Predicting the Hygro-Mechanical Behaviour of Stabilized Compressed Earth Bricks

Simon-Pierre Joy Salassi[1,2](✉), Philbert Nshimiyimana[1], Decroly Denouwe Djoubissie[1], Adamah Messan[1], and Luc Courard[2]

[1] Laboratoire Eco-Matériaux et Habitats Durables (LEMHaD), Institut International d'Ingénierie de l'Eau et de l'Environnement (Institut 2iE), Rue de la Science, 01 BP 594, Ouagadougou 01, Burkina Faso
spjsalassi@uliege.be, joy.salassi@2ie-edu.org

[2] Urban and Environnemental Engineering (UEE), Université de Liège (ULiège), Allée de la Découverte, 9, 4000 Liège, Belgium

Abstract. This study evaluates the influence of water content on the mechanical performances of stabilized compressed earth bricks (CEBs). Two clayey-rich materials were stabilized with 10% and 20% of lime-rich calcium carbide residue (0-20CCR). The stabilized CEBs were produced with the optimum moisture content of each mixture and cured for 45 days in ambient conditions. After the curing and drying, the CEBs were tested. Firstly, the water content was increased gradually, at an average step size of 5%, to evaluate the absorption kinetics and lately its effect on the physico-mechanical properties of CEBs. The CEBs showed rapid absorption kinetics from the first 20 to 30 min, before reaching a relative saturation of the CEBs. The increase in water content decreased the compressive strength. This evolution of the compressive strength with water content was fitted using a model proposed in the literature. By combining the water absorption kinetic with the hydro-compressive strength equations of CEBs, the evolution of the compressive strength was expressed with the time of bulk immersion in water. These results can allow us to predict the evolution of the bulk strength with respect to the rainfall time or other water absorption phenomena.

Keywords: clayey material · lime-rich residue · compressed earth bricks · water absorption · mechanical property

1 Introduction

The scientific community is increasingly recommending the use of environmentally friendly building materials, which require little processing energy, locally available, and easily recycled. Raw compressed earth bricks (CEBs), among other materials, meet all these criteria. This explains the growing number of studies carried out to better understand the behavior of CEBs [1]. However, the CEBs are still used mostly as a filling or decorative material [2]; although they can be better used as load-bearing material in two or three storey buildings [3, 4]. To achieve this, the behavior of CEBs has to be accurately predicted with all the phenomena which can potentially occur.

C. Beckett et al. (Eds.): ICEC 2024, RILEM Bookseries 52, pp. 261–269, 2024.
https://doi.org/10.1007/978-3-031-62690-6_27

One of these phenomena is the transport of water in all its forms (mainly liquid and vapor) [5] and its effect on the residual performances of CEBs. Indeed, the strength of CEBs, even if they are stabilized, is strongly influenced by its water content [3, 4, 6–8]. It was shown that in wet conditions, CEBs lose between 20 and 40% of their strength and become heavier than in dry conditions [3, 4]. The water absorption phenomena of CEBs are well known; i.e. by total immersion, capillary rise, water vapor adsorption [3, 5, 9]. The kinetics of capillary absorption is generally assumed as a linear function of the square root of time, from 1 h to 24 h for compact materials such as stabilized CEBs or to the saturation of capillary pores for non-compact materials such as adobes [10–14]. [15] plotted total absorption curves with the square root of time in hours. [13] plotted the same absorption but with the time in days. [14] also plotted total absorption with the time in hours. All of these studies reported the same bilinear shape of curves with an explicit saturation line. However, only the time of beginning of the saturation changed from one to another. [15] reported the saturation around 8 h, [13] showed a saturation after one day of immersion. [14] did not show a clear saturation even after 24 h of immersion.

Concerning the compressive strength, it is generally accepted to consider the strength of CEB in dry conditions. Although this strength provides an ideal basis for comparison and interpretation of results, it is not realistic regarding the phenomena encountered in situ. Several authors have attempted to evaluate the evolution of compressive strength with the variation in water content [4, 7, 8]. [7] proposed a power equation to estimate the compressive strength with respect to the water content, in the form of $f_c(w) = A * W^B$. In this equation, A [MPa] is the compressive strength of the brick at 1% water content and B is a material-dependent parameter. The use of this equation is limited as it does not predict the dry compressive strength. [8] assessed the compressive strength at water contents of less than 6%. This water content was due to the sorption capacity of the CEB exposed to the humidity. The authors reported the linear regression of the compressive strength $f_c(w) = A * w + B$; where A [MPa] is related to the variation of the compressive strength due to 1% change in water content, and B the compressive strength at 0% water content. The results obtained are not exhaustive, because the water content in the CEB can reach more than 6%, mostly when it is due to the absorption of liquid water (especially during flooding or excessive rainfall), and the response of compressive strength is not linear at high content of water. Therefore, [4] proposed a model for cement stabilized soil blocks of the form: $f_c(w) = A * \left(1 - B * \sqrt{w}\right)$; where A [MPa] is the compressive strength at 0% water content and B is a material-dependent parameter taken equal to 0.21 by the authors [4]. This model seems to be more accurate, more realistic, and more coherent in predicting the evolution of the compressive strength of earth-based bricks with water content. However, its parameters have to be adapted to other types of earth materials produced using other types of stabilizers.

The present study aims to predict the influence of water on the mechanical properties of CEB; while proposing the relationships between the compressive strength and water content absorbed through the total immersion time.

2 Materials and Methodology

Two clay earth materials were used to produce the stabilized CEB. The two materials are named A and B and are respectively taken from Kossodo and Saaba localities near Ouagadougou-Burkina Faso. These two materials differ substantially in their mineralogical composition and geotechnical parameters [3, 16, 17]. The chemico-mineralogical compositions and geotechnical parameters of these materials were reported in [3] and presented in Table 1.

Table 1. Chemico-mineralogical and geotechnical characteristics of the clay materials [3]

Chemical composition				
Oxides		Soil A	Soil B	Ratio B/A
SiO_2 (%)		55	60.9	1.11
Al_2O_3 (%)		23.4	27.6	1.18
Fe_2O_3 (%)		8.1	0.6	0.074
Others (%)		13.5	10.8	–
Mineral composition (XRD method)				
Kaolinite (%)		35	78	2.23
Quartz (%)		30	14	0.47
Goethite (%)		12	3	0.25
Others (%)		23	5	–
Geotechnical parameters				
Atterberg limits (%)	Plasticity index (PI)	40	55	–
	Liquidity limit (LL)	25	35	–
	Plasticity limit (PL)	15	20	–
OMC		14	18	
Particle size distribution (%)	Clay	>10	20–25	–
	Silt	15	25–30	–
	Sand	35	40–45	–
	Gravel	40	10	–

The CEBs were produced using the optimum water content as recommended in the literature [3, 18, 19]. They were stabilized using an industrial by-product of calcium carbide residue (CCR) containing essentially 43% $Ca(OH)_2$ [3, 20]. The amount of CCR recommended for the stabilization of earth material is about 0–25% of the mass and depends on the reactivity of materials and curing time [3, 20]. In the present study, the stabilizer content was 10 and 20%. The stabilized CEB were produced and cured for 45 days, and dried before testing their hygro-mechanical properties. The compressive strength was tested at different contents of water.

These tests were carried out following standard NF XP P13-901 [21]. Before acquiring these basic parameters, the water absorption kinetics of CEB was carried out. This very useful step allowed to control the target water content over the time of total immersion for the hydromechanical tests. At different water contents, the wet compressive strength were determined. Equations derived from fitting the kinetic total water absorption, on one hand and hydro-mechanical properties, on the other hand, allowed to propose the relationship between the compressive strength and immersion time of the tested CEB.

Table 2. Physical properties of bricks [3]

Specimens	A-10CCR	A-20CCR	B-10CCR	B-10CCR
Bulk density [kg/m^3]	1892	1849	1617	1613
Total porosity [%]	34	34.6	38.8	38.6
Total water absorption at saturation -Measured (TWA) [%]	21.69	22.61	24.67	25.98
Total water absorption at saturation Predicted (TWA = e^a) [%]	20.90	24.78	23.57	25.53

3 Results and Discussion

3.1 Water Absorption Kinetics

Figure 1 shows the kinetic of water absorption when the specimens were completely immerged in water. The rate of increase is higher in the first thirty minutes and relatively slow after around one hour, depending on the type of CEB specimen. For CEB from material A, the absorption reached the saturation due to their high porosity and therefore their higher absorption kinetics [3], while for CEB from material B, the absorption does not reach the saturation until beyond 2 h (Fig. 1). This can also be observed from the literature [15]; where the CEB stabilized with 8% cement (CEB-8CP) present an increase of water absorption in around 400 min. In Fig. 1a; a numerical plot is presented from fitting the experimental data from the present study and the study in the literature [15]. The curves are extended to 24 h general considered to be a necessary immersion time to achieve the saturation of CEB. Figure 1b zoomed in the plot to 5 h to illustrated the variations in absorption kinetics of bricks from different soil.

Water content increases exponentially with time (Fig. 1). Equation 1 represents the evolution of the total water absorption with time. W [%] represents the water content; t [minutes] represents the time of total immersion; a, b and c are material dependant parameters. As presented in Table 3, the parameter a is more or less the same for all materials (between 3 and 3.2), which shows (Table 2), how the saturation amount of water is close for both bricks. Contrary to parameters b and c which respective vary between −−2.89 and −12.80 and 0.69 and 5.69. The values of b are higher for bricks from material B than bricks from material A. the variability of that two parameters can be related to intrinsic characteristic of the material like earth-CCR reactivity which is more important for soil B than soil A, or the particle size distribution which is coarser for soil A than soil B [3, 6, 16]. Indeed, because of the high amount of fine particles in material B, it moisture demand is higher than B material which is more coarser. Therefore, the departure of all of that water seems to create higher connected microporal structure. These are just a few ideas. More experimental studies need to be carried out to determine the physical phenomenon behind this equation.

Regarding Eq. (1), water content at each time, W(t), is a factor of two parameters: the total water absorption at saturation TWA and a time dependant factor, expressing a reduction factor over time, Rf(t). In fact, the measured values of TWA comparable to the predicted values of TWA (Table 2) and Rf(t) is comprise between 0 and 1.

$$W(t) = e^{\left(a+\frac{b}{t+c}\right)} = e^{(a)} * e^{\left(\frac{b}{t+c}\right)} = TWA * Rf(t) \quad (1)$$

Figure 1 shows that all the CEB specimens did not reach the same level of saturation after the 2 h of immersion, as some CEB standards recommend to perform the wet compressive tests after the 2 h [21]. Some specimens can continue to absorb over 2 h, due to their micropores. This is confirmed by [14, 15]. After obtaining water absorption kinetic, the compressive strengths of specimen have been tested with different moisture content.

Table 3. Parameters of fitting of the kinetic of water absorption defined for the CEB

Samples	a	b	c	R^2
A-10 CCR	3.04	−2.81	0.69	0.99
A-20 CCR	3.21	−3.5	1.66	0.99
B-10 CCR	3.16	−10.39	3.89	0.99
B-20 CCR	3.24	−12.8	5.69	0.97

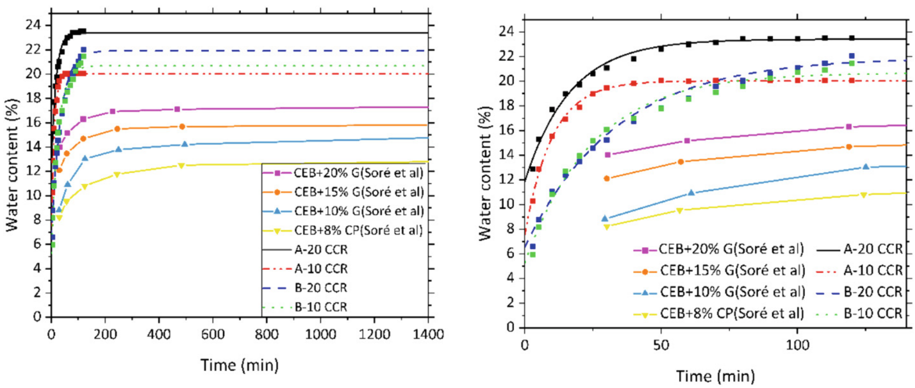

Fig. 1. Kinetic of the total water absorption: a) full scale b) zoomed plot

3.2 Compressive Strength

Figure 2 shows the evolution of the compressive strength with the moisture content. This decrease evolution was fitted with Eq. 2, as proposed by [4]. In this equation: $f_c(w)$ is the wet compressive strength (MPa); w is the moisture content (%); f_c^{dry} is the dry compressive strength (MPa) and B is a parameter depending on specimens. [4] assumed values of B between 0.2 and 0.25 and proposed to use 0.21. However, the value of B depends on the material characteristics, as previously assumed and 0.21 can correspond to cement-stabilized CEB, but not to CCR-stabilized CEB. Therefore, the values of B are estimated between 0.08 and 0.17 for CCR-stabilized CEB used in this study.

$$f_c(w) = f_c^{dry} * (1 - B * \sqrt{\omega}) \quad (2)$$

According to R^2 values in Table 4, this equation is more or less accurate. However, more experimental studies have to be done with other samples and other stabilizing products for the total validation of this model. With the same aim in mind, these studies will have to be extended to study the influence of water content on specimen's total strains, Young Modulus and Poisson's Coefficient. Some results along these lines can be seen in [22]. Figure 3 shows the accuracy of this model by comparing measured values and calculated ones.

Knowing the evolution of water content with time on one hand, and the evolution of compressive strength with water on the other hand, it is possible to express the evolution of compressive strength with time of immersion of sample in water, by combining Eqs. 1 and 2, as presented in Eq. 3. In this equation $f_c(t)$ is the compressive strength depending on time (MPa); t is the time of immersion (minutes); f_c^{dry} is the dry compressive strength (MPa); B, a, b and c are dimensionless parameters depending on the specimen. These

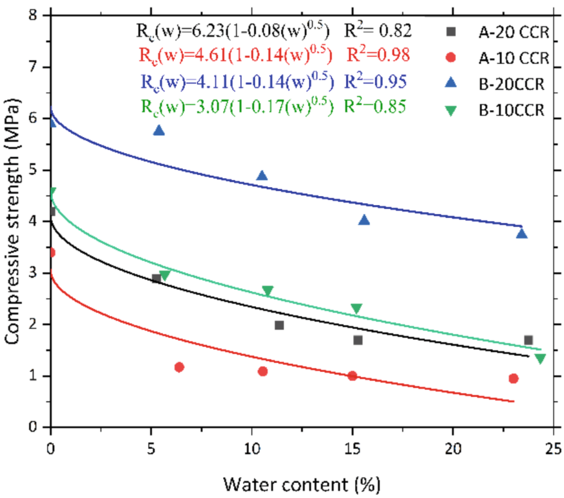

Fig. 2. Evolution of the compressive strength with the water content measured and predicted using the Heathcote's model

parameters are presented in Table 1 and 2.

$$f_c(t) = f_c(w)oW(t) = f_c(w(t))$$

$$f_c(t) = f_c^{dry} * \left(1 - B * \sqrt{e^{a+\frac{b}{t+c}}}\right) \tag{3}$$

Table 4. Parameters of Heathcote models estimated for CCR stabilized CEB

Specimen	f_c^{dry} (MPa)	B	R^2
A-10 CCR	3.1	0.17	0.85
A-20 CCR	4.1	0.14	0.95
B-10 CCR	4.6	0.14	0.98
B-20 CCR	6.2	0.08	0.82

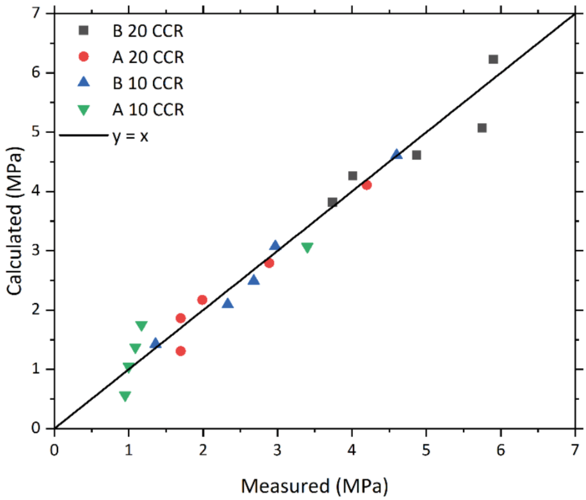

Fig. 3. Measured values vs predicted values of the compressive strength

Figure 4 shows the evolution of compressive strength plotted from the Eq. 3 for bricks from soil A. This shows that it is possible to correlate the compressive strength with time of immersion in water. This can be related to wall immersion time during flooding or excessive rainfall and must be taken in consideration in the evaluation of the load bearing of walls masonry.

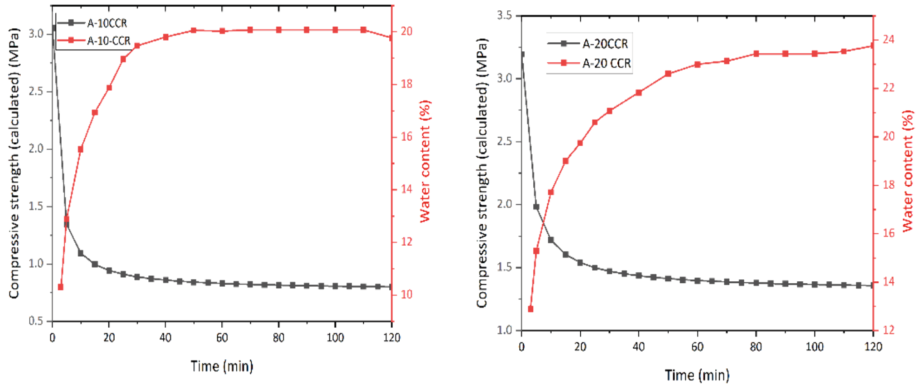

Fig. 4. Compressive strength and water content vs immersion time: a) A-10CCR; b) A-20CCR

4 Conclusion

This study aimed to predict the hygro-mechanical properties of CEB with increasing water content. The increase of moisture content decreases the wet compressive strength, following the model of in the literature. It has been shown the possible to fit the evolution of total water absorption with immersion time by exponential equation. By combining the relationship between the water absorption kinetic and model in the literature, it is possible to plot the decrease of compressive strength with time of immersion. This method could further be applied with capillary absorption to better understand the behavior of CEB with water content in the scenario of exposure to capillary rise. Other CEB structural parameters such as Young modulus, Poisson's Coefficient, and total strains have to be studied with the influence of water content.

References

1. Raj, A., et al.: Building a sustainable future from theory to practice: a comprehensive PRISMA-guided assessment of compressed stabilized earth blocks (CSEB) for construction applications. Sustainability **15**(12) (2023). https://doi.org/10.3390/su15129374
2. Rots, J.G.: Numerical simulation of cracking in structural masonry. Heron **36**(2), 49–63 (1991)
3. Nshimiyimana, P.: Effect of the type of clay earthen materials and substitution materials on the physico-mechanical properties and durability of compressed earth blocks. Ph.D. thesis of the Institut 2iE & University of Liège (2020)
4. Heathcote, K., Jankulovski, E.: Relationship between moisture content and strength of soilcrete blocks: results of experimental investigation into relationship between moisture content and compressive strength of cement-stabilized soilcrete blocks. Build. Res. Inf. **21**(2), 103–108 (1993). https://doi.org/10.1080/09613219308727269
5. Brocken, H.J.P.: Moisture transport in brick masonry: the grey area between bricks. https://doi.org/10.6100/IR519159
6. Dime, T., Sore, S.O., Nshimiyimana, P., Messan, A., Courard, L.: Comparative study of the reactivity of clay earth materials for the production of compressed earth blocks in ambient conditions: effect on their physico-mechanical performances. J. Miner. Mater. Charact. Eng. **10**(01), 43–56 (2022). https://doi.org/10.4236/jmmce.2022.101004

7. Heath, A., et al.: Compressive strength of extruded unfired clay masonry units. https://doi.org/10.1680/coma.2009.162
8. Laou, L., Ait-Ali Said, S., Yotte, S., Ulmet, L., Maillard, P., Rossignol, S.: Evaluation des propriétés mécaniques des briques en terre crue à différentes hygrométries (2017)
9. Saidi, M., Cherif, A.S., Zeghmati, B., Sediki, E.: Stabilization effects on the thermal conductivity and sorption behavior of earth bricks. Constr. Build. Mater. **167**, 566–577 (2018). https://doi.org/10.1016/j.conbuildmat.2018.02.063
10. Dao, K., Ouedraogo, M., Millogo, Y., Aubert, J.E., Gomina, M.: Thermal, hydric and mechanical behaviours of adobes stabilized with cement. Constr. Build. Mater. **158**, 84–96 (2018). https://doi.org/10.1016/j.conbuildmat.2017.10.001
11. Nshimiyimana, P., Messan, A., Courard, L.: Hydric and durability performances of compressed earth blocks stabilized with industrial and agro by-product binders: calcium carbide residue and rice husk ash. J. Mater. Civ. Eng. **33**(6) (2021). https://doi.org/10.1061/(asce)mt.1943-5533.0003745
12. Kabre, S., Ouedraogo, F., Naon, B., Messan, A., Benet, J.C., Zougmore, F.: Évaluation des propriétés thermo-hydro-mécaniques des briques en terre compressée (BTC) issues de la carrière de Matourkou, au Burkina Faso. Afr. Sci. **15**(3), 12–22 (2019). http://www.afriquescience.net
13. Kiki, G., Nshimiyimana, P., Kouchadé, C., Messan, A., Houngan, A., André, P.: Physico–mechanical and durability performances of compressed earth blocks incorporating quackgrass straw: an alternative to fired clay. Constr. Build. Mater. **403** (2023). https://doi.org/10.1016/j.conbuildmat.2023.133064
14. Djibo, K.B., Sore, S.O., Nshimiyimana, P., Ouadraogo, H., Messan, A., Escadeillas, G.: Physico-mechanical performances of compressed earth blocks stabilized with calcined clay-based geopolymer. NanoWorld J. **9** (2023). https://doi.org/10.17756/nwj.2023-s2-046
15. Sore, S.O.: Synthèse et caractérisation des liants géopolymères à base des matériaux locaux du Burkina Faso en vue d'une stabilisation des Briques en Terre Comprimées (BTC). Institut International d'Ingénierie de l'eau et de l'environnement (2017)
16. Nshimiyimana, P., Messan, A., Zhao, Z., Courard, L.: Chemico-microstructural changes in earthen building materials containing calcium carbide residue and rice husk ash. Constr. Build. Mater. **216**, 622–631 (2019). https://doi.org/10.1016/j.conbuildmat.2019.05.037
17. Nshimiyimana, P., Miraucourt, D., Messan, A., Courard, L.: Calcium carbide residue and rice husk ash for improving the compressive strength of compressed earth blocks. MRS Adv. **3**(34–35), 2009–2014 (2018). https://doi.org/10.1557/adv.2018.147
18. Houben, H., Guillaud, H.: CRATerre: Traité de Construction en TERRE: L'encyclopédie de la construction en terre, Parathèses (2006)
19. Murmu, A.L., Patel, A.: Towards sustainable bricks production: an overview. Constr. Build. Mater. **165**, 112–125 (2018). https://doi.org/10.1016/j.conbuildmat.2018.01.038
20. Saldanha, R.B., Scheuermann Filho, H.C., Mallmann, J.E.C., Consoli, N.C., Reddy, K.R.: Physical–mineralogical–chemical characterization of carbide lime: an environment-friendly chemical additive for soil stabilization. J. Mater. Civ. Eng. **30**(6) (2018). https://doi.org/10.1061/(asce)mt.1943-5533.0002283
21. PR XP P13-901: Blocs de terre comprimée pour murs et cloisons Définitions- Spécifications - Méthodes d'essai - Conditions de reception. AFNOR, Saint Denis La Plaine Cedex, p. 37 (2017)
22. Bui, Q.B., Morel, J.C., Hans, S., Walker, P.: Effect of moisture content on the mechanical characteristics of rammed earth. Constr. Build. Mater. **54**, 163–169 (2014). https://doi.org/10.1016/j.conbuildmat.2013.12.067