sense. During this process, the clay platelets orientated themselves in the direction of extrusion and two directions can be considered: the perpendicular direction (D*perp*) and the parallel direction (D*para*) (*Fig. 2*). This phenomenon, little studied in the literature, is well known by brick manufacturers in fired clay bricks.

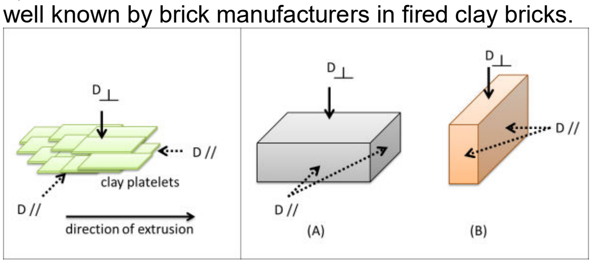

Fig. 2: Direction of extrusion for the bricks B3, B4, B5 (A) and the bricks B1, B2 (B) [Maillard 2014].

2.2 Procedures

Preparation of the samples

For the thermal conductivity and the water vapor permeability, cylindrical samples (Ø = 50 mm, thickness = 10 mm) were cored directly into the brick, without water, on two sides depending on the clay layer orientation: perpendicular (D*perp*) and parallel (D*para*). Each face of the samples was rectified using a grinding machine to obtain a plane surface. For the mechanical and sorption tests, cubes (50 mm) were cut into the brick without water.

Thermal Conductivity

Thermal conductivity measurements of the samples were carried out using the heat flow meter method according to ISO 8301 with a Lasercomp Fox 50 at 30°C (with a "hot" plate at 40°C and the "cold" plate at 20°C) [AFNOR 1991]. Samples were previously dried at 105°C for 48h.

Water vapor permeability

To determine the water vapor factor resistance (µ), water vapor permeability tests were carried out following the standard dedicated [AFNOR 2001]. Tests were run at 23°C; the "dry" cup conditions were 0% RH inside the cup containing a salt, $CaCl_2$, and 50% RH inside the climatic chamber where the samples sealed on the cup were placed.

Water vapor sorption isotherm

The water vapor sorption measurements were performed according to the standard [AFNOR 2013]. For each reference, two cubes of 50 mm were cut from the brick and then dried at 105°C during 48 hours.
Then, four of the faces of each cube were coated with a mixture of wax and paraffin as follows: for the cubes (D*perp*), the two free faces were perpendicular to the direction of extrusion; for the cubes (D*para*), the two free faces were parallel to the direction of extrusion. The cubes were weighed before and after the deposition of the wax/paraffin mixture. The cubes were placed in a climatic chamber at 23°C and 40% RH until a constant weight was obtained. The relative humidity (RH) was varied in steps at 60, 80, and 95% RH. The samples were weighed regularly to determine the weight evolution curves as a function of the time. The relative humidity of the climatic chamber was changed when the weight of samples became constant. To obtain the desorption curves, the same procedure was followed with decreasing levels of relative humidity from 95 to 40% RH. The moisture content of each samples, denoted θ, was determined from the mass curve recorded which was calculated at each equilibrium step of humidity following the equation: θ = 100 x (humid mass – dry mass)/dry mass.

Compressive strength

The compression tests were carried out using a hydraulic press with a capacity of 50 kN. The tests were run at a constant rate of 0.08 $MPa.s^{-1}$. Before the tests, a part of the specimens was cured in an air-conditioned room at 20°C and 50% relative humidity until their mass was constant, the second part of the specimens was dried at 105°C (48h). In this study, specimens, 5*5*5 cm^3 cut directly into the brick without water, were thus sufficiently flat and parallel for no specific capping to be necessary to correct them.

3 RESULTS AND DISCUSSION

3.1 Thermal conductivity

Tab. 2 presents the thermal conductivities of the earth bricks measured in two directions (λ D*perp* and λ D*para*). The values are the average of three samples and the anisotropy ratio is obtained by dividing λ D*para* by λ D*perp*. The thermal conductivity values differed depending on the sample D*para* or D*perp*. For all the bricks, the values D*perp* were lower than that the samples D*para*, and the anisotropy ratio being scattered from 1.12 (B1) to 1.67 (B2). As shown by Laurent [Laurent 1987], the density is one of the main physical parameter that affects the thermal conductivity: in our study, the densities of the five bricks were the same except for B1 that is coherent with the low variations observed on the values of thermal conductivities. The significant difference of the thermal conductivity values between the samples D*perp* and the samples D*para* shows that extruded earth brick can be considered as an anisotropic material.

Tab. 2: Thermal conductivity of unfired clay bricks (average of 3 samples).

Unit code	λ D*perp* ($W.m^{-1}.K^{-1}$)	λ D*para* ($W.m^{-1}.K^{-1}$)	Ratio λ D*para* / λ D*perp*
B1	0.57 ± 0.02	0.64 ± 0.02	1.12
B2	0.66 ± 0.05	1.10 ± 0.02	1.67
B3	0.66 ± 0.06	0.93 ± 0.05	1.41
B4	0.57 ± 0.08	0.86 ± 0.08	1.51
B5	0.62 ± 0.04	0.72 ± 0.04	1.16

As explained earlier, during the extrusion process, the clay layers oriented themselves following the direction of extrusion. The thermal properties were thus dependent on the direction considered (perpendicular or parallel to the orientation of clay platelets). In the perpendicular direction, the clay particles inhibit the heat flow and the thermal conductivity is thus lower. On the contrary, in the parallel direction, the heat flow is favored by the orientation of clay platelets and the thermal conductivity value is higher.

3.2 Water vapor factor resistance

The water vapor factor resistance values are summarized in *Tab. 3* (each value is the average of 5 samples). The more this factor is high, the more the vapor permeability is low; the anisotropic ratio was calculated by dividing μ *Dperp* / μ D*para* to compare the ratios between them.
As shown with the thermal conductivity, there is a significant difference between the samples D*perp* and D*para*. For all the bricks, the values of the samples D*para* are lower. As previously, the anisotropy ratios are scattered, but there is no direct correlation with the thermal conductivity ratios except for the reference B1 which had the two lowest ratios. This brick B1 had the lowest dry density (1680 kg/m^3) and the lowest amount of fine particles (28.8%).

3.3 Water vapor sorption isotherm and kinetic of sorption

The water vapor sorption measurements have shown that, at equilibrium, the difference between the samples D*perp* and D*para* is weak. Thus, only the results obtained with the sample Dperp are presented on the *Fig. 3*. The highest moisture contents (θ) are attributed to the bricks B3, B4 and B5 which contain the higher amount of fine particles (Ø<2.5μm), respectively 55, 58 and 47 %. These results highlight that the earth bricks have a high potential for the hydric regulation in a building.

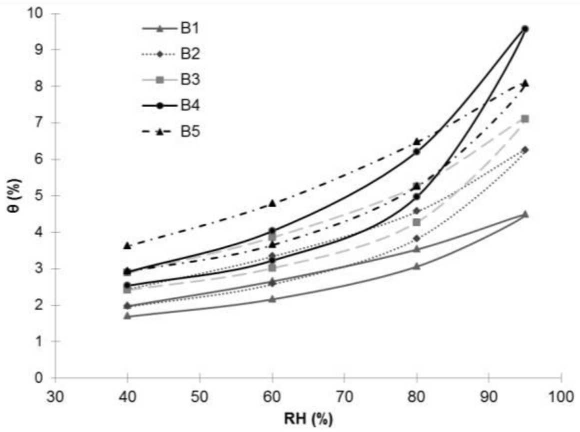

Fig. 3: Sorption and desorption curves of the unfired clay brick (Dperp) at 23°C.

The values of the moisture content reached at equilibrium are similar but the kinetics of sorption are different between the samples D*perp* and D*para* which reveal again an anisotropic behavior especially marked for B3 and B4, the two references having a high amount of fine particles (>50%) (*Fig. 4*). During the sorption phase, a significant difference was observed progressively at each step between both samples D*perp* and D*para* particularly at the last stage at 95% RH. For the sample D*para*, the moisture content (θ) increased faster than that of the sample D*perp*. During the desorption phase, the moisture of the sample D*para* decreased more rapidly and the stabilization was reached before that of the sample D*perp*. Moreover the gap between the both curves is more noticeable than during the desorption phase indicating the different behavior of the water vapor flow linked to the microstructure of the brick. As observed with the water vapor permeability test, parallel to the orientation of the clay platelets (i.e. to the direction of extrusion), the water vapor flows more easily. However, once equilibrium is reached, the samples D*perp* and D*para* contain the same amount of water.

Tab. 3: Water vapor factor resistance of the extruded earth bricks (average of 3 samples).

Unit code	μ D*perp*	μ D*para*	Ratio μ D*perp* / μ D*para*
B1	11.4 ± 0.8	9.8 ± 0.9	1.16
B2	24.0 ± 2.1	16.0 ± 0.9	1.50
B3	44.0 ± 4.1	23.1 ± 1.6	1.90
B4	32.6 ± 3.5	18.8 ± 1.3	1.73
B5	21.8 ± 2.4	16.6 ± 1.3	1.31

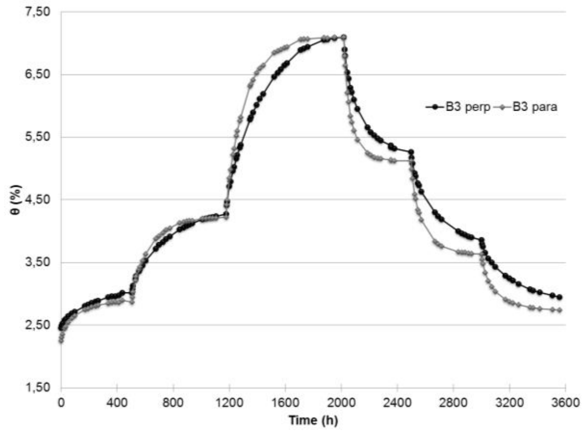

Fig. 4: Evolution of the moisture content (θ) of the samples Dperp and Dpara for the brick B3 at 23°C.

3.4 Compressive strength

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 [Aubert 2015]. For our study, it was not possible to manufacture samples (5*5*10 cm^3) in the perpendicular direction for all the bricks so a geometry 5*5*5 cm^3 was chosen. Due to this geometry, the effect of confinement could not be taken into account but it was similar for all the samples. The results show that the compressive strength seems to depend on the loading direction: in the perpendicular direction the values are higher than the others obtained in the parallel direction *(Tab. 4)*. For the two first bricks tested, the difference between the values D*perp* and D*para* is around 1 MPa. For the brick B1 which has the lowest dry density, the compressive strength is the lowest.

The relative humidity has also a major influence on the compressive strength. For the reference B1, at 0%HR, just after a dry at 105°C during 48h, the average of the compressive strengths is higher: 6.7 MPa in the perpendicular direction and 5.3 MPa in the parallel direction *(Fig. 5)*. From 0%HR to 50%HR, it represents a decrease of 59.7% and 65.4% respectively (*Tab. 5*).

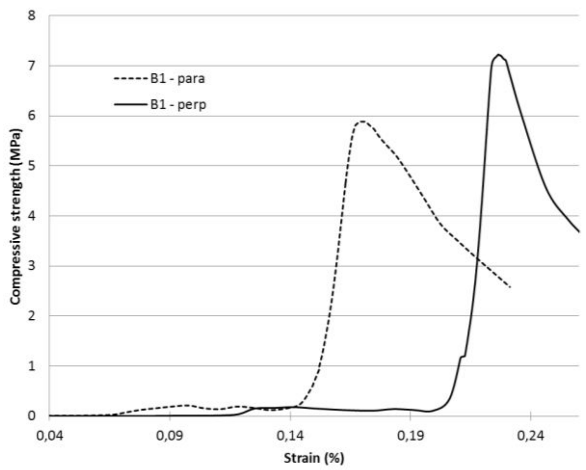

Fig. 5: Example of strength-strain curves for the brick B1 at 0% HR after drying in the two directions (parallel and perpendicular).

4 CONCLUSION

In this study, five extruded earth bricks were characterized and the thermal conductivity, the water vapor factor resistance, the water vapor sorption and the compressive strength were measured. The bricks came from several French brickworks, the densities and the dimensions were similar except for the first one (B1). For each reference, the properties were studied in two directions: perpendicular and parallel to the direction of extrusion. The results underlined that the properties are anisotropic and directly linked to the direction of extrusion and thus to the clay platelets orientation. The extrusion process generates stresses on the clay paste, the clay platelets tend to move in the direction of extrusion. In the perpendicular direction, the thermal conductivity and the kinetic of sorption are lower; the water vapor factor resistance is higher compared to the parallel direction. The heat flow and the water vapor are slowed down by the clay platelets. In contrast, in the parallel direction, the heat flow and the water vapor are facilitated: the thermal conductivity and the kinetic of sorption are higher, the water vapor factor resistance is lower. In the perpendicular direction, the bricks are more resistant with a higher compressive strength value. The effects of the anisotropy are important with an anisotropy ratio ranged from 1.1 to 1.9.

In the future, it will be interesting for the brick manufacturers to consider these results to improve the characteristics of their products. Depending on the desired effect, they could extrude their bricks in the direction of the length or the height, or adjust the direction of the laying bricks.

*Tab. 4: Compressive strength depending on the load direction at 20°C-50%HR (average of 6 samples, size 5*5*5 cm^3).*

Unit code	Direction	f_{cmin} (MPa)	f_{cmax} (MPa)	$f_{c\ (average)}$ (MPa)
B1	perpendicular	2.3	3.4	2.7
	parallel	1.5	2.1	1.8
B2	perpendicular	8.2	9.1	8.6
	parallel	6.0	8.8	7.5

*Tab. 5: Compressive strength depending on the load direction at 0% and at 50%HR (average of 6 samples, size 5*5*5 cm^3).*

Unit code	Direction	f_{cmin} (MPa)	f_{cmax} (MPa)	$f_{c\ (average)}$ (MPa)
B1 (0%HR)	perpendicular	6.0	7.2	6.7
	parallel	4.2	5.9	5.3
B1 (50%HR)	perpendicular	2.3	3.4	2.7
	parallel	1.5	2.1	1.8

These first results should be completed with the compressive strength of the others references and by additional studies including microstructure studies to correlate the hygrothermal properties with the microstructure of the brick (amount of clay, clay n ature, porosity, etc.). SEM and optical microscopy observations should lead to an estimation of this anisotropy and underline if differences cloud be observed depending of the localization (center of the sample, edge and corner).

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