Hydric and durability performances of compressed earth blocks stabilized with industrial and agro by-product binders: calcium carbide residue and rice husk ash

Philbert Nshimiyimana, Ph.D. [1]; Adamah Messan, Ph.D. [2]; Luc Courard, Ph.D. [3]

[1] Post-doctoral researcher, 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 ; Urban and Environmental Engineering (UEE), Université de Liège (ULiege), Allée de la Découverte 9, 4000 Liège, Belgique.
E-mail: pnshimiyimana@doct.uliege.be

[2] Associate Professor, Dept. Génie Civil et Hydraulique, Institut 2iE, Rue de la Science, 01 BP 594 Ouagadougou 01, Burkina Faso (corresponding author).
E-mail: adamah.messan@2ie-edu.org

[3] Professor, Dept. Architecture, Géologie et Construction, ULiege, Allée de la Découverte 9, 4000 Liège, Belgique. E-mail: luc.courard@uliege.be

Abstract

This study investigated the hydric and durability performances of compressed earth blocks (CEBs) stabilized with calcium carbide residue (CCR) and rice husk ash (RHA). Dry mixtures were prepared using kaolinite-rich earthen material and 0 to 25 % CCR or 20:0 to 12:8 % CCR:RHA of the weight of earth. Moistened mixtures were manually compressed to produce CEBs (295x140x95 mm). Stabilized CEBs were cured at 30±5 °C, wrapped in plastic bags for 45 days. The cured CEBs were dried and tested for water absorption and other indicators of durability. Unstabilized CEBs immediately degraded in water. The stabilized CEBs were stable in water, with very low coefficient of capillary absorption (<20 g/cm².min$^{1/2}$) and excellent durability indicators. They resisted erosion at standard water pressure (50 kPa) and at a pressure of 500 kPa. The coefficient of surface abrasion improved far higher than 7 cm²/g recommended for the construction of facing masonry. It also increased after wetting-drying cycles and correlated with the evolution of compressive strength. This correlation can be used as the non-destructive test of stabilized CEBs.

Keywords: abrasion; carbide lime; compressed earth block; erodability; non-destructive test; rice husk ash; water absorption; wetting-drying cycles

Introduction

Earthen materials, particularly compressed earth blocks (CEBs), are currently regaining the global popularity in modern building constructions for abiding by environmental sustainability and circular economy. However, the society still has some wrong perceptions about the raw earth for construction, considering it as the material for the poor and/or less durable (Beckett et al. 2020; Dahmen 2015; Hughes et al. 2017; Medvey and Dobszay 2020; Morel and Charef 2019). The current popularity of earth is highlighted by the exponential increase of the scientific studies of earth-based construction materials and techniques, and durability testing methods (Beckett et al. 2020; Medvey and Dobszay 2020). Among various techniques, the stabilization using chemical binders such as cement, lime, pozzolanic or alkaline-activated binders not only improves the mechanical properties, but also the hydric and durability indicators of earthen material (Abhilash et al. 2020; Beckett et al. 2020; Bogas et al. 2018; Gomes et al. 2016; Mango-Itulamya et al. 2020; Sore et al. 2018).

The durability of earthen material is predominantly associated with the resistance to water and other agents such as (micro) biological, chemical, thermal or physical attacks, which may affect the longevity of the earth-based structure. "*Broadly speaking, moisture ingress occurs primarily from wind-driven rainfall, condensation, infiltration, absorption from the surrounding ground, and from general building use*" (Beckett et al. 2020). Depending on the rate of absorption, this moisture/water may result in the weakening of the integrity and mechanical resistance of earthen structure. Therefore, it is essential to test the durability of earthen materials.

The tests of the durability of earthen materials, particularly CEBs, are most commonly carried out in the laboratory vis-a-vis water ingress, either by capillary or total absorption, water erosion (spray or drip test), wetting-drying cycles (wire brush test), freeze-thaw cycles, as well as other tests in outdoor real conditions (Beckett et al. 2020; Medvey and Dobszay 2020). Additionally, the resistance to surface abrasion and mechanical resistance, in dry or wet conditions, can clearly indicate the durability of earthen material (AFNor 2001; CDI&CRATerre 1998). The usefulness of either one or more tests would be determined by the envisaged applications of CEBs in building: facing masonry in direct contact with rain or existence of protective eaves, water rising or existence of water proof foundation, etc. However, it is essential to carry out some of the tests in order to assess the suitability of earthen material and/or the efficiency of stabilizer for the durability performance in extreme environment (Beckett et al. 2020).

While the stabilization using chemical industrial binders like cement and/or lime generally improves the durability of stabilized CEBs, these binders are scrutinized to increase the embodied energy and CO_2 emission and thus tempering with the sustainability and other advantages of raw earthen materials (Arrigoni et al. 2017a; Medvey and Dobszay 2020). Therefore, further investigations have been carried out on alternative stabilization approaches and binders that can allow to improve different durability indicators of earth, with relatively limited environmental impact (Al-Fakih et al. 2019; Medvey and Dobszay 2020). These attempts consist of incorporating aggregates or by-product binders from different origins in the earthen materials (Abhilash et al. 2020; Arrigoni et al. 2017a; Azeko et al. 2018; Bogas et al. 2018; Latifi et al. 2018 ; Mango-Itulamya et al. 2020; Masuka et al. 2018; Seco et al. 2017).

The incorporation of aggregates (0-50 %) in clay-rich soil materials reduced the drying shrinkage, water absorption and improved the compressive and abrasion resistance of CEBs (Mango-Itulamya et al. 2020). Furthermore, Abhilash et al. (2020) incorporated wastes from construction-demolition and industries as aggregates and alkaline activated binders in the earthen materials for the production of CEBs. The CEBs stabilized with the pozzolanic materials: 5-15 % GGBS (ground granulated blast furnace slag) or FA (fly ash) activated by NaOH (12 M) recorded comparable water absorption (14-15 %) by total immersion as CEBs stabilized with 7-10 % cement. Seco et al. (2017) similarly reported that the stabilization using GGBS activated by hydrated lime or Portland cement allows to pass the durability tests, estimated in lab and measured in real conditions, of unfired clay bricks containing different fractions of sand (0-50 %). Additionally, Arrigoni et al. (2017a) reported that RE (rammed earth) stabilized with cement (5-10 %) or mixture of CCR (calcium carbide residue), a lime-rich industrial by-product, and FA in ratio of 6:25 % both passed the minimum required compressive strength (2 MPa), accelerated erosion and wire brush tests. More advantageously, the stabilization using CCR and FA, industrial by-products respectively from acetylene production and thermal power plant using coal, improved the overall environmental performance of the RE (Arrigoni et al. 2017a). In the present study, the CCR was mixed with RHA (rice husk ash), an agricultural by-product, for the stabilization of CEBs. These alternative binders were previously reported to undergo microstructural interactions with earthen materials which improved the physico-mechanical and hygrothermal properties of CEBs (Nshimiyimana, et al. 2020a, Moussa et al. 2019; Nshimiyimana, et al. 2019).

The present study specifically aims to investigate "*how the stabilization using by-product binders affect the hydric and durability performances of CEBs?*", compared to the unstabilized and cement-stabilized CEBs, mainly referring to the applications in the Sahelian climatic context. This study was carried out in the framework of a research and development project: "*improving the quality of earth-based habitats in Burkina Faso*" for implementation in this region. According to the Köppen and Geigers classification, the climate of the capital city, Ouagadougou (region Centre of Burkina Faso), is BSh: average annual rainfall of 788 mm and temperature of 28.2 °C (https://fr.climate-data.org/afrique/burkina-faso-14/, July 30, 2020).

This study specifically aims to improve the performances of CEBs, produced using local earthen materials/by-products, to be as competitive as conventional masonry (cement blocks), in order to encourage their applications in modern building constructions. This was achieved by assessing the resistance of stabilized CEBs to water absorption. The effects of stabilization with by-product binders were also assessed on other durability indicators of CEBs, such as the resistance to abrasion, erodability, wetting-drying cycles, as well as the compressive strength.

Materials and experimental methods

Materials

The particle size under 5 mm of a kaolinite-rich earthen material was stabilized with calcium carbide residue (CCR) and rice husk ash (RHA), available in the vicinity of Ouagadougou, Burkina Faso. The physico-chemical and mineral compositions of the materials were reported in previous studies (Nshimiyimana et al. 2020b and Nshimiyimana et al. 2018). The earthen material, from Kamboinse, is a silt-clay of medium to high plasticity (average plasticity index of 20 and average liquidity limit of 50). It contains 20 % clay particles (<2 µm), and mainly an average of 55 % kaolinite and 20 % quartz minerals, and other minerals (Nshimiyimana et al. 2020b). It has a specific density of 2.75. In the previous study, the kaolinite-rich earthen material reached better pozzolanic reactivity with the CCR and improvement of the mechanical properties than a quartz-rich material (Nshimiyimana et al. 2020c).

The CCR is finer than 125 µm, after grinding and sieving. It has median diameter D_{50} of 20.5 µm, a specific density of 2.49, and Blaine and BET specific surface area respectively of 8 286 cm²/g and 14 m²/g. The CCR contains up to 40 % of hydrated lime ($Ca(OH_2)$) and carbonates (Nshimiyimana et al. 2018). The RHA was produced by calcination of the rice husk in optimum conditions (500 °C for 2 hours). It was ground and sieved on 80 µm to reach D_{50} of 11 µm, with a specific density of 2.25, and Blaine and BET surface area respectively of

26 114 cm²/g and 154 m²/g. The RHA is mainly amorphous, with the reactive (amorphous) fraction of 89 %, according to the test proposed by Mehta (US4105459 A, 1978). The difference between the BET and Blaine, much higher for the RHA, is related to the internal porosity of particles, which is took into consideration by BET and not by Blaine.

Production of stabilized CEBs

Firstly, the dry earthen material was mixed with 0 to 25 wt % CCR alone. Secondly, the earthen material was mixed with 20 wt % CCR partially substituted by the RHA (CCR:RHA in 20:0 to 12:8 ratios). Moreover, control mixtures were produced using the earthen material and 8 wt % cement (8CEM). The appropriate moisture content was added to the dry mixtures and mixed until homogeneous moisture distribution. The optimum moisture content (OMC) was determined by static compaction method, according to CDE (2000). The OMC (%) for achieving maximum dry density of the mixtures linearly increased with the CCR content (%), i.e. OMC=0.21xCCR+17. The moisture content of 22 % was used for the mixtures containing the CCR:RHA.

CEBs were produced by manually compressing the moistened mixtures in prismatic mold (295x140x95 mm^3) of terastaram machine. Terastaram machine was designed to offer a compaction pressure of about 35 bars (Sore et al. 2018). At least three (03) test specimens were produced for each mix design. The stabilized CEBs were wrapped in plastic bags to prevent the loss of moisture and eventual carbonation and cured for 45 days in the ambient conditions of laboratory (30±5 °C), as suggested by the previous study (Nshimiyimana et al. 2020c). Cured CEBs were dried at 40±2 °C until the change of mass, between two consecutive weighing in 24 hours, was less than 0.1 %, before their characterizations.

Characterization of stabilized CEBs

The capillary water absorption of CEBs was measured on the bottom face (surface, *S*=29.5x14 cm²) of dry specimen which has a mass, *Md* (kg), immersed in water at a depth of 1±0.5 cm. The mass of wet specimen, *Mwi* (kg), was recorded over the time, i= 0.17 (10 min), 0.5, 1, 2, 4, 8, 16 and 24 hours of capillary immersion. The mass variation allowed to determine the coefficient of capillary absorption, Cb_{10min} (g/cm².min$^{1/2}$), after 10 min (0.17 h) (AFNor 2001, revised 2017) and capillary water absorption, *CWA* (g/cm²), over time, respectively using equations 1 and 2.

$$\mathrm{Cb}_{10\mathrm{min}} = 100\mathrm{x}(\mathrm{Mw}_{10\mathrm{min}} - \mathrm{Md})/(1000\mathrm{xSx}\sqrt{10}) \quad (1)$$

$$\mathrm{CWA} = (\mathrm{Mwi} - \mathrm{Md})/\mathrm{S} \quad (2)$$

$$\mathrm{TWA} = 100\mathrm{x}(\mathrm{Msat.air} - \mathrm{Md})/\mathrm{Md} \quad (3)$$

$$\mathrm{WAP} = 100\mathrm{x}(\mathrm{Mw.sat.air} - \mathrm{Md})/(\mathrm{Mw.sat.air} - \mathrm{Mw.sat.wat}) \quad (4)$$

The total water absorption (TWA) of CEBs was measured, after capillary measurement, on the specimens totally immersed in water (5 cm beneath water surface) for 24 hours, considered enough for water saturation at atmospheric pressure. This allowed to carry out hydrostatic weighing, referring to NF P 18-459 standard (AFNor 2010). The mass of saturated specimen was weighed in water, $M_W.sat.wat$ (kg), and in air, $M_W.sat.air$ (kg). The percentage of *TWA* (%) was determined from equation 3. Additionally, the percentage of water accessible porosity, *WAP* (%), was determined using equation 4.

The resistance to water erodability of CEBs was tested referring to the Bulletin 5 spray test (NZS 1998). It prescribes to apply the water pressure of 50 kPa on a diameter of 150 mm of the specimen, at a distance of 473 mm for 60 min (1 h). This diameter (150 mm) could not be realized if testing the side external face of the CEBs (height <95 mm). The test was thus adapted to a diameter of 90 mm. This did not only reduce the area exposed to erosion test, but also the amount of water falling on the specimen, and therefore, it can be presumed to achieve equivalent erosion effect. Firstly, the erodability test was carried out in the same conditions as the Bulletin 5 spray test (NZS 1998). Secondly, the water pressure was arbitrary increased to 500 kPa, keeping other parameters the same, to assess the effect of different stabilizers on the erodability of CEBs. After the erosion test, the average depth of erosion was measured for each specimen, by means of a needle inserted in each holes on the same specimen. The average percentage of the eroded area was also estimated on the face of each specimen, with respect to the total exposed area (diameter of 90 mm). Each eroded area was subdivided into geometric shapes (circle, rectangle, and triangle) to determine the area. These procedures were repeated on three specimens of the same design in order to determine the average values of the depth of erosion and eroded area of each design.

The resistance to abrasion of CEBs was tested referring to the XP P13-901 standard (AFNor 2001, revised 2017). The test was carried out by applying 60 cycles of abrasion on the side external face of dry CEBs, using a metallic brush loaded with 3 kg. After abrasion test, the weight loss and abraded area of the specimen were measured for determining the coefficient of abrasion (Ca) and percentage weight loss with respect to the total weight of dry specimen. The *Ca* (cm^2/g) was determined as the ratio between the abraded area (cm^2) and weight loss (g). The higher is the *Ca*, the better is the resistance to abrasion of CEBs.

The resistance to wetting-drying (W-D) cycles of CEBs was tested referring to the standard D559-03 revised in D559/D559M-15 (ASTM 2015). This assesses the weight loss of cement stabilized soil subjected to 12 cycles of W-D. The dry specimens of CEBs were soaked in tap water at room temperature (30±5 °C) for 6 hours, then dried in oven at 70±5 °C for 42 hours. This constitutes one cycle of W-D, which was repeated 12 times. After each cycle, the specimens were slightly brushed using a load of 1.5 kg to remove any degraded particles on all faces, in order to determine the weight loss. Moreover, the compressive strength of CEBs was determined before and after 12 cycles of W-D, referring to the XP P13-901 standard (AFNor 2001, revised 2017).

Results and discussion

The stabilization of CEBs with by-product binders affected the hydric behaviors and generally improved different durability indicators of CEBs, such as the resistance to erodability, abrasion and wetting-drying cycles, and compressive strength.

Capillary water absorption

The measurement of water uptake by capillary immersion allowed to determine the amount of capillary water absorption (g/cm²) through the bottom face of stabilized CEBs over the square root of time ($min^{1/2}$). Fig. 1a-b presents the linear correlations ($R^2>0.99$) between the capillary water absorption and square root of time in the range of 1-24 hours for CEBs stabilized with CCR and CCR:RHA, respectively. The slopes of the lines allowed to determine the sorptivity. This coefficient allows to qualitatively evaluate the rate of absorption in the capillary pores: the lower is the coefficient, the smaller is the pore radius (Cassagnabère et al. 2011). The water absorption was not determined for unstabilized CEBs which completely degraded in water. Table 1 shows that the average sorptivity evolved in the range of 0.071-0.084 $g/cm^2.min^{1/2}$ for CEBs stabilized with 5-25 % CCR, reaching the minimum with 15 % CCR. For CCR:RHA stabilized CEBs, the sorptivity evolved in the range of 0.056-0.089 $g/cm^2.min^{1/2}$, reaching the minimum with 18:2 CCR:RHA (Table 1). This is higher than the sorptivity for the CEBs stabilized with 8 % cement (0.045 $g/cm^2min^{1/2}$).

The evolution of the sorptivity suggested that the capillary pores reached the minimum radius (-) for CEBs stabilized with 15 % CCR; beyond which it increased (+) (Table 1). CCR:RHA stabilized CEBs recorded the lowest sorptivity with 18:2 % CCR:RHA, thus the smallest radius (-) of the capillary pores (Table 1). Table 1 also shows that the stabilization with more than

15 % CCR increased the pore size of CEBs produced at their respective OMC. This can be explained by the increase of the sorptivity with increasing OMC for the production of stabilized CEBs, as observed in a previous study (Morel et al. 2013). Moreover, the decrease of the pore radius with the substitution of CCR by RHA (18:2-16:4 % CCR:RHA) can be explained by better reactivity, forming more cementitious products (Nshimiyimana et al. 2019), and thus reducing the pore size .

Furthermore, the coefficient of capillary absorption (Cb_{10min}) was determined after 10 minutes of capillary immersion. The Cb_{10min} of 5-25 % CCR stabilized CEBs evolved in the range of 9-13 $g/cm^2.min^{1/2}$, reaching the minimum value with 15 % CCR (Table 1). The Cb_{10min} of CCR:RHA stabilized CEBs evolved in the range of 10-12 $g/cm^2min^{1/2}$, reaching the minimum with 14:6 % CCR:RHA, compared to 8.3 $g/cm^2min^{1/2}$ for CEBs stabilized with 8 % cement (Table 1). Therefore, all stabilized CEBs have $Cb_{10min} < 20$ $g/cm^2min^{1/2}$, and can be classified as CEBs of very low capillary absorption (AFNor 2001).

The Cb_{10min} can allow to evaluate the initial rate of water absorption in larger pores, in a sense that CEBs record the highest rates in the first minutes of absorption which decreased with time (Bogas et al. 2018). In fact, the Cb_{10min} reported in the present study was much lower than that of CEBs, produced using sandy soil and coarser recycled aggregates, stabilized with 8 % cement (20.8 $g/cm^2min^{1/2}$) or 4:4 % cement:lime (29.8 $g/cm^2min^{1/2}$) (Bogas et al. 2018). This confirms that finer earthen materials produce CEBs which have smaller pore size, as the finer particles fill in pores left by coarser particles, and thus resulting in high packing density. This was also reported by Mango-Itulamya et al. (2020) who observed that the soil containing higher fraction of clay particles reached lower Cb_{10min} than the soil containing lower fraction of clay.

Total water absorption

The water absorption by total immersion after 2 hours (Ab_{2h}) and 24 hours (Ab_{24h}: saturation) respectively ranged in 17-24 % and 19-24 % for CEBs stabilized with 5-25 % CCR (Table 1). For CCR:RHA stabilized CEBs, the Ab_{2h} and Ab_{24h} respectively evolved in the ranges of 17-18 % and 23-24 %, compared to 12 % and 16 % reached by cement stabilized CEBs (Table 1).

The ratio Ab_{2h}/Ab_{24h} evolved in the range of 0.87-0.96 and 0.74-0.80 respectively for CEBs stabilized with CCR and CCR:RHA (Table 1). The lower ratio for the CEBs stabilized with CCR:RHA can also qualitatively suggest lower rate of water uptake. While the Ab_{24h} increased with CCR content, it was quasi-constant during the substitution of CCR by RHA. Nevertheless, the Ab_{24h} for all CEBs was slightly higher than the recommended limits (15-20 %) for application in wet conditions (Bogas et al. 2018; Morel et al. 2013). Therefore, precaution should be taken if these CEBs are used in wet environment, by applying either surface coating or architectural protections.

Guettala et al. (2006) reported that the water absorption of CEBs decreased (Ab_{24h}: 8.3-7.4 %) with increasing cement content (5-8 %). Similar observation was reported by Masuka et al. (2018), Ab_{24h} of 16-11 % for CEBs stabilized with 4-10 % cement. By contrast, other binders may have an opposite effect. Indeed, Bogas et al. (2018) reported Ab_{24h} of 13.6 and 16.5 % respectively for CEBs stabilized with 8 % cement and 4:4 % cement:lime, produced using the moisture content of 9.5 and 10 %. Sore (2017) similarly reported the Ab_{24h} of 14-18 % for CEBs stabilized with 10-20 % geopolymer and produced using the moisture of 17-22 %, compared to Ab_{24h} of 12 % for 8 % cement-CEBs produced with the moisture of 17 %. This is equivalent to the ratio (Ab_{24h}/production moisture) in the range of 0.7-0.8 for CEBs stabilized with cement or geopolymer. This ratio is >1 and 0.8 respectively for CEBs stabilized with CCR (lime-rich stabilizer) or CCR:RHA and cement in the present study (Table 1).

This shows that the stabilization using cement or alkaline and thermal-activated geopolymer is more effective than lime (CCR in the present study) with regard to water absorption. It also shows that the water absorption capacity of CEBs is not only affected by the type and content of stabilizer, but also the type of raw earthen material. The materials requiring high production moisture would produce stabilized CEBs with high porosity resulting from the evaporation of production moisture, and thus high water absorption. Other production parameters such as compaction pressure and curing conditions also affect the hydric behaviors of stabilized CEBs. Therefore, the final water absorption capacity of CEBs can be controlled by optimization of the initial production and curing conditions (Nshimiyimana et al. 2020c).

Water accessible porosity

Fig. 2 presents the evolution of water accessible porosity (WAP), after saturation by total immersion, with respect to the total porosity (TP) of stabilized CEBs. Table 1 further summarizes the values of the TP and WAP. The WAP is in range of 33-36 % for the CEBs stabilized with 5-25 % CCR, equivalent to the ratios of 0.88-0.79 (WAP/TP) of total porosity (Table 1). The WAP slightly increases in the range of 36-38 % for CEBs stabilized with CCR:RHA, equivalent to 0.89-0.96 of the total porosity. This is higher than the WAP of 29 % for CEBs stabilized with 8 % cement, equivalent to 0.79 of total porosity (Table 1).

Bogas et al. (2018) reported the WAP of 25 and 29 % respectively for CEBs stabilized with 8 % cement and 4:4 % cement:lime, which is more than 0.80 of total porosity. Sore (2017) reported the WAP in the range of 36-38 % for CEBs stabilized with 10-20 % geopolymer, compared to 33 % with 8 % cement. In the present study, the CEBs stabilized with CCR:RHA reached higher WAP than the CEBs stabilized with CCR alone, but comparable to that of geopolymer-CEBs. This can be related to the production moisture (22 %) for CCR:RHA-CEBs taken equivalent to the production moisture for 20 % CCR-CEBs. CEBs stabilized with by-product binders in the present study reached comparable values of WAP as CEBs stabilized with common binders in the literature (Bogas et al. 2018). Therefore, the WAP, similarly to the Ab_{24h}, can be further reduced by optimizing the production conditions.

While the TP represents the bulk fraction of pores in the CEBs, the WAP represents the fraction which is readily accessible by water, i.e. the interconnected porosity. Fig. 2a clearly shows that the bulk porosity increased at a relatively higher rate than the interconnected porosity with respect to the CCR content, i.e. decreasing ratio WAP/TP (0.88-0.79: Table 1). Fig. 2b shows a quasi-constant evolution of the porosity around 18:2-14:6 % CCR:RHA, with the ratio WAP/TP of 0.9 (Table 1). This indicates that the improvement of the durability of stabilized CEBs was achieved around 18:2-14:6 % CCR:RHA. The sorptivity and initial rate of capillary water absorption reached the minimum values with 15 % CCR, and increased beyond. These parameters also reached the lowest values with 18:2 and 16:4 % CCR:RHA, respectively. Moreover, while the increase of total porosity is beneficial for the structural and thermal efficiency of stabilized CEBs (Nshimiyimana et al. 2020a), the WAP should decrease to improve the durability. This would turn into the decrease of capillary and total water absorption.

Resistance to water erodability

The assessment of the resistance to water erodability was based on the depth of erosion per hour (DE/hour) and percentage of eroded area, experimentally estimated with respect to the total area exposed to water erosion. CEBs stabilized with by-product binders and tested in standard conditions (50 kPa for 1 hour) were not eroded. The CEBs successfully passed the test, except unstabilized CEBs which were completely degraded in lesser than 15 minutes (Fig. 3a). Similar observation was reported for earth blocks stabilized with 8 % cement or 4:4 % cement:lime (Bogas et al. 2018) or GGBS activated by cement or lime (Seco et al. 2017). The present study presents the results obtained on stabilized CEBs tested using an arbitrary higher pressure (500 kPa for 1 hour). This pressure was deliberately used for assessing the effect of different types and contents of by-product binders on the erodability of CEBs (Fig. 3b-c). Other studies had previously used modified pressures, such as 300 kPa (Bogas et al. 2018) or 2070-4130 kPa (Obonyo et al. 2010).

The depth of erosion and percentage of eroded area of CEBs stabilized with 5-25 % CCR respectively decreased in the ranges of 7-4 mm/h and 41-3 % (Table 2). Table 2 shows that the depth of erosion and eroded area respectively ranged in 5-7 mm/h and 9-27 % for CEBs stabilized with 20:0-12:8 % CCR:RHA, which are slightly higher than 3.5 mm/h and 7 % with 8 % cement. For the record, the depth of erosion was less than 1 mm/h for CEBs stabilized with 8 % cement or 4:4 % cement:lime tested with water pressure of 300 kPa (Bogas et al. 2018). The depth was 1 mm/h and 20 mm/h respectively for CEBs stabilized with 7 % cement and 5:7 % cement:lime and tested at 4130 kPa (Obonyo et al. 2010).

Table 2 shows high coefficient of variation (CV up to 100) of the depth of erosion and eroded area which can be related to surface defects constituting the weak spots. The weak spots, which suffered aggressive erosion, were observed on some stabilized CEBs (Fig. 3b-c). In fact, cracks were initially formed on the surface of some stabilized CEBs just after production. These cracks may have been the origins of continuous and deep fissures: water penetrated through the cracks and induced internal pressure. This not only affected the resistance to surface erosion but also promoted the ingress of water and other agents and may compromise the durability and mechanical resistance of CEBs. Therefore, precautions should be taken to limit surface defects on CEBs or, if needed, apply surface treatment.

Although stabilized CEBs were tested using extremely high water pressure (500 kPa in the present study), they still underwent depth of erosion far below the limit of 120 mm/h recommended for a water pressure of 50 kPa. Therefore, they can be classified as no erodable CEBs (NZS 1998). In fact, the spray erosion test can be considered more like the test of the efficiency of stabilizer than a direct indicator of the durability of CEBs, given its severity

(Beckett et al. 2020). However, this shows that CEBs stabilized with by-product binders can resist the erosion, even if they are exposed to extremely harsh rainy conditions.

Moreover, the percentage of eroded area of CEBs stabilized with at least 10 % CCR reported in the present study was less than 40 %, previously measured by Guettala et al. (2006), in the real condition for wall masonry made of CEBs stabilized with 8 % lime. That study (Guettala et al. 2006) is only one of kind, to the best knowledge of the authors, where the masonry was exposed to real rainfall (120 mm/year) for 4 years in Biskra region of Algeria and underwent an erosion depth less than 1 mm.

This suggests that assessing the resistance to erodability only on the basis of the depth of erosion may mislead into over-estimating the depth of erosion resulting from testing the weak spots. Therefore, the depth should be accompanied by the percentage of eroded area for a better interpretation. Nevertheless, there is still need for more studies to couple the analysis of the common durability indicators and percentage of eroded area in order to establish the validation criteria.

Testing the erodability with water pressure of 500 kPa was equivalent to an average water discharge of 22.4 liter/minute. The knowledge of the total area (diameter of 90 mm) of the specimen exposed to the erosion test and time of exposure (1 hour) allowed to estimate the total amount of water (mm) which fell on the sample. Considering the average rainfall of 788 mm/year in Ouagadougou (region Centre of Burkina Faso) allowed to estimate the time, equivalent to 270 years, for exposure to an equivalent amount of rain water used in the present study. It is noteworthy that this is just an indicative comparison, between the water erosion in the lab and rain erosion in real condition, given the differences in impact forces. The (accelerated spray) erosion test in the lab is usually more severe than under normal rainfall conditions (Beckett et al. 2020).

This can theoretically imply that the CEBs stabilized by by-product binders (maximum depth of erosion of 7 mm) would undergo a linear erosion rate less than 0.03 mm/year, if exposed to the climatic conditions of Ouagadougou. It is noteworthy to mention that earth practically undergoes a non-linear rate of erosion: it is high at the beginning and decrease over time (Bui et al. 2009). Previous study reported an erosion rate of 0.1 mm/year for rammed earth walls stabilized with 5 % hydraulic lime and exposed to real climatic conditions (average rainfall of 1000 mm/year) for 20 years in France (Bui et al. 2009). Moreover, the erosion rate was 0.25 mm/year, as deduced from Guettala et al. (2006).

Resistance to abrasion

The resistance to abrasion was assessed based on the evolution of the coefficient of abrasion, increasing for high resistant CEBs. The average coefficient of abrasion increased in the range of 1-30 cm²/g for CEBs stabilized with 0-25 % CCR (Fig. 4a). The substitution of 20 % CCR by RHA (20:0 to 12:8 % CCR:RHA) resulted in further increase of the coefficient of abrasion in the range of 20-70 cm²/g (Fig. 4b). The CEBs stabilized with CCR:RHA comparatively reached the same average coefficient of abrasion as CEBs stabilized with 8 % cement (70 cm²/g). The CEBs stabilized with CCR:RHA were very hard that they barely lost either 1 or 2 g during the abrasion test, which resulted in very high fluctuations of the average values and standard deviations of the coefficient of abrasion (Fig. 4b). However, the coefficient of abrasion for CEBs stabilized with by-product binders is far higher than 7 cm²/g required for CEBs for application in facing wall masonry of three-storey buildings (CDI&CRATerre 1998).

For CEBs steam-cured for 24 hours, the coefficient of abrasion also increased (6-10 cm²/g) with lime content (6-10 %) and reached the maximum value (23 cm²/g) with lime:natural pozzolan (7:3 %) (Izemmouren et al. 2015). This highlights that coupling the lime-rich stabilizer (CCR) with pozzolan (RHA) for the stabilization of CEBs yields better resistance to abrasion than lime alone.

Table 2 additionally presents the evolution of the average percentage weight loss by abrasion, before W-D. The weight loss ranged in 2.43-0.06 % and 0.08-0.02 %, respectively, for CEBs stabilized with CCR and CCR:RHA. The weight loss was far below the recommended value of 10 %, according to CRATerre (Ngowi 1997). Table 2 also details the average values of the coefficients of abrasion and weight loss, before wetting-drying (W-D), along with the coefficients of variations (CV). It shows that the CV for the coefficient of abrasion is equal or less than 27 for CCR stabilized CEBs, while it is as high as 71 or 47 for CEBs stabilized with 16:4 or 12:8 % CCR:RHA. This indicates that the coefficient of abrasion of CEBs stabilized CCR:RHA has higher variability compared to CEBs stabilized with CCR alone. This variability can again be related to the surface defects (weak spots: Fig. 3b-c) observed on the CEBs containing the CCR:RHA.

Resistance to wetting-drying cycles

According to the standard ASTM D559-03 revised in D559 / D559M-15 (ASTM 2015), the resistance to wetting-drying (W-D) test assesses the weight loss of cement stabilized soil subjected to 12 cycles of W-D. In the present study, the test was adapted because the CEBs stabilized with CCR (5-20 %) did not degrade or loss weight over the W-D cycles. Similar observation was reported for earth blocks stabilized with GGBS activated by cement or lime (Seco et al. 2017). The W-D test was rather combined with the abrasion and mechanical tests for CCR stabilized CEBs. It was not tested for unstabilized (0 % CCR) CEBs, which immediately degraded in water (Fig. 3a).

Table 2 shows that the coefficient of abrasion and compressive strength of CEBs increased with CCR content, even after W-D cycles. The coefficient of abrasion and compressive strength respectively evolved in the ranges of 14-52 cm²/g and 5.9-6.8 MPa after W-D, compared to 12-27 cm²/g and 4.3-4.6 MPa reached before W-D, for CEB stabilized with 10-25 % CCR (Table 2). This is equivalent to the compressive strength of 0.4-0.5 times higher after 12 cycles of W-D than before W-D. It is indeed accompanied by the decrease of the weight loss on abrasion after W-D (0.08-0.03 %) for CEBs stabilized with ≥10 % CCR, which is smaller than the weight loss before W-D (0.12-0.06 %) (Table 2). By contrast, the value of the coefficient of abrasion and compressive strength after W-D was smaller or comparable to the value before W-D for CEBs stabilized with 5 % CCR. This suggests that the CEBs should be stabilized with at least 10 % CCR for keeping the long term performances.

The increase of the coefficient of abrasion and compressive strength is explained by further hygro-thermo-activation of the pozzolanic reaction between the clay earthen material and the excess CCR (≥10 %) during the W-D cycles. In fact, above 10 %, the CCR could not effectively react during the curing at ambient temperature (30±5 °C), which resulted in asymptotic evolution of the compressive strength of CCR stabilized CEBs before W-D cycles (Table 2). However, the W-D cycles created the favorable conditions of temperature (up to 70 °C) and humidity (up to 100 %) for further pozzolanic reaction to take place. The same phenomenon took place by increasing the curing temperature (40 °C), which resulted in continuous increase of the compressive strength, up to 20 % CCR (Nshimiyimana et al. 2020c).

This reveals that the stabilization of CEBs with CCR (lime-rich stabilizer) is beneficial and further improves the performances with W-D cycles, which is not the case with cement (CEM). In fact, Arrigoni et al. (2017b) showed that the compressive strength of earthen material stabilized with CEM and FA improved by 0.4 times after W-D curing compared to standard curing, while that of the earthen material stabilized with CCR and FA improved by 1.6 times. This was related to better consumption of the calcium hydroxide from the CCR through the pozzolanic reaction with the earth and FA over the W-D cycles. Additionally, the compressive strength decreased by 0.3 times for CEBs stabilized with 4 % cement (Hakimi et al. 1998) and 0.5 times with 8 % cement (Yogananth et al. 2019) respectively after 6 and 12 cycles of W-D, with respect to the initial strength.

Durability indicators versus compressive strength

The compressive strength is considered as an indirect indicator of the quality and durability of CEBs (Abhilash et al. 2020; AFNor 2001). Its improvement can be related to the ability of CEBs to resist to attacks of different environmental agents such as water ingress and erosion, abrasion, etc. Indeed, the standard ARS 675:1996 (CDI&CRATerre 1998) recommends that *"if the test to establish the water absorption or abrasion are not feasible […], this deficiency can be compensated by increasing the requirements for the dry and/or wet compressive strength by one category."* The three structural categories of CEBs are defined by standard ARS 671:1996 (CDI&CRATerre 1998), with respect to the dry compressive strength ≥2, ≥4, or ≥6 MPa.

In the present study, the evolution of the compressive strength (Rc in MPa) was tentatively correlated with the coefficient of abrasion (Ca in cm²/g) of CEB stabilized with CCR (before W-D) and CCR:RHA (Fig. 5a). It reached the best fit with an equation $R_c=1.6 \times C_a^{0.35}$, $R^2=0.9$. This suggests that the compressive strength can be predicted from the test of abrasion, and vice versa. This can be useful as a non-destructive abrasion test of CEBs for preliminary design or quality control in the lab or onsite, contrary to the destructive compressive test which requires high end equipment. Fig. 5b shows a good agreement between the predicted and measured compressive strength, mainly below the compressive strength of 4 MPa. However, this correlation still needs validation for other type of materials, and also stabilized with classical binders.

The durability of earthen materials is also commonly related to the compressive strength, mainly the ratio between the wet (Rc_{wet}) and dry (Rc_{dry}) strength. This ratio, defined as the coefficient of water strength ($CWS=Rc_{wet}/Rc_{dry}$), evolved in the range of 0.4-0.6 for CEBs stabilized with CCR and CCR:RHA (Nshimiyimana et al. 2020a). The CWS of CEBs should reach at least 0.5 to be considered durable, according to standards XP P13-901 (AFNor 2001) and ARS 675:1996 (CDI&CRATerre 1998). Although, CWS in the range of 0.3-0.7 are still acceptable (Bogas et al. 2018; Morel et al. 2013).

Moreover, the ratio between the compressive strength ($Rc_{wet\text{-}dry}$) of CEBs after soaking in water (2 h) and drying until constant mass (40 °C) and the initial compressive strength (Rc_{dry}) of dry CEBs, after curing, allowed to define the coefficient of strength reversibility ($\mathrm{CSR}=\mathrm{Rc}_{\mathrm{wet\text{-}dry}}/\mathrm{Rc}_{\mathrm{dry}}$). The CSR of CEBs stabilized with 5-25 % CCR ranged in 0.7-0.9 compared to 0.8 for CEBs stabilized with 8 % cement (Fig. 5c). This suggests that the stabilized CEBs would not only resist the degradation and erosion in contact with water, but also almost fully recover the strength after drying.

While the stabilization of CEBs with by-product binders was detrimental on the absorption behaviors, it was beneficial on the resistance to erodability, abrasion and wetting-drying cycles. In fact, Bogas et al. (2018) previously reported that binders have more direct effect on the mechanical and durability properties than on total porosity, thus the water accessible porosity. This confirms that the most challenging indicator of the durability of CEBs is still the resistance to water absorption which is also a factor of the deterioration of mechanical performances in wet conditions. Nevertheless, the reversibility of the compressive strength and its improvement over the W-D cycles are promising indicators for the long term performances of CEBs stabilized with by-product binders after exposure to environmental conditions.

Conclusions

This study investigated the durability of CEBs stabilized with by-product binders, mainly referring to the applications in the Sahelian climatic context of Burkina Faso. Different independent investigations showed that by-product binders are indeed valuable for the stabilization and improvement of various durability indicators of CEBs. The durability indicators of CEBs reached optimum values with 10 to 15 % CCR or 18:2 to 16:4 % CCR:RHA, such that:

The coefficient of capillary absorption was far below the recommended limit of 20 g/cm².min$^{1/2}$ for very low capillary CEBs. It reached the minimum values of 9.9 g/cm².min$^{1/2}$ with 15 % CCR and 10.4 g/cm².min$^{1/2}$ with 16:4 % CCR:RHA. Nevertheless, the water absorption increased (18-24 %) and exceeded the limits (15-20 %) recommended for usage in wet environment. This affected the water accessible porosity which reached ratios of 0.96 with respect to the total porosity. The WAP should ideally decrease for the improvement of the durability. This would results in the decrease of capillary and total water absorption.

The resistance to erodability of stabilized CEBs was improved. Stabilized CEBs remained intact when tested at standardized water pressure (50 kPa), while the unstabilized CEBs fully degraded. At higher pressure (500 kPa), the stabilized CEBs underwent light erosion. The depth of erosion and percentage of eroded area, respectively, reached 4.8 mm/h and 3 % with 15 % CCR. They respectively reached 5.8 mm/h and 9 % with 18:2 % CCR:RHA. The lifespan estimated in the Sahelian climatic context exceeds 270 years, equivalent to the linear rate of erosion <0.03 mm/year.

The coefficient of abrasion of stabilized CEBs was far higher than 7 cm²/g required for application in facing wall masonry; it reached 16 cm²/g with 15 % CCR and 46 cm²/g with 16:4 % CCR:RHA. The stabilization with the 10-25 % CCR further increased the resistance to abrasion and compressive strength of CEBs after wetting-drying cycles. It suggested that the stabilization with at least 10 % CCR is beneficial for the long term durability of CEBs.

The correlation ($R_c=1.6xC_a^{0.35}$) was established between the compressive strength (Rc in MPa) and coefficient of abrasion (Ca in cm²/g). This can allows the production and construction engineers to predict the compressive strength from the test of abrasion and vice versa. It can be useful as a non-destructive test of CEBs for preliminary design or quality control in the lab or onsite. The correlation established in the present study was established for one type of (kaolinite-rich) earthen materials and stabilized with by-product binders (CCR and RHA). Therefore, it needs validation for other type of materials, and/or stabilized with common binders (cement, lime).

While the stabilized CEBs would not meet the requirement of water absorption for application in wet environment, their performances vis-a-vis other durability indicators are excellent. This clearly confirms that the most challenging indicator of the durability/stability of stabilized CEBs is the water absorption which also remarkably deteriorates the mechanical resistance in wet conditions. Therefore, it is recommendable to take precautions during the usage of stabilized CEBs, minimizing direct exposure to water by applying either surface coating or architectural protections.

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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