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Research Paper

Assessing the mechanical behaviour of adobe masonry under uniaxial compressive strength.

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ABSTRACT

Earth building has always existed on all continents; it constitutes an integral part of the cultural heritage of mankind. The present study is particularly interested in the valorisation of adobe masonry. To do this, a series of adobe units (three types: a, b and c) and adobe masonry wallets (A, B, and C) were prepared manually and infilled with 1cm thick earth mortar. In order to study the mechanical behaviour of the wallets in the laboratory, we study the mechanical behaviour of adobes and earth mortar then we apply the uniaxial loading method on the wallets. Also we present a new analytical formula which gives the mechanical properties of wallets derived from those of bricks and mortar that were determined before they were assembled. The experimental study shows that the compressive strength of wallets is 33% lower than that of adobes, and the deformations are similar to those of bricks, but they are 6 to 8 times smaller than those of mortar. The experimental mechanical properties of wallets were compared with those determined analytically. It give us results similar to the experimental ones with a ratio E_{Manal}/E_{Mexp} equal to 1.2.

1 Introduction

It is widely acknowledged that currently about half of the world's population lives in earthen constructions [1]. In 2021 this proportion is decrease to 10% in the worldwide and about 25% in developing countries [2]. It is worth specifying that earthen masonry contributes to the protection of the environment, ensures durability and architectural appearance, and above all meets the concepts of bio habitat, bioclimatic construction and sustainable development [3-8]. In the south of Algeria, and particularly in the Wilaya (Province) of Adrar, three types building materials are generally used (stone, adobe and fired brick) for the construction of houses. For this, and in order to adapt the constructions to their environment in the region of Adrar, which is characterized by an arid climate, it was decided to focus on the valorisation of the construction in adobe (raw earth brick, banco, thoub). It should be remembered that this type of masonry has exhibited great durability in constructions that

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are made of adobe; many of these constructions are several hundred years old. It should be noted that the adobe walls of houses in the region of Adrar are built on shallow stone foundations. The thickness of these walls is at least 30 cm, which gives them a fairly significant thermal inertia. One should also know that the raw earth brick bonding is ensured by mortar made of the same composition, i.e. sand, clay and water. In addition, the foundations, when they exist, are made of stone in order to protect the walls from capillary rise and most importantly from irrigation water (fig.1a). It should also be noted that the beams, called Khechba, used in houses are made of trunks of palm trees cut in four (fig.1b). The whole is then covered with a layer of 30 to 40 cm of rammed and whitewashed clay; this should provide good protection against heat. The plasters do not always have a smooth surface; they have the appearance of ripples. In addition, buttresses are placed at the base of the adobe walls to reinforce their stability.

Although adobe constructions possess thermo-hydro-mechanical properties [9-14], they started to disappear after World War II [9], due to the degradation that generally appears on the joints, plasters, and even on the masonry itself, which requires rigorous periodic maintenance. These degradations are probably due to the non-compliance in the manufacturing techniques, preconceived ideas about the fragility of the earth material, and the lack of international standards for the evaluation of the performance of these materials. For all these reasons, industrial materials, such as the red products and cementitious materials started supplanting earthy materials, despite their climatic environment unsuitability and their higher costs. So, this work comes to master the emphasis on the behaviour of adobe masonry, where we determine the mechanical properties of wallets, made up of several adobe bricks jointed with an earth mortar, experimentally and analytically. The analytical properties were derived from the mechanical properties of bricks and mortar that were determined before they were assembled.

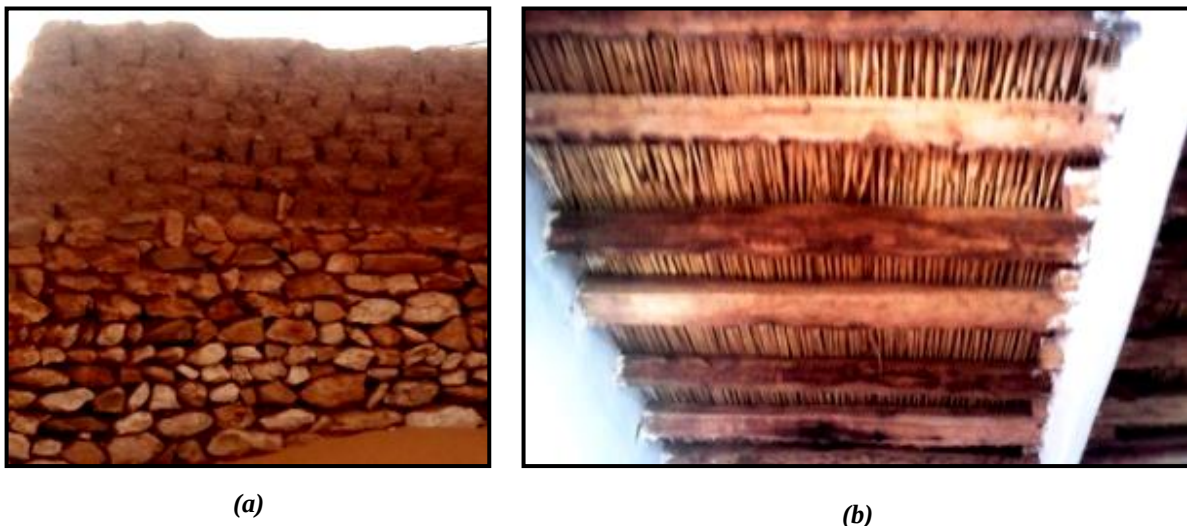


Fig. 1 – (a) An ancient adobe wall with a stone base; (b) adobe floors with traditional roofing.

It is worth indicating that the compressive strength and Young modulus are the most important mechanical properties in masonry walls. These properties can be determined either directly through experimental tests on representative walls [15, 16] or indirectly using methods based on analytical formulas that express relationships between the mechanical properties of these walls and their constituents such as bricks and mortar [17-21].

It should be mentioned that this experimental work was carried out in three stages that consist in determining the mechanical properties of adobe, earthen mortar and low walls. To complete this work, more than 120 adobe bricks were made and transported from Adrar to the EOLE laboratory (Water and Structures in Their Environment laboratory) at the University of Tlemcen. It should be pointed out that the construction of the wallets required a few tens of kilograms of dune sand and clay from the region of Adrar. Nine wallets of dimension (length x height x width) $60 \times 40 \times 14 \text{ cm}^3$ were then made and subjected to uniaxial compressive stresses in order to determine their mechanical properties (Young modulus, compressive strength and deformations). Analytical formulas were subsequently developed to determine the mechanical properties of adobe masonry based on those of bricks and mortar. These same properties were identified for bricks and mortar, separately, before they were used in the wallets.

1 Experimentation:

2.1 Materials characteristics:

The masonry elements (brick and mortar) are made from the dune sand and the clay of Adrar. The dune sand of Adrar is characterized by its cleanliness and the absence of fine particles. Figure 2 shows that the form of the particle size distribution curves presents a steep slope which characterizes materials with narrow granulometry and poor graduation [22] (table 1). It is mainly composed of silica [23]. The clay of Adrar has a very high plasticity and a normal activity close to the mineral Illite [24-27](table 2).

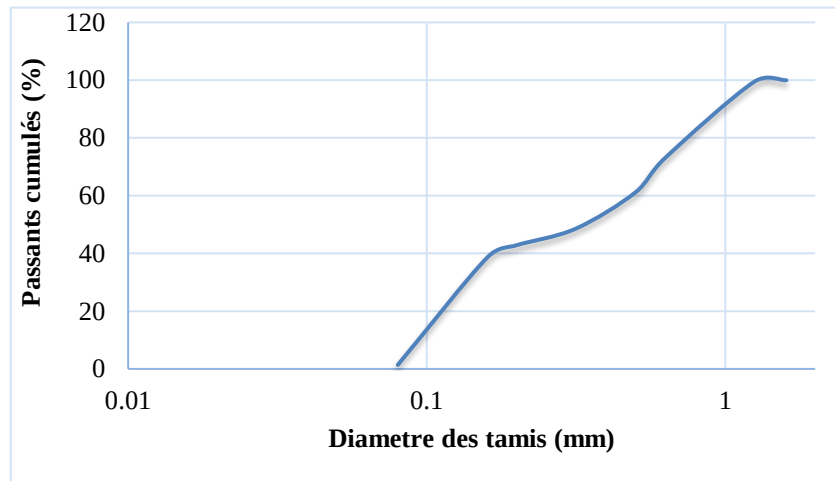


Fig. 2 – Grain size curve of sand dune of Adrar.

Table 1 – Characteristics of the sand dune of Adrar [28]

Parameters	Density (kg/m ³)	ES	<80 μm (%)
Sand dune	27.1	85	4

Table 2 – Characteristics of Adrar clay [26]

Parameters	Adrar clay	Unit
Passing< 2μm	44	%
liquid limit	76,8	%
plasticity Limit	38.46	%
plasticity Index	38.34	%
Skempton coefficient	0.73	-
The value of Methylene blue (MB)	8.1	-

2.2 Masonry units:

2.2.1. Adobe samples caractiristics:

Adobe samples were made from local materials, i.e. dune sand and clay from the region of Adrar, numbering 18, and divided into three categories: a, b and c. The proportions of the components used are those recommended by the Algerian Centre for Cultural Heritage Built in Raw Earth (Centre Algerien du Patrimoine Culturel Bati en Terre - CAPTerre). It is worth specifying that the preparation of adobes was carried out outdoors (Temperature $33^{\circ}\pm 2^{\circ}\text{C}$), in bottomless metal molds (fig.3a), with dimensions (length x height x width) $29 \times 9 \times 14 \text{ cm}^3$ [29] instead of the traditional ones of (length x height x width) $40 \times 20 \times 15 \text{ cm}^3$, firstly because there are no national or international standards, and secondly to facilitate their transport and use. The proportions of their components are recommended by the CAPTerre. Table 3 shows the composition of the adobe samples.

Table 3 - Composition of the three types of adobe samples.

Adobe type	Dune sand	Clay	Crushed sand (0/3)	Water	Quicklime
a	75%	25%	-	26%	-
b	50%	25%	25%	25%	-
c	50%	25%	25%	35%	4.7%

The amount of water is determined by the traditional finger consistency test recommended by the Earth Research and Application Centre CRATerre [30]. The amount of quicklime is taken from the results of Bada's research [10].

For the characterization of bricks (Young modulus, compressive strength, deformation), the 18 adobe samples are surfacing with a 1cm layer of plaster, to allow a uniform distribution of the forces during the application of the vertical loading (fig.4). The test is undertaken using a 160 kN compression testing machine (Controlab), according to the European norm NF EN 772-1. The mechanical properties of adobes at 60 days are presented in the results and discussion part.

2.2.2. Production of adobes for the construction of wallets:

For the production of the adobe units, we hydrate the clay for 24 hours in half the amount of water used in the mixing operation. Then we mix the dry components: dune sand and/or crushed sand and/or quicklime. After that we add the dry mixture and the remaining amount of water to the hydrated clay. For the moulding of the adobe units we use the so-called water-blow method [30], which creates a film of lubricating water between the mould and the mixture, making it easier to remove from the mould. The adobe units are demoulding in their wet state (fig.3b), and drying in the open air for 3 days on a surface covered with dune sand (fig.3c).



(a)



(b)



(c)

Fig. 4 – (a) Bottomless metal moulds; (b) demoulding of the bricks; (c) air drying of the bricks.



Fig. 3 – Adobe testing machine.

1.1 Earth mortar:

The composition of the earth mortar is the same as the adobe type (a) with an increase in the amount of mixing water (table 4), to ensure fluidity, workability, and to reduce the effects of hardening of the mortar in the brick-mortar assembly. The amount of water is determined by the use of Vicat apparatus according to the European norm EN 196-3 [31].

Table 4 – The composition of the earth mortar.

	Dune sand (%)	Clay (%)	Water (%)
Earth mortar	75	25	28

The test is undertaken using a 160 kN compression testing machine (Controlab), where we compress 08 specimens of $4 \times 4 \times 16 \text{ cm}^3$ according to the European standard EN 1015-11 [32]. Also, we record the deformations using a displacement sensor. The device is connected by a system data acquisition for data recording. The compressive stress-strain curve and

mechanical properties (Young modulus, compressive strength, deformation) of the earth mortar at 60 days are shown in the results and discussion part.

2.3 Construction of the wallets

The wallets are built according to the rules of the art, while respecting the transversal and longitudinal flatness (fig.5a). The thickness of the horizontal and the vertical mortar joint is fixed using a wooden template (fig.5b). The dimensions of the nine wallets are shown in figure 6 (fig. 6). The adobes are moistened slightly with a sponge before using them. The wallets samples are surfacing with a 1cm layer of plaster, to ensure the flatness of the upper surface and a uniform distribution of the load during testing. The final dimensions of the wallets are $60 \times 40 \times 14 \text{ cm}^3$ instead of $59 \times 40 \times 14 \text{ cm}^3$ due to the manufacturing defects of the bricks. The masonry assemblages are allowed to cure in the laboratory ($20 \pm 2^\circ \text{C}$) in order to guarantee sufficient bonding between the bricks and the mortar. After 60 days of curing, the nine wallets (03 wallets for each type of brick a, b and c) are subjected to uniaxial vertical compressive stresses according to European standard EN1996-1-1 [17].

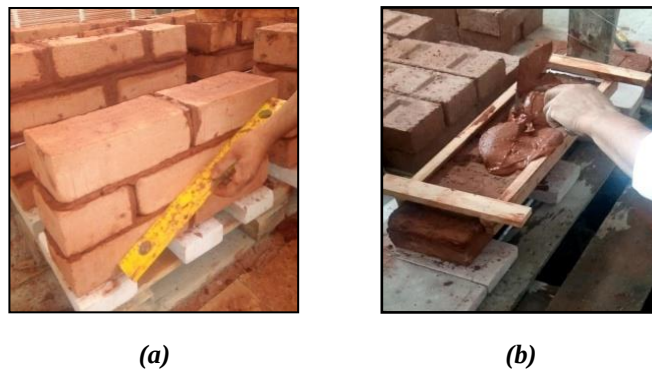


Fig. 5 – (a) Construction of wallets; (b) the first horizontal mortar layer using a wooden template.

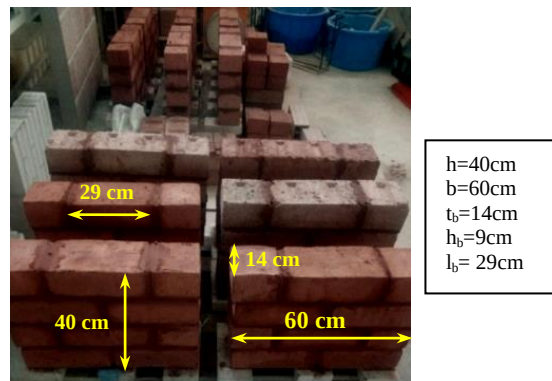


Fig. 6 – Geometry of the wallets.

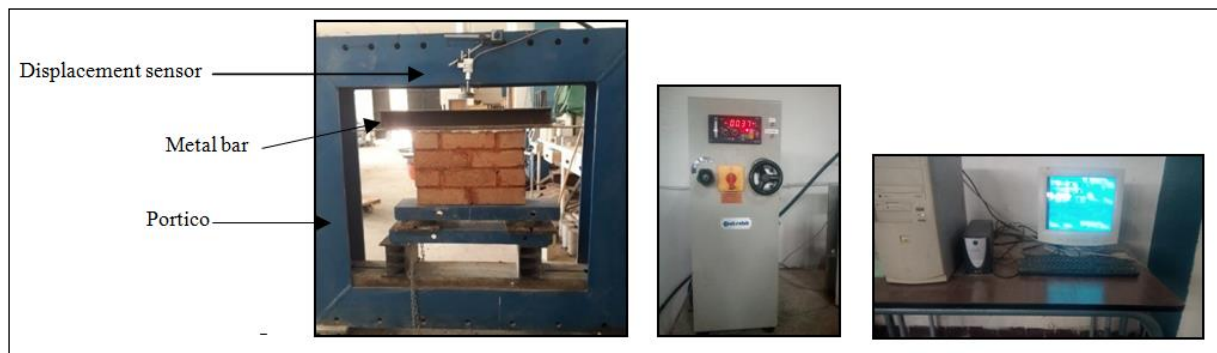


Fig. 7 – Wallets testing apparatus.

For the realization of the tests we use a portico of 1.5 m x 1.7 m and a capacity cylinder 160 kN exerts pressure increments of 0.5kN/s to rupture(fig.7) Also a metal bar for the transmission of forces without any eccentricity is used. As well we put a displacement sensor above the wallets. For the treatment of the data, we use a computer, and a software that allows us to draw the stress-strain curves.

2 Results and discussion

2.1 Raw earth brick testing

The Young modulus of the three types of bricks are determined from the secant slope between the stresses at 5% and 33% of the maximum compressive strength of the stress-strain curves [33] shown in figure 8. Only this range of stresses is considered because beyond, the inelastic strains become significant [34]. A summary of the mechanical properties of the 18 adobes samples are given in table 05.

Loading speed: 0,5kN/s.

Table 5 – The mechanical properties of the three types of adobe at 60 days.

Type	N°	σ_b (MPa) for à	$\varepsilon_b (10^{-3})$	E_b
Adobe a	1	0.800	11.80	103.44
	2	0.802	12.12	103.40
	3	0.807	12.07	103.33
	4	0.790	12.00	103.29
	5	0.814	12.43	103.39
	6	0.823	12.06	102.95
Average		0.806	12.08	103.30
Adobe b	1	0.940	13.12	126.90
	2	0.980	13.30	127.94
	3	0.898	13.14	127.71
	4	0.960	13.28	128.03
	5	0.972	13.40	127.70
	6	1.094	13.74	128.52
Average		0.974	13.33	127.80
Adobe c	1	0.604	10.02	39.39
	2	0.633	10.21	39.80
	3	0.580	10.32	39.50
	4	0.650	10.19	39.44
	5	0.630	10.22	39.70
	6	0.725	10.66	40.85
Average		0.637	10.27	39.78

With :

a, b and c: The three types of handmade adobe used in this study;

σ_b , ε_b , E_b : The compressive strengths, the deformations and the Young modulus in the elastic range of the adobes;

R: The correlation coefficient of stress-strain curves.

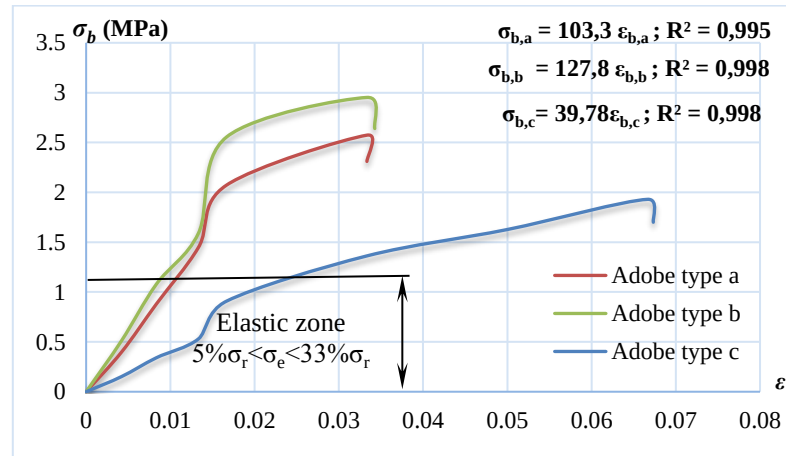


Fig. 8 - Stress-strain curves of adobe type a, b and c in the elastic range.

According to table 05 and Figure 08, It was found that type (b) adobes were more resistant than types a and c, with a compressive stress of 1MPa. In addition, their compressive strengths turned out to be 3 times lower than the stabilized and treated adobes previously studied [16] and [35] ; however, they were about 3 to 6 times smaller than those of compressed and stabilized earth blocks early investigated by [36]. The work carried out at the Earth Research and Application Centre CRATerre [30] showed that the strength of lime stabilized adobes increased about 4 times over time; this strength could reach optimal values after 30 weeks. Moreover, the results of this study (table 05) allowed noticing a 0.1 MPa increase in the compressive strength after 04 weeks, i.e. from 0.637 MPa at the age of 28 days to 0.697 MPa at 60 days. In addition, type c bricks warped less than a and b bricks and was more malleable during its manufacturing process (mixing time twice as short as that of non-stabilized adobe bricks a and b). It should be noted that the improvement in the consistency and mechanical strength over time, of the mixture stabilized with lime, is certainly due to the reaction of clays with lime, leading to the formation of calcium bridges and new hydrate compounds with bonding properties [37].

2.4 Earth mortar testing:

The mechanical properties of the mortar (σ_m , E_m , ε_m), and the compressive stress-strain curve are shown in table 06 and Figure 09. The formula (1) represents the equation of the trend curve of the graph $\sigma_m = f(\varepsilon_m)$.

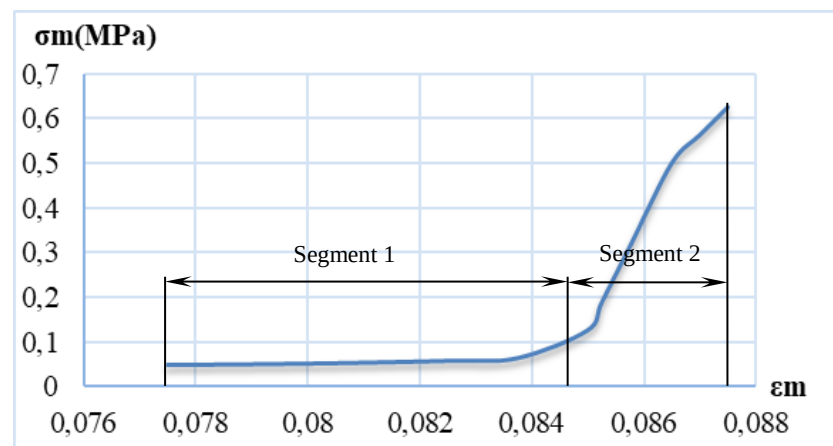


Fig. 9 – Stress-strain curve of the earth mortar in the elastic range.

Loading speed: 0.5kN/s.

Table 6- The mechanical properties of the earth mortar at 60 days.

Properties	σ_m (MPa)	ε_m (10^{-3})	$\sigma_m = E_m \cdot \varepsilon_m + C$
Earth mortar	0.28	84	σ_m (Eq. 1)

$$\sigma_m = 55.93\varepsilon_m - 4.45 \quad (1)$$

with: σ_m , ε_m , E_m : Compressive strength, deformation and modulus of elasticity of earth mortar in the elastic range; C: a constant.

The earth mortar studied has a linear behaviour in the elastic range (33% of the maximum compressive strength of the stress-strain curves). The stress-strain curve in figure 09 shows two straight line segments, which means that the pores of the material were closed at the beginning, and this made the material more compact. These pores can be seen in the form of micro-cracks over the entire surface of the test pieces. Moreover, it is interesting to know that the difference between the mechanical properties of mortar and those of type a adobe (despite they have the same composition of dune sand and clay) are mainly attributed to the large amount of mixing water used in the preparation of mortar. In addition, [38] indicated that the compressive strength of soil decreased 10 times from its initial value when the soil is saturated.

2.5 Adobe masonry testing:

The Young's modulus and the compressive strength of the wallets in the elastic zone are summarized in table 7. Figure 10 present the stress strain curves of the nine wallets. It was shown that when the ultimate stress is reached, the wallets A and B exhibited a brittle behaviour that is characterized by a sharp shape of the curve $\sigma_{Mexp,A,B}(\varepsilon)$ (fig.10). Regarding type C wallets, the curve representing $\sigma_{Mexp,C}(\varepsilon)$ shows a rather rounded shape, which indicates a softening behaviour, unlike wallets A and B which exhibited a clear break

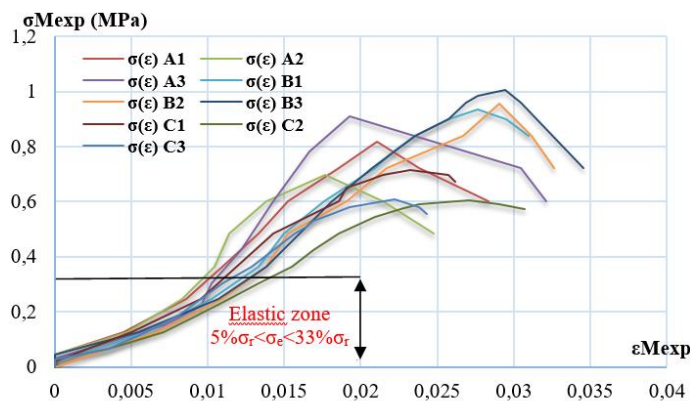


Fig. 10 – Stress strain curve for the wallets type A B and C.

Table 7 – Experimental results of the mechanical properties of wallets (at 60 days)

Wallet type	A			B			C		
N°	1	2	3	1	2	3	1	2	3
$E_{Mexp}(MPa)$	28.49	28.75	21.87	28.32	24.12	28.05	25.67	20.22	23.65
Average	26.57			27.16			23.18		
$\sigma_{Mexp}(MPa)$	0.270	0.230	0.301	0.309	0.316	0.332	0.236	0.199	0.201
Average	0.267			0.319			0.212		
$\varepsilon_{Mexp} (10^{-3})$	11	10.5	15.7	13.3	13.8	13.8	9.5	11.40	9.50
Average	12.4			13.6			10.10		
E_{Mexp}/E_b	0.26			0.21			0.58		
E_{Mexp}/E_m	0.47			0.48			0.41		
E_{Mexp}/σ_{Mexp}	99.7			85.2			116.3		
σ_{Mexp}/σ_b	0.33			0.33			0.33		
σ_{Mexp} / σ_m	0.95			1.14			0.76		

with: A, B and C: The three types of adobe wallets built with the three type of adobe unit a, b and c respectively; σ_{Mexp} , E_{Mexp} , ε_{Mexp} : Compressive strength, Young's modulus and deformations of masonry in the elastic range, of the wallets A, B and C obtained by the stress strain curve (Fig. 10). σ_r : The ultimate compressive stress. Loading speed: 0.5kN/s.



(a)



(b)

Fig. 11 – (a) Rupture of the wallets type A: appearance of the first fissure at $t=34s$; rupture at $t=42s$; (b) Rupture of the wallet type B.



Fig. 12 – Rupture of the wallets type C: Obtaining of the first fissure at $t=26s$; Rupture of the wallets at $t=63s$.

As a result, the adobe masonry has the same behaviour as the conventional one, but with lower resistances. Also, during the loading of the wallets, the cracks appeared at the ends of the adobes (fig.11a and fig.12), and then spread to mortar (fig.11b and fig.13a), This finding is different from that of [38] and [39] who found out that mortar does not crack during loading. Furthermore, it should be noted that the cracks in mortar are due to its poor mechanical properties in comparison with those of adobe bricks. It is also worth noting that when the ultimate limit is reached, a lateral failure of the wallets is then observed (fig.13b and fig.13c) with cracks at the interface between the adobe and mortar (fig.14). These failure modes are mainly due to the triaxial compression generated at the joints and also to the biaxial compression and traction of the adobe bricks.



(a)



(b)



(c)

Fig. 13 – (a) Cracking of the adobes and the mortar joints in the wallets after failure; (b) and (c) The wallets after failure.

According to table 7, the mechanical properties of adobe masonry wallets obtained experimentally are lower than those of its constituents, i.e. brick and mortar, taken separately, which is in agreement with the results suggested by [40] and [41]. Also, Young's modulus of low walls was found to be 2 times lower than that of mortar, and 2 to 5 times lower than that of bricks. Also, the ratio σ_{Mexp}/σ_b between the compressive stress of the wallets and that of the adobe is fixed and equal to 0,33 which is different from the value 0,6 found by [13] and [42]. It should be pointed out that the degradation of the mechanical properties of masonry samples, unlike those of their constituents, is due to the lines of discontinuity at the interface between bricks and mortar, as previously reported by F. Fouchal [15].



Fig. 14 – Cracking at the adobe - mortar interface.

Furthermore, the deformations observed in the wallets were similar to those of adobes before assembly; they were found 6 to 8 times lower than those of mortar tested before assembly. Consequently, it can therefore be said that the behaviour of adobe walls is little influenced by that of mortar, which is in agreement with the results found by [11] and [18]. The fragile behaviour of mortar may be attributed to its confinement state and to its reduced thickness that is smaller than that of adobe.

On the other hand, it was observed that type C wallets are less deformed, though they are less resistant due to the presence of calcium silicate hydrate (CSH) gel which partially crystallizes over time, thus leading to higher compressive strength [43].

Furthermore, the relationship between the compressive strength and Young's modulus of walls can be obtained from Table 7, with: $E_M \approx (85 - 115) \sigma_M$. This expression is different from those previously derived by [44] ($E_M \approx 750 \sigma_M$), [45] ($E_M \approx 1000 \sigma_M$) and [46] ($E_M \approx 850 \sigma_M$). This difference can be attributed to the significant vertical deformations that are clearly visible during the loading test of the adobe wallets by a reduction in the height of the wallets.

It is also worth noting that the fragility of adobe wallets is mainly assigned to the fact that they are built with non-monolithic materials, as opposed to cementitious materials. It should also be mentioned that achieving adobe masonry with high compressive strength is not the most sought-after objective, considering the urban style of the earth-brick constructions with small number of floors that are generally realized in the area. Table 8 shows an example of the calculation of vertical loads of an adobe house that was built in the 90s and is still in good condition until today (fig. 15). It gives us a maximum stress of 0,06 MPa which is inferior to the allowable load on soil, $\sigma_{soil}=0.15$ MPa.

Table 8 – A load decay of an adobe house, Timimoune, Algeria.

Element	Length L (m)	large l (m)	Thickness e(m)	Density ρ (kg/m ³)	Weight M (kg)	Permanent load G (MN . 10 ⁻⁶)
Multi-layer waterproofing	15	5	0.05	10	37.5	367.875
Clay layer	15	5	0.15	1474	16582.5	162674.325
Palm wood	15	5	0.1	309	2317.5	22734.675
Load bearing wall	40	2.5	0.45	1474	66330	650697.3
Base	40	0.5	0.45	1300	11700	114777
Total						951251.175

We have:

$$N_s = G + Q \quad (2)$$

So : $N_s = 1.025 \text{ MN}$

Also:

$$\sigma = \frac{N_s}{S} \quad (3)$$

So : $\sigma = 0.06 \text{ MPa}$, with :

$$S = 40 \times 0.45 \text{ m}^2$$

N_s : the total load of the building;

Q : the operating charge, $Q = q \times L \times l \times g$;

q : the operating load for an inaccessible deck, equals to 100 kg/m^2 ;

g : gravity, equals to 9.81 m/s^2 ;

σ_{soil} : the allowable load of soil.

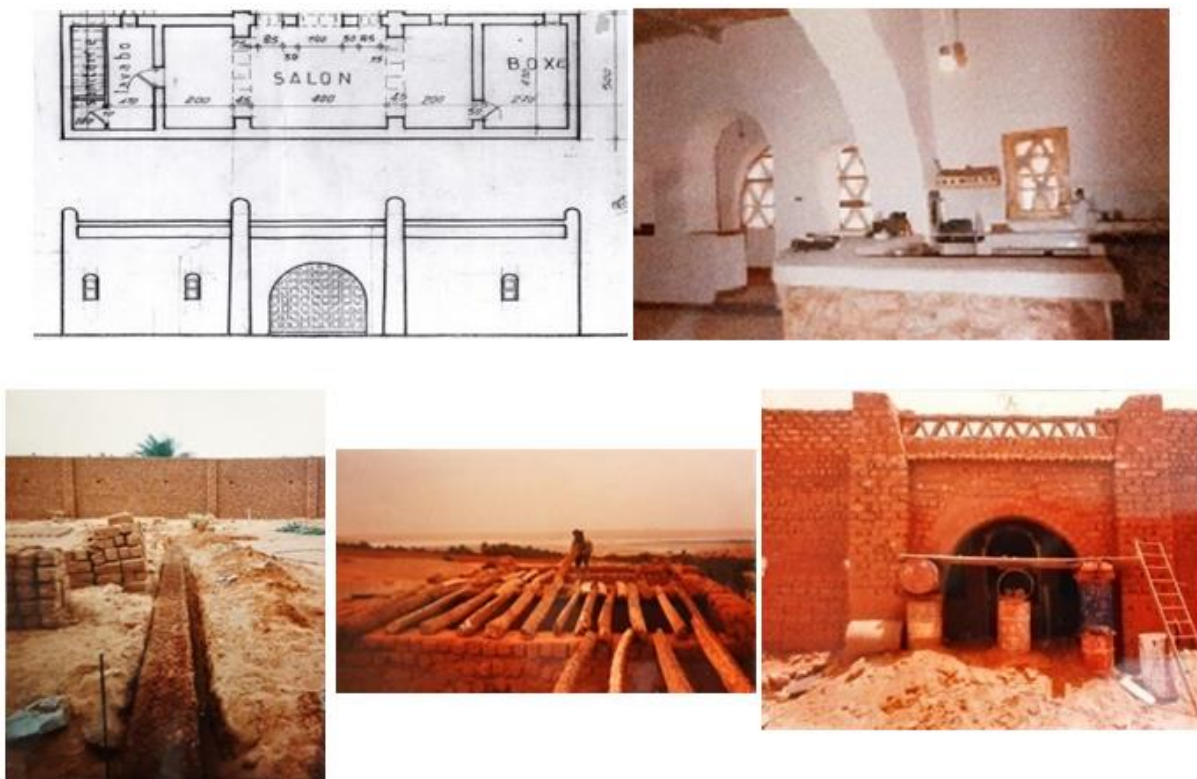


Fig. 15 – Adobe house built in the 90s by an artisan, Timimoune, Adrar, Algéria.

2.2 Analytical formula:

Among the analytical formulas generally used for determining the properties of masonry walls as a function of those of bricks and mortar, that of Eurocode 96 [32] the most widespread. Indeed, this formula makes it possible to find the mechanical compressive strength of masonry as a function of the compressive strengths of mortar and bricks, while using the form coefficient K . In this context, several researchers in the field, such as Page, TL Bui, etc., have previously developed similar formulas that generally give higher results than those obtained experimentally. An analytical formula is suggested in the present work for the calculation of the mechanical properties of a mud brick wall (σ_{Manal} , E_{Manal} , $\varepsilon_{\text{Manal}}$), with:

σ_{Manal} , E_{Manal} , $\varepsilon_{\text{Manal}}$: Compressive strength, Young modulus and deformations of the masonry in the elastic range, calculated analytically.

ΔL_M , ΔL_b , ΔL_m : Displacements (in millimetres), in the elastic range, of the masonry, brick and mortar respectively.

ε_M , ε_b , ε_m : Deformations in the elastic range of the masonry, bricks and mortar respectively.

L_M , L_b , L_m : The length in the vertical direction of the wallets, bricks and mortar respectively

K : shape coefficient related to the structure and to the type of the block, given by [32].

$\sigma_{M \text{ EN96}}$: the compressive strength of masonry given by.

Assumptions:

We work with the same hypotheses used by Page and T.L. Bui, (2014), with:

- I. The stress is uniformly distributed over the entire horizontal section;
- II. Bricks and mortar are homogeneous and isotropic materials;
- III. The bond between bricks and the mortar is perfect;
- IV. Vertical joints are neglected;
- V. The thickness of the joint is constant;
- VI. The total vertical displacement of the joint (ΔL_M) is equal to the sum of the displacement due to the brick (ΔL_b) and that due to the mortar (ΔL_m);
- VII. The compressive stress applied to the wall is the same in all components.

According to hypothesis VI, we can write the equation (4):

$$\Delta L_M = \Delta L_b + \Delta L_m \quad (4)$$

The displacement is written: $\Delta L = \varepsilon \cdot L$, so, we can write the equation (5):

$$L_M \varepsilon_M = \varepsilon_b L_b + \varepsilon_m L_m \quad (5)$$

$$\frac{\sigma_M}{E_M} L_M = \frac{\sigma_b}{E_b} L_b + \left(\frac{\sigma_m - C}{E_m} \right) L_m \quad (6)$$

Applying hypothesis VII gives us the equation (7):

$$\sigma_M = \sigma_b = \sigma_m \quad (7)$$

Then, the equation (6) becomes:

$$\frac{L_M}{E_{\text{Manal}}} = \frac{L_b}{E_b} + \frac{L_m}{E_m} - \frac{C \cdot L_m}{E_m \cdot \sigma_m} \quad (8)$$

So, the analytical modulus of elasticity of adobe masonry E_{Manal} is written as follows:

$$E_{\text{Manal}} = \frac{L_M}{\left(\frac{L_b}{E_b} + \frac{L_m}{E_m} - \frac{C \cdot L_m}{E_m \cdot \sigma_m} \right)} \quad (9)$$

Through the two mechanical properties E_{Manal} (equation 9) and $\varepsilon_{\text{Manal}}$ (equation 5), and according to the law of linear behaviour $\sigma = E \cdot \varepsilon$, we can determine the analytical compressive strength of the adobe walls σ_{Manal} , with:

$$\sigma_{\text{Manal}} = E_{\text{Manal}} \cdot \varepsilon_{\text{Manal}} \quad (10)$$

The analytical Young modulus E_{Manal} , compressive strength σ_{Manal} and deformations $\varepsilon_{\text{Manal}}$ of the 03 types of wallets are summarized in Table 9.

Table 9 – The analytical Young modulus, compressive strength and deformations of the wallets A, B and C.

Wall type	A	B	C
$E_{\text{Manal}}(\text{MPa})$	30,88	31.28	27.89
$E_{\text{Manal}}/E_{\text{Mexp}}$	1.2	1.2	1.2
$\varepsilon_{\text{Manal}} (10^{-3})$	12.93	13.40	12.26
$\varepsilon_{\text{Manal}}/\varepsilon_{\text{Mexp}}$	1.04	0.98	1.21
$\sigma_{\text{Manal}} (\text{MPa})$	0.399	0.419	0.342
$\sigma_{\text{Mexp}}/\sigma_{\text{Manal}}$	0.7	0.8	0.6
Average		0.7	
$\sigma_{\text{M(EN96)}} (\text{MPa})$	0.263	0.297	0.225
$\sigma_{\text{Mexp}}/\sigma_{\text{M(EN96)}}$	1.01	1.07	0.94

With:

$\sigma_{\text{M(EN96)}}$: Analytical formula of the compressive strength of masonry walls giving by the Eurocode 96 [32], with:

$$\sigma_{\text{M(EN96)}} = K \sigma_b^{0.65} \sigma_m^{0.25} \quad (11)$$

The results obtained in table 9 indicate that the tests carried out are quite reliable. Indeed, it was found that the mechanical properties of type B brick walls have the best mechanical properties and are more resistant than wallets A and C.

The analytical formula (11) of the Eurocode 96 [17] gives us results similar to those found experimentally, with a standard deviation of less than 4%. Also, the ratio $\sigma_{\text{Mexp}}/\sigma_{\text{Manal}}$ is about 0,7 (table 9). This difference may certainly be attributed to the simplicity of the analytical approach which takes into account solely the deformations on the surface, on the one hand, and on the other hand, the wetting and hardening state as well as the mortar location, in both cases. In the first experimental case, the 1cm thick mortar was subjected to triaxial compression, while in the analytical case, the mortar sample with dimensions 4x4x16 cm³ was subjected to vertical compression applied by the testing apparatus.

3 Conclusion

This study allowed us to better understand the behaviour of mud brick masonry, and to see how difficult it is to interpret the results of a heterogeneous assembly. The initial objective was to enhance and modernize mud brick masonry constructions in regions characterized by an arid climate, while taking into account the sustainable development principles. Through a series of mechanical tests on raw earth bricks, earthen mortar, and earth wallets, it was found that it is highly recommended to develop mud constructions in the arid region of Adrar. In this work, 120 bricks were thus made, using local materials that are available in almost inexhaustible quantities.

Furthermore, it was revealed that adobes exhibit a rigid linear behaviour in the elastic domain, with elastic compressive strength values between 0.6 and 1MPa, and some degradation at their ends when the maximum stress is reached. The Young modulus lies between 103.3 MPa and 127.8 MPa for adobe a and b, and reduce to 39.78 for adobe stabilized with quicklime. This last present a low behaviour compared to adobe's a and b, but with an amelioration in the consistency and a decrease in the deformation due to the creation of a calcium bridges and a new hydrated compounds with binding properties.

Moreover, earthen mortar exhibits a behaviour similar to that of adobes but with reduced mechanical properties. Although earthen mortar has the same composition as adobes (a), this reduction in mechanical properties is mainly due to the large quantity of mixing water used in the preparation of mortar; this would decrease its compressive strength and increase its deformation.

It is worth indicating that the nine wallets exhibited identical failure modes, with cracks at the joints, bricks, and joint - brick interfaces. In addition, the stress - strain curves of both wallets A and B showed a rigid linear behaviour in the elastic region, which engenders a brittle behaviour at failure. On the other hand, the same failure modes were observed in type C wallets, but with a smoother behaviour. A simple comparison between the mechanical properties of the wallets and those of mortar and bricks shows that the compressive strength of wallets is 33% lower than that of adobes; this is certainly due to the

lines of discontinuity at the brick-mortar interface. Furthermore, the deformations of the walls are similar to those of bricks, but they are 6 to 8 times smaller than those of mortar. Therefore, it can be concluded that the behaviour of masonry depends directly on the behaviour of bricks, while it is little affected by the behaviour of mortar.

The analytical study conducted in this work led to the development of a new formula that can be used to calculate the modulus of Young of masonry based on the mechanical properties of adobe and mortar previously determined separately. This analytical study made it possible to obtain results similar to the experimental ones with a ratio $E_{\text{Manal}}/E_{\text{Mexp}}$ equal to 1.2.

Finally, it can be concluded that adobe masonry has the same behaviour as conventional masonry but with lower mechanical properties which still remain acceptable given the urban style of mud constructions with a limited number of floors in the region of Adrar. Our future work will be focusing in the study of the numerical response of adobe masonry and a development of an adobe masonry oriented model.

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REFERENCES

- [1]- M.S. Zami, A. Lee, Use of Stabilized Earth in the Construction of Low Cost Sustainable Housing in Africa: An Energy Solution in the Era of Climate Changes. *Int. J. Archit. Res.*, 3(2) (2009) 51-65.
- [2]- A.T.M. Marsh, Y. Kulshreshtha, The state of earthen housing worldwide: how development affects attitudes and adoption. *Build. Res. Inf.*, (2021) 1-17. doi:10.1080/09613218.2021.1953369.
- [3]- C. Dove, The Development Of Unfired Earth Bricks Using Seaweed Biopolymers. *WIT Trans. Built Env.*, 142 (2014) 219-230. doi:10.2495/ARC140201.
- [4]- G. Giada, R. Caponetto, F. Nocera, Hygrothermal Properties of Raw Earth Materials: A Literature Review. *Sustainability*, 11(19) (2019) 5342.
- [5]- A. Heath, P. Walker, C. Fourie, M. Lawrence, Compressive strength of extruded unfired clay masonry units. *Proc. Inst. Civil Eng.-Constr. Mater.*, 162(3) (2009) 105-112. doi:10.1680/coma.2009.162.3.105.
- [6]- N. Kumar, M. Barbato, R. Holton, Feasibility Study of Affordable Earth Masonry Housing in the U.S. Gulf Coast Region. *J. Archit. Eng.*, 24(2) (2018) 04018009. doi:10.1061/(ASCE)AE.1943-5568.0000311.
- [7]- R. Anger, L. Fontaine, *Bâtir en terre, du grain de sable à l'architecture*, éditions Belin. Cité des sciences et de l'industrie, Paris, (2009).
- [8]- A.A. Abdessemed-Foufa, Identification du corpus des typologies constructives en terre pour la préservation du patrimoine bâti en et la construction en Algérie. *J. Mater. Environ. Sci.*, 7(10) (2016) 3605-3613.
- [9]- A. Fabbri, J.-C. Morel, D. Gallipoli, Assessing the performance of earth building materials: a review of recent developments. *RILEM Technical Letters*, 3 (2018) 46-58. doi:10.21809/rilemtechlett.2018.71
- [10]- A. Bassoud, A. Bada, H. Khelafi, Caractéristiques thermophysiques des matériaux de construction par ajout des fibres végétales, in *International Seminar on Local Materials and Sustainable Construction Adrar University, Algeria*. (2016). 1-7.
- [11]- A. Bada, A. Bassoud, H. Khelafi, M. Abderahmane, B. Balegh, Caractérisation thermomécanique des matériaux locaux à vase d'argile. *Argile d'Adrar*, in *International Seminar on Local Materials and Sustainable Construction Adrar University, Algeria*. (2016). 1-5.
- [12]- F. El Fgaier. *Conception, production and qualification of fired and unfired clay bricks - Conception, production et qualification des briques en terre cuite et en terre crue*. Thèse de doctorat. Ecole Centrale de Lille, 2013.
- [13]- M. Lateb. *Calcul de la capacité portante des murs en maçonnerie de petits éléments sous charges verticales*. Thèse de doctorat. Ecole Nationale des Ponts et Chaussées, 1995.
- [14]- A. Shukla, G.N. Tiwari, M.S. Sodha, Embodied energy analysis of adobe house. *Renew. Energy*, 34(3) (2009) 755-761. doi:10.1016/j.renene.2008.04.002.

-
- [15]- F. Fouchal, C. Pelissou, F. Lebon, I. Titeux. Modèles d'interface endommageable pour les maçonneries. in XVIIIe Congrès Français de Mécanique. Grenoble. (2007).
- [16]- R. Illampas, I. Ioannou, D.C. Charnpis, A study of the mechanical behaviour of adobe masonry. WIT Trans. Built Env., 118 (2011) 485-496. doi:10.2495/STR110401.
- [17]- B. Standard, EN 1996-1.1 - Eurocode 6 - Design of masonry structures : General rules for reinforced and unreinforced masonry structures. British Standard Institution. London, (2005).
- [18]- R.M. Bennett, K.A. Boyd, R.D. Flanagan, Compressive Properties of Structural Clay Tile Prisms. J. Struct. Eng., 123(7) (1997) 920-926. doi:10.1061/(ASCE)0733-9445(1997)123:7(920).
- [19]- A. Ohler, Zur Berachnung der Druckfestigkeit von Mauerwerk unter Berücksichtigung der mehrachsigen Spannungszustände in Stein und Mörtel. Bautechnik (Berlin, 1984), 63(5) (1986) 163-169.
- [20]- C.-L. Khoo. A failure criterion for brickwork in axial compression. Doctoral Thesis, University of Edinburgh, 1972.
- [21]- A. Committee. Building code requirements for structural concrete:(ACI 318-02) and commentary (ACI 318R-02). American Concrete Institute. (2002).
- [22]- M. Akacem, R. Zentar, B. Mekerta, A. Sadok, H. Moulay Omar, Co-valorisation of Local Materials Tuffs and Dune Sands in Construction of Roads. Geotech. Geol. Eng., 38(1) (2020) 435-447. doi:10.1007/s10706-019-01035-4.
- [23]- M. Akacem, M. Bouteldja, V. Cerezo, A. Hachichi, A method to use local low performances aggregates in asphalt pavements – An Algerian case study. Constr. Build. Mater., 125 (2016) 290-298. doi:10.1016/j.conbuildmat.2016.08.035.
- [24]- H.M. Omar, M. Abbou, M. Akacem, B. Mekerta, A. Semcha, Etude des caractéristiques mécaniques des matériaux locaux de la région d'Adrar utilisés en constructions routières. Afr. Rev. Sci. Technol. Develop. 2(1) (2017) 34-36.
- [25]- H. Lamouri, A. Semcha, Caractérisation du sable de dunes et de l'argile d'Adrar, in International Conference on Materials, Heritage and Environment in Drylands Ahmed Draia University, Adrar, Algeria. (2019). 1-5.
- [26]- M. Abbou, H.M. Omar, M. Akacem, A. Semcha, B. Mekerta, Caractérisation des gisements de la région d'Adrar, en vue de leur valorisation dans l'industrie des matériaux de construction, in International Seminar on Local Materials and Sustainable Construction Adrar University, Algeria. (2016). 1-5.
- [27]- K. Belaidi, A.M. Amine, B. Mekerta, Caractérisation physico-chimique et mécanique des gisements d'argile de la région d'Adrar. Application dans les centres de stockage des déchets de classe 3, in International Seminar on Local Materials and Sustainable Construction Adrar University, Algeria. (2016). 1-5.
- [28]- M. Akacem, B. Mekerta, R. Zentar, H.M. Omar, M. Abbou. VALORISATION OF FINE DUNE SAND IN ASPHALT CONCRETE. in 6th International Symposium on Sediment Management San Cristóbal de Las Casas, Chiapas, Mexico June 19-23, 2018. (2018), 317.
- [29]- V. Rigassi, Blocs de terre comprimée: Vol I Manuel de Production. Braunschweig: GTZ Eschborn Vieweg Verlag, (1995).
- [30]- P. Doat, A. Hays, H. Houben, S. Matuk, F. Vitoux, Construire en terre, par le CRATerre, Collection And Architecture. 272p. Novembre, France. (1979).
- [31]- NF, EN 196-3 - Méthodes d'essai de ciments- partie 3 : Détermination du temps de prise et de la stabilité. AFNOR, Paris, (2017).
- [32]- NF, EN 1015-11 - Méthodes d'essai des mortiers pour maçonnerie- Partie 11 : Détermination de la résistance à la flexion et à la compression du mortier durci. AFNOR, Paris, (1999).
- [33]- G. Mohamad, P.B. Lourenço, H.R. Roman, Mechanics of hollow concrete block masonry prisms under compression: Review and prospects. Cem. Concr. Compos., 29(3) (2007) 181-192. doi:10.1016/j.cemconcomp.2006.11.003.
- [34]- T.L. Bui. Contribution à l'étude de murs maçonnés renforcés par matériaux composites (FRP et TRC): application aux sollicitations dans le plan. Thèse de doctorat. Université Claude Bernard-Lyon I, 2014.
- [35]- L.A. Mango-Itulamy, F. Courtejoie, N. Fagel. The raw earth brick: a building material to meet the needs of local populations. in International conference: Architectural Research for a Global Community The Built Environment Shaping the Quality of Life. Philadelphia, Etats-Unis: Architectural Research Centers Consortium. (2018).
- [36]- X. Yang, H. Wang, Strength of Hollow Compressed Stabilized Earth-Block Masonry Prisms. Adv. Civil Eng., 2019 (2019) 7854721. doi:10.1155/2019/7854721.
- [37]- A.A. Firoozi, C. Guney Olgun, A.A. Firoozi, M.S. Baghini, Fundamentals of soil stabilization. Int. J. Geo-Eng., 8(1) (2017) 26. doi:10.1186/s40703-017-0064-9.
- [38]- P. Chakraborty, A.R. Roshan, A. Das, Evaluation of Dynamic Properties of Partially Saturated Sands Using Cyclic

- Triaxial Tests. *Indian Geot. J.*, 50(6) (2020) 948-962. doi:10.1007/s40098-020-00433-3.
- [39]- E. Quagliarini, S. Lenci, The influence of natural stabilizers and natural fibres on the mechanical properties of ancient Roman adobe bricks. *J. Cult. Herit.*, 11(3) (2010) 309-314. doi:10.1016/j.culher.2009.11.012.
- [40]- H. Varum, A. Costa, J. Fonseca, A. Furtado, Behaviour Characterization and Rehabilitation of Adobe Construction. *Procedia Eng.*, 114 (2015) 714-721. doi:10.1016/j.proeng.2015.08.015.
- [41]- H. Varum, N. Tarque, D. Silveira, G. Camata, B. Lobo, M. Blondet, A. Figueiredo, M.M. Rafi, C. Oliveira, A. Costa, Structural Behaviour and Retrofitting of Adobe Masonry Buildings, in *Structural Rehabilitation of Old Buildings*, A. Costa, J.M. Guedes, H. Varum, Editors. Springer Berlin Heidelberg: Berlin, Heidelberg. (2014), 37-75. doi:10.1007/978-3-642-39686-1_2.
- [42]- A.W.H. Fouad M. Khalaf, R.F. Daniel, Reinforced Blockwork Masonry Columns. *ACI Structural Journal*, 90(5). doi:10.14359/3941.
- [43]- İ. Türkmen, E. Ekinçi, F. Kantarcı, T. Sarıcı, The mechanical and physical properties of unfired earth bricks stabilized with gypsum and Elazığ Ferrochrome slag. *Int. J. Sust. Built Env.*, 6(2) (2017) 565-573. doi:10.1016/j.ijse.2017.12.003.
- [44]- T. Paulay, M.J.N. Priestley, Index, in *Seismic Design of Reinforced Concrete and Masonry Buildings*. John Wiley & Son: New York, United States. (1992). doi:https://doi.org/10.1002/9780470172841.index.
- [45]- NF, EN 1052-1 - Methods of test for masonry. Part 1: determination of compressive strength. CEN. AFNOR, Paris, (1998).
- [46]- C.S. Association, CSA S304. 1: Design of Masonry Structures. Mississauga, ON, Canada, (2004).