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EXPERIMENTAL STUDY OF THE MECHANICAL BEHAVIOR OF COMPRESSED STABILIZED EARTH BLOCKS AND WALLS

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ABSTRACT

The use of compacted stabilized earth blocks (CSEB) in load bearing masonry is largely developed during the last decades. This paper reports on an experimental study of the chemical and mechanical stabilization effects on the compressive strength of earth blocks and triplet/walls. The blocks prepared with a high sandy soil mixed with rising cement and/or lime contents and compacted at 7 MPa, are tested in uniaxial compression. The triplet and walls built with these CSEB units were joined with a cement/earth mortar. Static uniaxial compression tests have been performed on samples of small triplets/walls made of CSEB. The results show that the compressive strength values of earth blocks treated with stabilisers were generally increased by rising the additive content. The increase of earth/cement blocks resistances was found more marked in comparison with those of earth/lime. It was also observed that the blocks prepared with an optimal content of lime along with cement have led to continuous increases of mechanical strength up to values greater than 5MPa. The relationship between the blocks and triplets compressive strengths as function of stabilizer content (cement/lime) is linear. In the range of cement content from 6 to 8 %, the compressive strength of triplets are respectively 16 %and 20 % higher than those of walls.

Keywords: earth blocks, stabilization, compaction, masonry.

INTRODUCTION

Earth construction is considered as the widespread solution for residential housing in a large rural area around the world, due to locally available materials and relatively simple construction methods. However, a rapid deterioration of the materials under harsh weather conditions is pointed out as the main drawback. To overcome this disadvantage, the physical and hydro-mechanical properties of the wall unit or block should be improved. The enhancement of these properties is generally performed by three possible ways: mechanical, physical or chemical stabilization (Bui 2008, Bahar2004). The mechanical stabilization consists on applying a compacting stress to reduce the surface porosity of the blocks and consequently enhance their resistance, whereas the chemical stabilization is based on mixing binders with earth. Generally, the cement and/or lime are the most used stabilizers in earth constructions. The amount and the type of binders depend on the soils characteristics and economical consideration. For instance, in aim to avoid the block friability, it is recommended to use more than 5 % of cement (Walker, 1995). As reported by Vankatarama (2005) injecting 6 %, 8 % and 12 % of cement influences significantly the compressive strength, the stress-strain and the elastic properties of the cured earth block. The stabilization by lime could also improve the mechanical and hydrous properties of CSEB as demonstrated by Guettala, (2006). More adapted for clayey soil, the lime impart a long-term strength gain to earth blocks (Bell, 1990; Herrier, 2012). The use of the lime and cement has been also studied by Burroughs (2006)in order to overcome the problem resulting from drying shrinkage. Furthermore, Nagarej (2014) pointed out the mutual benefits of admixture of cement and lime in imparting strength to the blocks.

The utilization of compressed and stabilized earth blocks (CSEB) in load bearing masonry poses naturally a scale-transition problem from blocks to wall in the assessment of the mechanical properties. It is worthwhile to notice thatthe relationships between the compressive strength of blocks, triplets and walls are not sufficiently studied. From the literature, the triplet resistance in compression represents 50 % to 95 % of earth block compressive strength (P'kla, 2002). This fluctuation depends on the type and amount of the stabilizers, the compacting energy of the blocks and the presence or not of a vertical joint in the triplet. The influence of mortar used for joint is important for wall construction. Under compression, the wall and earth block mechanical behaviors nearly similar as reported by Zine-Eddine (2000). Furthermore, the behavior of the CSEB walls and the conventional masonry notably their failure mode is similar (Walker, 1999). The compression modulus of the walls represents 1/3 of earth blocks ones, whereas their difference between the cracking and nominal failure loads approaches 30 % as pointed out by Olivier (1994). A plastic field in the constitutive law of the unstabilized walls under uniaxial compressive loading is not observed.

In the present study, the influence of mechanical and chemical earth stabilization on the compressive strength of block is investigated. Effects of binders such as cement, lime and cement/lime mixes used to impart strength gain to CSEB are studied. The paper treats the relationship between the compressive strength of triplet and wall and that of their constitutive blocks.

MATERIALS AND PREPARATION

Soil Composition

The soil used in this study was sourced from an area located in the coastal Algiers region (Souidania). The earth blocks were prepared by using a high sandy soil as revealed by the mineralogical compositions listed in Table 1. The mineral characteristic is typical of homogenous earth composing, with a significant presence of quartz, whereas the clayey phase is represented by Illite and Kaolin. The soil contains 14 % of clay, so within the range recommended by (Houben, 1984 and CNERIB recommendations, 1994).

Table 1 - Mineralogical composition of soil

Minerals:	Mineralogical composition (%)
Quartz	74
Kaolinite	10
Illite	04.50
Calcite	02
Albite	02
Feldsparths	03
Ferruginous minerals + background RX	04.50

Soil preparation and stabilization

Before mixing, the excavated soil was immediately dried on exposure to sun, then crushed and finally passed through a 5 mm sieve to eliminate the large lumps. According to Houben (1984), the small elements of clay must be dissociated in order to avoid nodules, which affect considerably the block resistance. A static compactive method was used to select the optimum moisture content in accordance with NF P94-093 standard and local recommendations CNERIB (1993). This method provides a maximal dry density to the CSEB specimen.

Ordinary Portland cement type CEM II 32.5 and ordinary commercial lime is used to stabilize chemically the compressed earth blocks. The cement is well accommodated with low clayey and plastic soils as reported in (CNERIB, 1994). In addition, lime and mixes of cement/lime are also tested. The additives contents and compactive efforts studied are summarized in Table 2.

Table 2 - Mixtures and compactive efforts

<table>
<tr><th rowspan="2">Compactive effort (MPa)</th><th colspan="5">Cement</th><th colspan="3">Lime</th><th colspan="2">Cement and Lime</th></tr>
<tr><th colspan="5">Percentage (%)</th><th colspan="3">Percentage (%)</th><th>Percentage of Cement (%)</th><th>Percentage of Lime (%)</th></tr>
<tr><td rowspan="3">2, 5, 7</td><td rowspan="3">0</td><td rowspan="3">2</td><td rowspan="3">4</td><td rowspan="3">6</td><td rowspan="3">8</td><td rowspan="3">0</td><td rowspan="3">5</td><td rowspan="3">8</td><td>5</td><td>3</td></tr>
<tr><td>5</td><td>5</td></tr>
<tr><td>5</td><td>8</td></tr>
</table>

Blocks, triplets and walls preparation and testing

The different mixtures are vertically compressed by using a hydraulic machine under three different compactive efforts (2, 5 and 7 MPa). The CSEB dimensions are 29.5 cm of length (l), 14 cm of width (w) and 9 cm of height (h), Figure 3(a). After being demolded, the compacted mixture was left in air laboratory until the age of testing. The required time for curing are28 and 90 days respectively for CSEB/cement and CSEB/lime blocks (Rigassi, 1995; CNERIB, 1994).

The triplets are composed of three CSEB units (45 cm in height). For this study, only horizontal joints were considered as shown in Figure 3(b). The mortar is an admixture of earth with 12 % of cement. The tested walls were prepared by using four blocks in elevation and two blocks in width, joined horizontally and vertically with a mortar (1.2 cm thick), Figure 3(c). The dimensions of the walls are 80 cm x 60 cm x 9 cm. The blocks were partially saturated by soaking them in water for a period of (30 s) prior to casting of the masonry walls. The period of cure is fixed to 28 days.

The compression tests on blocks and triplets was carried out using a hydraulic press with 1000 kN capacity. The test was run at a constant displacement rate of 0.02 mm/s. The imposed displacement to the bottom platen and the associated load are automatically recorded. Walls were tested in a compression testing machine having a constant displacement rate of 1.25 mm/min and a 2000 kN capacity.

(a) (b) (c)

Fig. 3 - Fabrication earth blocks masonry walls, (a) CSEB, (b) triplets, (c) wall.

RESULTS AND DISCUSSION

Compressive strength of CSEB

Table 3 shows the result of the blocks resistance values versus additive contents. Generally, the compressive strength of the blocks increases with the increase of the stabilizer content. Furthermore, the evolution of the compressive strength values of the CSEB/cement blocks is more marked than the CSEB/lime ones. Indeed, for the same additive content, the imparted gain by using cement exceeds 4 times the unstabilized earth blocks resistance, whereas this ratio is less than to 2 for earth/lime blocks. These findings are in accordance with the previous works, for instance (Burroughs, 2006, Nagarej, 2014). Moreover, the combination of cement and lime enhances the block resistance. In particular, adding 8 % of lime instead of 5 % (with 5 % of cement) imparts to the block a resistance gain of 2.4 MPa with the highest compaction level.

As set out in literature, an ascending trend of the compressive strength as the compacting energy increases is highlighted. This influence becomes more important as the stabilizer amount is increased. However, this gain in the compressive strength did not emerge from the CSEB/lime blocks. The values of the compressive strength of these blocks in dry state are still less than those indicated in the standard recommendation (Lunt, 1980 or CNERIB, 1993), respectively 6 and 5 MPa. The results show also a convergence between the evolutions of the compressive strength of cement and cement/lime admixture, where the block resistance value reaches 8 MPa. Guettala (2006) obtained similar results when using 8 % of cement content, which is considered as a good quality/price ratio for earth blocks.

Table 3 - Results of the CSEB compressive strength

	Cement (c)					**Lime (l)**			
Compaction (MPa)	**0 %**	**2 %**	**4 %**	**6 %**	**8 %**	**5 %**	**8 %**	**5% c +5 % l**	**5 %c +8 % l**
2	0.6	1.50	2.65	3.70	4.18	1.25	2.32	3.85	3.70
5	1.8	1.9	3.8	6.26	7.17	2.15	3.2	5.1	5.4
7	1.90	2.11	4.44	7.38	8.13	2.66	3.50	5.70	8.10

Figure 4 shows the strain-stress curves of the CSEB for the different stabilizers. The continuous compression is applied along the block width direction. The shape of the curve in compression is parabolic as pointed out by (Hakimi, 1999 and P'kla, 2002). The strain-stress curves could be divided into two parts: the pre-compression stage and the real-compression stage. The lower level of strain at strength peak is around 0.4 %. Stress-strain curves usually showed a yield point where the blocks start to slide gradually until friction set in. The blocks exhibited a brittle failure in a short time after reaching their maximum compressive stress. The ultimate vertical strain is varying between 0.4 % and 0.5 % and usually exhibits an abrupt failure. However, the blocks treated with cement (6 and 8 %) have residual strengths and more deformation capability.

The elastic modulus increases by 1.72 times when the cement content is increased from 6% to 8 %. This ratio is still under the enhancement level of the elastic modulus reported by Venkatarama *et al*. (2005). In their study, by rising the cement content from 6 to 8 %, the elastic modulus of the earth block is multiplied by 2.5. In the mixed composition, a ratio of 1.4 is obtained when rising the lime content from 5 % to 8 %. However, for the blocks treated only with lime, no increase in modulus of elasticity is observed (Figure 4c).

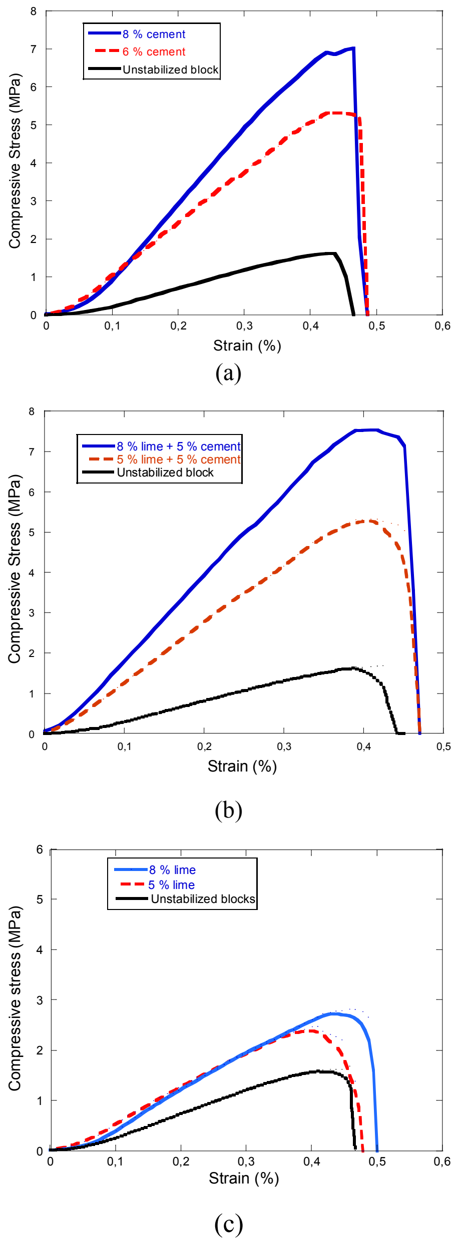


Fig. 4 - Stress-strain relationship of the tested CSEB, (a) stabilized with cement, (b) cement+lime, (c) lime

Compressive strength characteristics of triplets

In this section, the results of uniaxial compression test on triplets are presented. The failure mode showed in Figure 5 is usually observed for triplets subjected to compressive loads. The first damages of the triplets appear at the joints, which are gradually crushed under the compression force. Subsequently, vertical cracks with progressive openings affect the middle block along its entire length. At the onset of the failure, these vertical cracks are less than 2 mm in width. Furthermore and as presented in Figure 5, the diagonal cracks also appear around the edges of the sample. This result corroborates with the findings of (Ben Ayed, 2015), who observed in their experimentation a stress concentration between the clearance of the two and the three stacked blocks. Afterwards, the compression zones formed at the top corners broke off and the block was gradually dislocated until total collapse.

Fig. 5 - Typical failure mode of triplet compression test with CEB stabilized with 6 % cement.

Figure 6 shows the CSEB/triplets compressive strength values as function of stabilizer content (cement for Figure 6a and cement/ lime for Figure 6b), under a compactive effort of 7 MPa.

The results show that the triplet resistance is systematically enhanced as the binder content is increased. Thus, rising the cement content in the CSEB from 4 % to 8 % confers to the triplet resistance an enhancement of around 58 %. In addition, as the cement content exceeds 4 %, the resistance discrepancy of the CSEB and the triplet is reduced. As depicted on Figure 6-a, the resistance of the triplet represents 86 % of that of their (at 6 %) cement stabilized blocks, and this triplet resistance drops to only 30 % for unstabilized constitutive blocks. The same evolution trend is observed for blocks stabilized with mixed additives. Concerning the other type of stabilizers, and as illustrated on Figure 6-b, rising the lime content in the CSEB from 5 % to 8 % (with 5 % of cement) induces an enhancement about 17 % of the triplet resistance. However, the increase of the lime content (from 5 % to 8 %) leads to a significant gap between the CSEB and the triplet resistances. For example, at 5 % and 8 % of lime content, this difference reaches respectively 0.6 MPa and 2.1 MPa.

A linear correlation between the compressive strength of the blocks and triplets is highlighted, Figure 7. This relationship is derived only from experimental data of triplets prepared with cement stabilized blocks (at 2, 4, 6 and 8 % content) under a compactive effort of 7 MPa. The strength relationship between block/triplet is strongly linear over the entire experimental range (regression coefficient: 0.90).

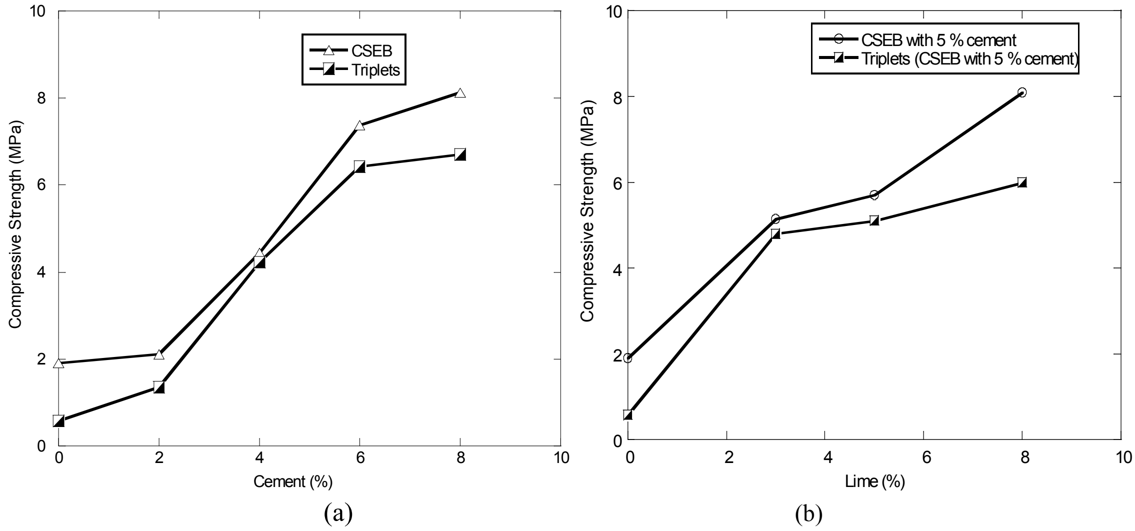


Fig. 6 - Influence of stabilizer contenton block and tripletcompressive strength.
For (a) cement (b) lime(added to 5% of cement)

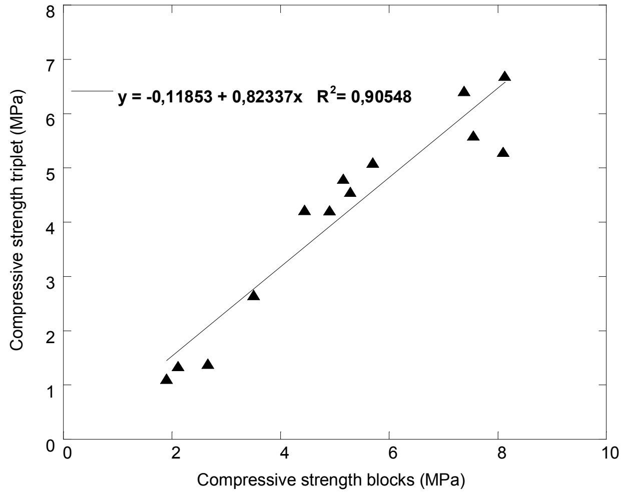


Fig. 7 - Compressive strength of triplets as function of compressive strength CEB stabilized with cement

Mechanical behavior of walls

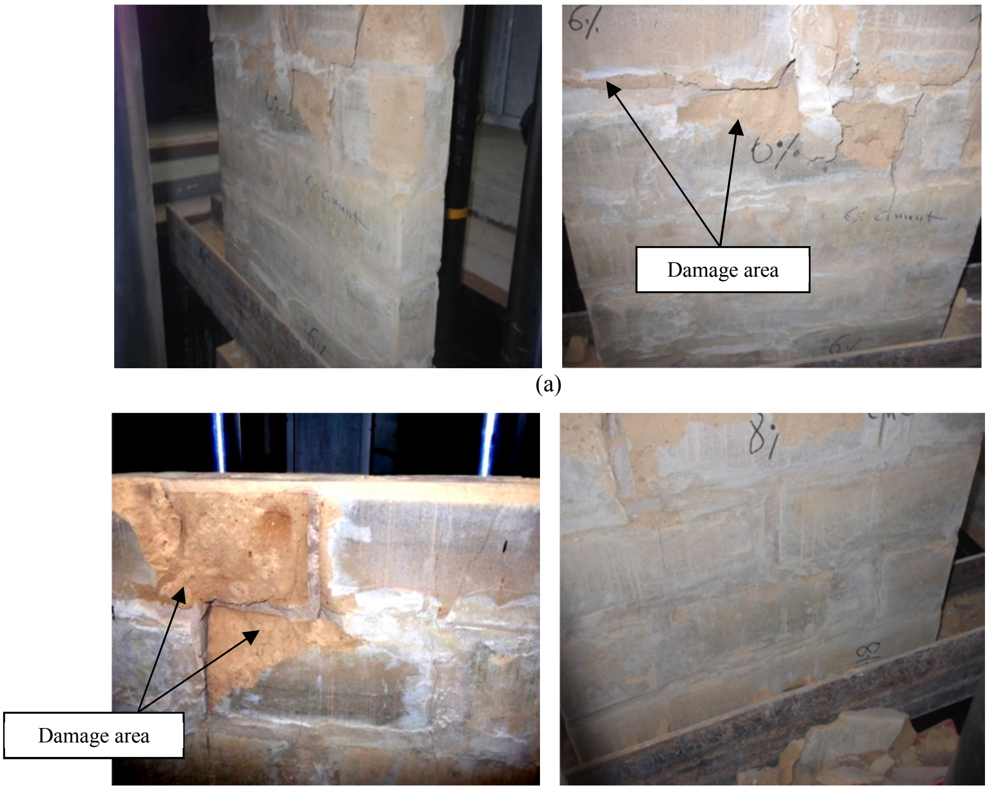
It is known that the strength of the CSEB walls depends on many parameters, such as masonry units/blocks geometry, the strength of the mortar, joint arrangement and even from the workmanship. The experimental setup used for the determination of the compressive strength of walls is shown in Figure 8. After covering the top with a hard mortar (earth cement admixture) in order to reduce the impact of fretting between the walls and the loading plates, a stiff steel beam is placed on top of the walls to uniformly distribute the vertical load of the actuator (planeness defect).

The compressive strength values are about 3.15 MPa and 4 MPa for walls built respectively with CSEB at 6 % and 8 % cement content. The results show that the compressive strength values of walls represent 49 % to 59 % of the triplet resistances. Thus, the smaller the size of the masonry the stronger and stiffer is its behavior. Cracking are the most current type of damage observed on earth blocks masonry structures.

(a) (b)

Fig. 8 - Compressive strength test on walls, (a) CSEB 6 % cement, (b) CSEB 8%cement.

The damages can be localized onto the masonry unit, in a mortar joint as well as at the interface between masonry unit and mortar joint. An example of the failure patterns of the walls is illustrated in Figure 9. The mode of failure (trough vertical cracking) is typical for walls subjected to compressive loads. The crack can be either perpendicular through head and bed joints or pass through units and head joints in the CSEB walls. This type of failure implies continuous cracks through blocks units and head joints. Afterwards, at the peak load the splitting of the blocks is observed. This experimental statement is in accordance with the failure mode reported by Miccoli (2015), who observed also that the stress-strain curve of the wallet tested exhibits a short phase of post-peak strain softening, due to its brittle behaviour under uniaxial load.



(a)

(b)

Fig. 9 - Typical failure mode of mortar bound CSEB masonry walls under uniaxial compression stabilized with: (a) 6%, (b) 8% of cement.

CONCLUSION

This paper presents a set of experimental results obtained in a recent investigation on the improvement of the mechanical characteristics of earth wall units by compaction and chemical stabilization, by using different contents of cement and/or lime. The evolution of the compressive strength values of blocks, triplets and walls are discussed. The main conclusions that can be drawn from this study may be summarised as follows:

- the block resistance is globally enhanced by increasing the stabilizer content
- the impact of the compactive effort is more significant for earth blocks stabilised with cement than for lime mixes
- the stabilization by mixing cement and lime also imparts a non-negligible strength gain to the CSEB
- the elastic modulus increases by 1.72 times when the cement content is increased from 6 % to 8 %. Whereas, for the mixed composition of earth blocks, a strength ratio of 1.4 is obtained when rising the lime content from 5 % to 8 %.
- the compressive strength values of triplets represent respectively 87 % and 82 % of their constitutive blocks stabilized at 6 % and 8 %cement content respectively, whereas they diminish to 42 % and 49 % for the walls.

Further experimental work research is required to confirm the obtained qualitative results by testing various blocks (triplets, wall) sizes and materials.

REFERENCES

[1] AFNOR. Sols: reconnaissance et essais-Détermination des références de compactage d'un matériau-Essai Proctor normal-Essai Proctor modifié. NF P 94-93, Octobre 2014.

[2] Bahar.R, M. Benazzoug and S. Kenai, Performance of compacted cement-stabilised soil, Cement Concrete Composites,2004, 26, pp. 811-820.

[3] Bell, F.G., Coulthard, J.M. Stabilization of glacial deposits of the Middlesbrough area with cementitious material. In: Price, D.G. (Ed.), Proc. 6th Intl. Congress, International Association of Eng. Geology, Amsterdam, Rotterdam, 1990, 3, pp. 797-807.

[4] Ben Ayed H, Limam O, Aidi M, Jelidi A. Experimental and numerical study of interlocking stabilized earth blocks mechanical behavior. Journal of Building Engineering, 2016, 30069-9.

[5] Bui Q. B, Stabilité des structures en pisé, durabilité, caractéristiques mécaniques. PhD thesis, MEGA, Lyon 2008. France.

[6] Burroughs, S. Strength of compacted earth: linking soil proprieties to stabilizers. Building research and information, 2006, 34(1), pp. 55-65.

[7] CNERIB, Guide technique du béton de terre stabilisée, CNERIB, Ministry of Housing, Algiers, Algeria, 1994, p. 55.

[8] CNERIB, Recommandations pour la production et mise en œuvre du béton de terre stabilisée, CNERIB, Ministry of Housing, Algiers, Algeria, 1993, p. 33.

[9] Guettala.A, A. Abibsi and H. Houari, Durability study of stabilized earth concrete under both laboratory and climatic conditions exposure, *Construction and Building Materials*.2006, 20, pp. 119-127.

[10] Hakimi A., Fassi-Fehri O., Bouabid H., Charifd'Ouazzane S., El kortbi M., Non-linear behaviour of the compressed earth block by elasticity damage coupling, Materials and Structures, 1999, pp. 539-545.

[11] Herrier, G., Berger, E., Bonelli, S., The Friant-Kern canal: a forgotten example of lime-treated structure in hydraulic conditions.In: 6th International Conf. on Scour and Erosion, Paris, France, 2012, pp. 1527-1534.

[12] Houben H, H. Guillaud, (CRATerre), Earth "Construction", Primer Brussels, CRATerre / PGC / CRA / UNCHS /. 1984.

[13] MG. Lunt, Stabilised soil blocks for building construction. Overseas building notes, 1980.

[14] Miccoli. L, Garofano. A, Fontana. P, Müller. U. Experimental testing and finite element modelling of earth block masonry. Engineering Structures, 2015, 104, pp. 80-94.

[15] Nagaraj, H.B, M. V. Sravan. T.G. Arun and K.S. Jagadish.Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks.International journal of SustainableBuilt Environnent.2014, 3, Issue 1, pp. 54-61.

[16] Olivier M. Le matériau terre, compactage, comportement, application aux structures en blocs de terre, PhD, INSA, Lyon, 1994. France.

[17] P'Kala A, Jean-Claude Morel, AbaloP'kala, Hervé Di Benedetto, Essai in situ sur blocs de terre comprimée, Revue française de génie civil.2003, 7-2.

[18] Pkla A. Caractérisation en compression simple des blocs de terre comprimées (BTC): application aux maçonneries BTC-mortier de terre, PhD, INSA, Lyon; 2002.France.

[19] RigassiV, Compressed earth blocks, CRATerre-EAG, Manuel de production. 1995, 1.

[20] Venkatarama, R and A. Gupta, Characteristics of soil-cement blocks using highly sandy soils, Materials and Structures J. 2005, 38, pp. 651-658.

[21] Walker. P.J. Strength, durability and shrinkage characteristics of cement stabilized soil blocks. Cement and concrete composites J, 1995, 17-4, pp. 301-310.

[22] WalkerP, Bond characteristics of earth blocks masonry, Journal of Materials in Civil Engineering.1999, 11-3, pp. 249-256.

[23] Zine-Dine K, Boualid. H, EL Korbi. M, Charif-Ouazzane, Hakimi.A. Rhéologie des murs en blocs de terre comprimée en compression uniaxiale: étude et modélisation. Materials and Structures, 2000, 33, pp. 529-536.