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REVIEW

A snapshot review on the improvement of structural performances of compressed earth blocks stabilized with alternative binders: the case of Burkina Faso

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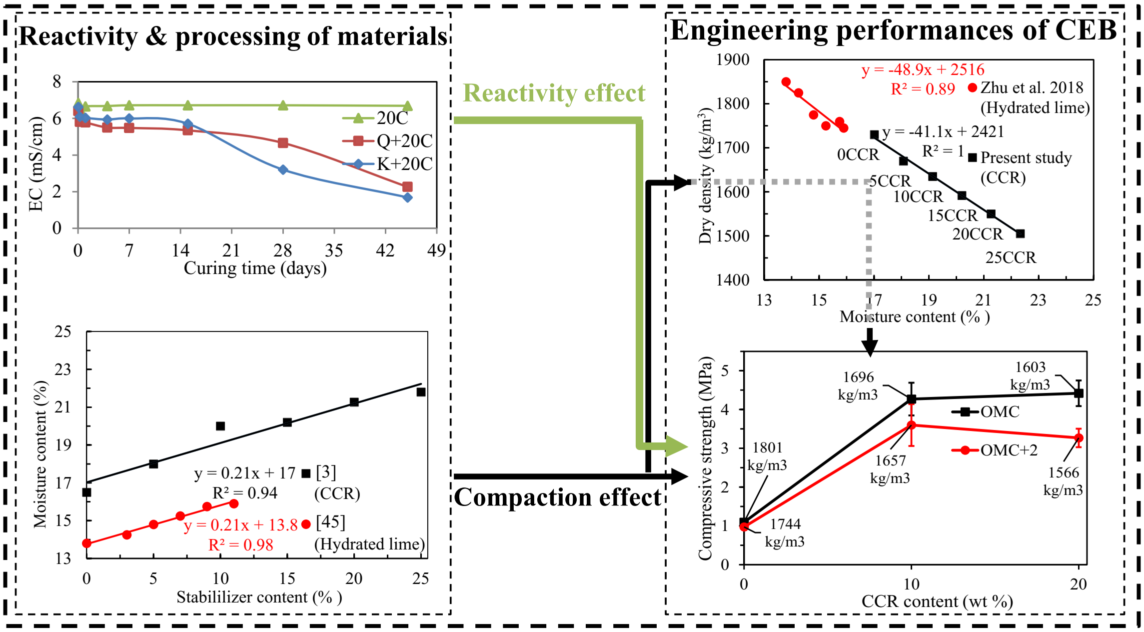
Abstract

Alternative construction materials can allow the modern built environment to abide by sustainability and circularity. This snapshot review highlights some advances made in the stabilization of compressed earth blocks (CEB) using alternative binders in the context of Burkina Faso. The review put forward the considerations of the reactivity and processing of earth materials and binders to produce stabilized CEB. Moreover, it highlights the effects of the changes at chemico-micro-scale of materials to the macro-scale densification, strengthening, and hardening of stabilized CEB. Furthermore, it relates the physical and mechanical properties through the coefficient of structural efficiency and correlates the resistance to surface abrasion with the resistance to bulk compression of stabilized CEB. This could later be extended to the structural efficiency of CEB masonry and allow to easily assess the strength from the quasi-non-destructive test of abrasion.

Graphical abstract



Keywords Alternative binder · Burkina Faso · Compressed earth block · Reactivity · Structural performance

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Introduction

Globally, there have been many attempts to adopt compressed earth blocks (CEB) as alternative and sustainable construction material. In fact, "*earth-based and vernacular technologies which have been derived over the course of centuries and today point out to be climate-friendly and greener than established technologies*" [1]. In the context of Burkina Faso, these attempts are linked back in history; where the capital city Ouagadougou was known as "Bancoville" meaning "built using banco: adobe brick" (Fig. 1a). Today, many efforts are carried out to scale up the applications of earth-based materials in contemporary constructions (Fig. 1b). These efforts are demonstrated through various interventions carried out using different approaches and techniques such as adobe, CEB; and targeting interconnected objectives such as material development and architecture (thermal) optimisation of construction [2, 3], structure stability, value-creation, comfort improvement and potential energy saving [4, 5], sustainability/circularity, and identity re-appropriation [6]. However, challenges still arise from the lack of technical certification and quality control, the social and economic acceptance, the lack of ecological and economic data that would allow to certify their environmental impacts and cost, among others, of CEB; which are considered as the modern version of earth-based construction technique [6].

Earth materials for application in building construction are not mostly strong enough, in their natural form, to bear load in wall masonry of storey buildings. This required the construction of thick walls which resulted in very heavy structures, which not only compromises their structural efficiency [7]; but also, the material efficiency and sustainability of the construction industry. The latter is related to the use of large amount of materials which may lead to their depletion overtime and their excavation which creates pit that may be abandoned without proper rehabilitation. Additionally, earth-based materials are mostly unstable against environmental (water driven) attacks, resulting in immediate or gradual degradation of their mechanical performances and durability [8]. Some of these issues can generally be remedied by the stabilization of CEB.

The stabilization of CEB aims to improve the structural performances of earthen materials over the lifespan of the structure [9]. Table 1 summarizes the key physical and mineral parameters used to select earth material for stabilization with cement or lime, which would depend on its granular size, plasticity and mineral activity. It also shows the production moisture and curing time necessary to achieve the physico-mechanical performances of CEB stabilized with these industrial binders. In fact, the dry compressive strength of CEB must reach at least 4 MPa for the construction of load-bearing walls [10]. Table 2 presents the benchmark values for the required properties of CEB for classification in the three structural categories, based on the existing standard [10–12] and proposals from the literature [13]. This aims at providing the regulating specifications for the use and competitiveness of CEB with other wall masonry materials. The mechanical performances of CEB stabilized with cementitious industrial binders, such as cement and/or lime, have been well investigated [7, 14] Nevertheless, their hygro-thermal behavior, durability, and onsite performances in wall masonry are still subjects for further investigations [9, 15].

The stabilization of CEB using the industrial binder, specifically cement, is criticized for tempering with the natural advantages of earth, i.e. low energy and carbon footprint, recyclability, moisture exchange capacity, and other environmental advantages [16, 17]. Moreover, it was repetitively recommended for further studies to investigate the feasibility of incorporating recycled or secondary materials in earth

Fig. 1 Earth-based constructions in the city of Ouagadougou: **a** historical "Bancoville" in 1931; **b** contemporary construction using CEB in 2018 [3]

Table 1 Recommended values of common parameters to produce CEB stabilized with cement or lime: physical and mineral characteristics, processing conditions and the achieved physico-mechanical performances [44]

Parameters		Type of chemical stabilizer (mass percent)	
		Cement (5–10%)	Lime (6–12%)
Physical and mineral characteristics of material	Clay particle (%)	10–30	30–50
	Plasticity index (%)	10–20	20–30
	Mineralogy	Inactive	Active
Processing conditions of stabilized CEB	Moisture of production (%)	10–15	15–20
	Curing time in ambient condition (days)	28	> 28 (up to many months)
Physico-mechanical performances of cured CEB	Bulk density (kg/m^3)	1600–2200	1400–2000
	Dry compressive strength (MPa)	4–12	2–7

Table 2 Structural categories of CEB: requirements of mechanical, hydric and durability properties of facing CEB (CEB F) for applications in wall masonry

Constraint category*			Compressive strength**		Water absorption ***		Abrasion ****	
CEB	Environmental	Mechanical	Dry Rc (MPa)	Wet Rc (MPa)	Capillary (%)[a][(g/cm^2.s$^{0.5}$)][b]	Total (%)[c]	Mass loss[a](%)	Coef.[b] (cm^2/g)
F 1D	Dry environment (D)	1	≥ 2	NA	NA		≤ 10	≥ 2
F 2D		2	≥ 4	NA	NA		≤ 5	≥ 5
F 3D		3	≥ 6	NA	NA		≤ 2	≥ 7
F 1R	Water by lateral spraying (R)	1	≥ 2	≥ 1	NA	15–25	≤ 10	≥ 2
F 2R		2	≥ 4	≥ 2	NA		≤ 5	≥ 5
F 3R		3	≥ 6	≥ 3	NA		≤ 2	≥ 7
F 1C	Water by vertical penetration (C)	1	≥ 2	≥ 1	≤ 15 [40]	15–25	≤ 10	≥ 2
F 2C		2	≥ 4	≥ 2	≤ 10 [20]		≤ 5	≥ 5
F 3C		3	≥ 6	≥ 3	≤ 5		≤ 2	≥ 7

CEB F 1D: compressed earth block (CEB) of constraint category 1 for application in dry (D) environment; Rc: Resistance to compression, NA: not applicable

* The use of CEB in R and C category environments requires using a stabilizer if the architecture protection against water damage is not guaranteed. If the protection is guaranteed, the environment can be regarded as category D [10]

** The values given are average values obtained from tests carried out on a set of samples [10]

***[a] Water absorption at saturation by capillary immersion [10]

***[b] (Coefficient of capillary absorption ≤ 20 g/cm^2.s$^{0.5}$: very low capillary CEB and ≤ 40 g/cm^2.s$^{0.5}$: low capillary CEB [11])

***[c] Total water absorption by total immersion: 15–25% [13]

****[a] Loss of matter after abrasion[10]

****[b] Coefficient of abrasion [11]

If tests to establish water absorption or abrasion resistance are not feasible, this deficiency can be compensated by increasing the required dry and/or wet compressive strength by one category [12]

materials for geotechnical and/or building applications [9, 18–26]. If applied to CEB, this can potentially enhance the environmental sustainability and socio-economic acceptance of stabilized CEB in contemporary construction [27–29].

Recent decades have recorded a boom in the number of research and review publications on the applications of earth-based materials, specifically CEB, and other non-conventional materials for sustainable green building constructions [27]. Among many other studies, the most relevant are: *building a sustainable future from theory to practice: a comprehensive PRISMA-guided assessment of compressed stabilized earth blocks (CSEB) for construction applications* [30], *analysis of the effect of incorporating construction and demolition waste on the environmental and mechanical performance of earth-based mixtures* [31], *sustainable utilization of biomass waste-rice husk ash as a new solidified material of soil in geotechnical engineering: a review* [32], *optimisation of compressed earth blocks (CEBs) using natural origin materials: a systematic literature compilation review* [33], *natural* *additives and biopolymers for raw earth construction stabilization—a review* [34] *An overview of the remaining challenges of the RILEM TC 274-TCE, testing and characterisation of earth-based building materials and elements* [34] *weathering the storm: a framework to assess the resistance of earthen structures to water damage* [27]; *durability of stabilized earthen constructions: a review* [35]*; life cycle assessment of traditional and alternative bricks: a review* [36] *improvement of lifetime of compressed earth blocks by adding limestone, sandstone and porphyry aggregates* [37]*; is stabilization of earth bricks using low cement or lime contents relevant?* [38]; *a state of the art review to enhance the industrial scale waste utilization in sustainable unfired bricks* [39]; *the potential and current status of earthen material for low-cost housing in rural India* [40]; *earth mortars stabilization: A review* [41]. These publications show the global interests of the scientific community towards earth-based materials, especially CEB, as a sustainable construction material. Unfortunately, such publications are inexistant in the local context and only few focus on the CEB (Sect. "An overview of research interests on earth-based materials and applications in Burkina Faso"). It is therefore important for us to review the current state of the art of the studies on the CEB, specifically stabilized with alternative binders, to propose the recommendations for the full adoption of CEB in Burkina Faso.

Moreover, the conceptual framework for achieving sustainable building through CEB for the case of Ouagadougou highlighted that "*full-scale production of compressed earth blocks has proven that this type of building material has a promising future as a low- to medium-cost building construction material that contributes to long-term sustainability*" [42]. This can be achieved not only through the recognition and acceptance of the potential of CEB by the local populations and public policies [6]; but also, through the awareness of entrepreneurs and other construction actors who should be able to produce CEB that abide by the technical performances throughout their life cycle [3, 43]. The builders should also be able to optimize the envelopes of CEB-based housing to minimize the thermal discomfort and potentially reduce the energy consumption on mechanical air-conditioning [2, 5]; and eventually contribute to reducing the CO_2 footprint of the housing.

However, the limited number of existing local producers and distributors stabilize CEB using Portland cement, whose clinker is imported from neighbouring countries. This not only constitutes a financial leakage; but also, has environmental impacts mostly linked to the pollution of (imported) clinker. These aspects, though out of the scope of the present review, still need appropriate assessment in the local context; in a sense that the impact of the stabilization of CEB using cement is still not clear on the cost and environmental impacts. In this context, the more scientific and applied research need to be carried out to encourage the large-scale use and therefore production and commercialization of CEB.

Therefore, it is essential to highlight the research efforts that have contributed to improving the structural deficiencies of CEB to encourage their appropriation by the producer and ways towards their certification. The present snapshot review highlights the research advances made so far on the improvement of the quality of CEBs (based-housing) in Burkina Faso by stabilization using alternative binders. The snapshot review also recommends the considerations to take to scale up the production and use of stabilized CEB.

An overview of research interests on earth-based materials and applications in Burkina Faso

The literature survey carried out on Scopus using the keywords "compressed earth block" and "Burkina Faso" has beard only 12 references, among which only 10 are relevant to the application in building construction. This shows the limited scientific output so far done on CEB in the context of Burkina Faso. However, a look at the whole literature on the use of earth materials in Burkina Faso for building construction has beard more results on different and yet interconnected aspects, such as the properties of earth-based materials: adobe, CEB, plaster; thermal behavior of earth-based constructions: thermal properties optimization and evaluation, thermal comfort and energy consumption evaluation; social acceptance and economical viability of CEB.

Some studies reported the improvement of the thermophysical and hygro-mechanical properties, and microstructure of CEB, adobe and plasters stabilized with the common industrial binders, such as cement [45–47] or hydrated lime [48–51]. Other studies reported the incorporation of (natural) fibers [48], sawdust [52], and paper/cellulose [46] in earth blocks and plasters [46, 48, 51–56]. It is noteworthy that most studies focused mainly on the stabilization of adobes and using common industrial binders and sometimes incorporating different forms of fibers. However, recent studies reported the improvement of the microstructural, physico-mechanical, hygro-thermal properties and durability of CEB stabilized with innovative (geo)polymer binder, such as MKG (metakaolin based geopolymer and SBB (shea butter residue based biopolymer) [57–59]; by-product based binders such as CCR (calcium carbide residue) lime-rich industrial waste and RHA (rice husk ash) silica-rich agricultural waste [44, 60–66]; and even their performances at elevated temperature [67].

Other studies reported on the design of CEB-based envelopes, in terms of thickness and insulation, and the potential of their hygro-thermal performances for improving the thermal comfort and energy performance in buildings [68–79]. In addition, some studies have assessed the socio-anthropological factors that affect the large-scale application of CEB. The logics and motivations for the use of CEB for housing construction in Ouagadougou show a paradox in the sense that the CEB are looked as the material for the poor, and yet it is used by the elite who have a higher intellectual and economic capital. In this context, the CEB are used by the population who have a post-materialistic vision of sustainability and comfort [80, 81]. This highlights the potentials for future adoption of CEB. Therefore, there are need to fully master and assess the technical and socio-economical considerations needed to scale up the use of CEB.

The innovative approaches carried out in the local context allowed to achieve the goal of stabilization: improve the most useful properties of CEB such as the mechanical, hygroscopic, and weathering resistance and dimensional stability (Table 2). It turns out that common industrial binders, such as cement and lime; as well as alternative binders such as geo- and bio-polymer, rich-rich calcium carbide residue, silica-rich rice husk ash are the most used for the stabilisation of CEB in the context of Burkina Faso. Therefore, this snapshot review essentially recapitulates various technical considerations that have been taken to achieve the structural improvements of CEB via the stabilization using alternative binders.

Considerations of the reactivity for materials selection towards the microstructural changes in mixtures

The selection of materials of suitable quality is the first step towards reaching the performance of the final product. The quality of clay earth materials to produce CEB has long been characterized mainly considering their geotechnical properties of granularity and plasticity [33]. This has been important to assess the water demand of earth materials for reaching the maximum compressibility, and eventually allowing to predict density and strength of the CEB. However, the selection of material only based on the physical consideration is not enough for efficient stabilization of CEB using chemical binders, where the chemical and mineralogical compositions should be considered [82].

In the context of Burkina Faso, the physical, chemical, and mineralogical characteristics of earth materials used to produce CEB vary widely. They essentially contain clay-silt-sand particles of medium plasticity to plastic behaviors and aluminosilicates compound of crystallin or slightly disordered kaolinite clay and eventually quartz minerals (Table 3). For example, the consideration of chemical reactivity has allowed t use the clay earth material from Kossodo (Ko) to produce CEB stabilized with 20% lime-rich CCR. This material would not be considered for stabilization with lime based only on their physical properties (particle size and plasticity). However, its reactivity with lime allowed to improve the compressive strength of stabilized CEB up to 3.4 times [44]. The reactivity was characterized through the monitoring of the evolution of the electrical conductivity (EC) of aqueous mixtures of earth materials and lime-rich CCR over time: the quicker the decrease of the EC, the quicker the consumption of lime ($Ca(OH)_2$) and the reaction kinetics of clay materials [44]. However, more characterizations need to be done to fully exploit the reactivity potentials of earth materials to produce stabilized CEBs.

The reactivity depends on the chemical composition and mineralogical structure of the materials, the type of chemical binder, the time, and the conditions of curing, among others [66]. Therefore, increasing the curing temperature increased the reactivity of earth materials with lime-rich CCR. Moreover, the earth material containing mainly kaolinite-rich clay mineral was more reactive than the material containing mainly quartz mineral (Fig. 2). Moreover, the materials containing kaolinite mineral of lower crystallinity showed better reactivity with lime than those with crystalline structure [44].

The chemical reactions in the mixtures of clay material and chemical binders result in microstructural changes. The addition lime-rich ($Ca(OH)_2$) binder to kaolinite-rich ($2SiO_2.Al_2O_3.2H_2O$) clay materials in an aqueous solution was responsible for the modification and stabilization of the microstructure of the mixture. In the short term, the modification of the texture by the coagulation of particles decreases the plasticity and shrinkage of clay material. This takes place through cation exchange, of mainly calcium ion (Ca^{2+}) from the dissociation of $Ca(OH)_2$ into Ca^{2+} and OH^-, which increases the pH of the solution up to 12.4, considered as the minimum required for the pozzolanic reaction [83, 84]. On the long term, the stabilization of microstructure by the pozzolanic reaction of clay with lime results from the formation of cementitious products. In fact, beyond the pH of 12.4, the aluminosilicates in the clay material dissolve and combine with Ca^{2+} to form calcium silicate hydrates, calcium aluminate hydrates, and eventually calcium aluminosilicate hydrates (C-S-H, C-A-H, C-A-S-H), comparable to those from the hydration of OPC [85]. These products bind the earth particles and increase the mechanical and durability performances of the mixtures [60]. Moreover, it was reported that fine particles of quartz can possibly react with lime or at least serve as nucleation sites for the formation of CSH products [49].

The XRD characterization showed the occurrence of new peaks of cementitious products of CSH and CAH in the cured mixtures of clay materials and lime; following the decrease of the peak intensity of kaolinite. These

Table 3 Physical, chemical, and mineral characteristics of some earth materials used to produce stabilized CEB in Burkina Faso

Parameters		Materials [references]				
		Materials [44]				Materials [57]
		K	P	Ko	S	
Particle size fractions (%)	Gravel (20–2 mm)	0–20	0–5	~40	<10	36.18
	Sand (2–0,06 mm)	15–45	15–35	~35	40–45	48.41
	Silt (0.08–0.002 mm)	30–65	40–55	~15	25–30	1.05
	Clay (<0.002 mm)	10–35	20–30	~10	20–25	5.36
Plasticity (%)	Limit of liquidity, LL	40–65	35–40	~40	45–55	50.5
	Plasticity index, IP	10–35	15–25	~15	5–25	27.9
Chemical composition (%)	$SiO_2 + Al_2O_3 + Fe_2O_3$	86–89	92	87	89	96.4
	Others	1–2	2	4	1	2.49
	Loss on ignition	10–11	6	10	11	0.9
	SiO_2/Al_2O_3 ratio	2.1	6.6	2.4	2.2	1.8
Mineral composition (%)	Clay (Kaolinite)	54–74	31	36	58–81	63.1
	Quartz	11–31	61	30	14–31	11.5
	Others	15–17	8	34	5–11	20.7
Compressibility of earth material	OMC (%)	17.4	15.4	12.9	17.9	16.7
	Proctor max density, ρa (g/cm^3)	1.77	1.86	2.10	1.71	1.95
	Particle specific density, ρs (g/cm^3)	2.75	2.66	2.91	2.66	2.78
	Compressibility index, ρa/ρs	0.64	0.70	0.72	0.64	0.70
Compressive strength of CEB (MPa)	Unstabilized, Rcu	1.1	2.0	1.4	0.8	1.36
	Stabilized, Rcs (20%)	4.7 (CCR)	7.1 (CCR)	6.4 (CCR)	8.3 (CCR)	8.95 (MKG)
	Stabilization index, (Rcs-Rcu)/Rcu	3.3	2.5	3.4	10	5.6

K, kamboinse; P, Pabre; Ko, Kossodo; A, Saaba; OMC, optimum moisture content; CCR, lime-rich calcium carbide residue; MKG, metakaolin-based geopolymer; Rcu, compressive strength of dry unstabilized CEB; Rcs, compressive strength of dry stabilized CEB

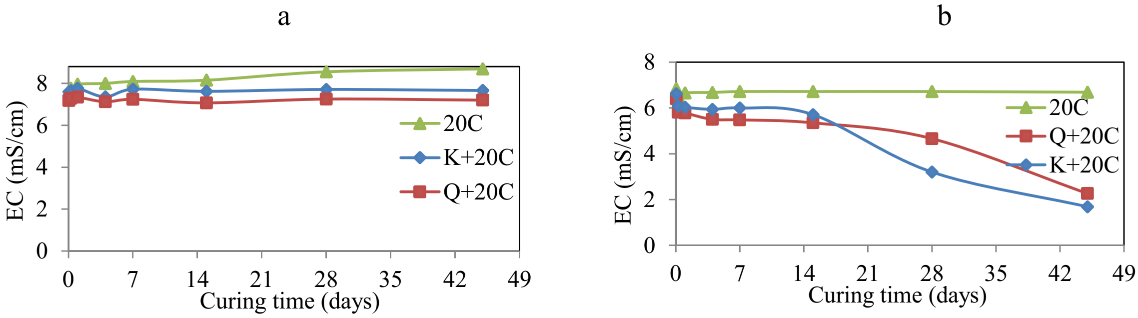

Fig. 2 Evolution of the electrical conductivity (EC) of mix solutions of kaolinite (K) and quartz (Q)-rich earth materials and 10% CCR (10C) or 20% CCR (20C) cured at **a** 20 °C and **b** 40 °C [66]

products result from the consummation of kaolinite in the earth material, through the pozzolanic reaction with lime. Moreover, the RHA not only accelerated the pozzolanic reaction; but also contributed to the formation of more cementitious products [60]. These products of the pozzolanic reaction contribute to the cementation and cohesion of earth particles and the improvement of the physico-mechanical stability of stabilized CEBs.

Considerations of the processing towards the physico-mechanical improvement of stabilized CEB

Processing and curing conditions

The processing of stabilized CEB should not only consider the geotechnical (physical) properties and chemical reactivity of earth materials and binders, but also the physical parameters related to the water demand and compressibility of the mixtures. Each type of earth material requires an optimum moisture content (OMC), at a given compression pressure, to reach the maximum compaction and densification of particles. The value of OMC is usually estimated using common dynamic Proctor compaction [86]; although, static compaction is more realistic to produce CEB [3, 12]. Moreover, increasing the compaction pressure decreases the value of OMC and increase the density for a given material [82].

In the context of Burkina Faso, the OMC of earth materials used to produce unstabilized CEB varied between 12 to 18%, to reach the compressibility index of 0.64 to 0.72 (Table 3). The stabilization of earth materials using chemical binders impacts the OMC of the mixtures (Fig. 3a). The stabilization of CEB using 0 to 25 wt% CCR increased the static OMC (Eq. 1a), from the OMC (17%) of raw earth material [66]. Moreover, the stabilization of CEB using 0 to 20 wt% MKG increased the OMC (Eq. 1b), from 16.7% of the raw earth material [57]. Unfortunately, a high amount of production moisture may result in shrinkage cracking of CEB, mainly when they are produced using water sensitive clay earth materials, such as those of high plasticity and/or containing active (swelling/shrinking) clay minerals. In this scenario, it would be essential to assess the shrinkage potential of the material to prevent the cracking effect on (stabilized) CEB. The stabilization using lime or a mix of lime and cement allows to quench the activity of the materials and its sensitivity to water (Table 1). This is not common in case Burkina Faso, where the earth materials characterized in the vicinity of Ouagadougou contain mostly inactive kaolinite or quartz minerals (Table 3). Therefore, it is particularly important to control the OMC of the mixtures for effective stabilization of CEB; the lack of it would rather results in devastating effect on their performances.

$$\mathrm{OMC} = 0.21 \times \mathrm{CCR} + 17 \tag{1a}$$

$$\mathrm{OMC} = 0.3 \times \mathrm{MKG} + 16.7 \tag{1b}$$

$$\rho = -41.1 \times \mathrm{OMC} + 24212 \tag{2}$$

Additionally, the OMC should not be left to dry, by covering the stabilized CEB throughout the curing, to allow for effective pozzolanic reaction and development of the performances [66]. This would eventually be applied on hydration, geopolymerisation, … reactions [57]. Moreover, the effect of the curing temperature and time should be considered, which affect the reactivity depending on the type of the material and binders. The kinetics of pozzolanic reaction was accelerated when the mixtures of clay earth materials and CCR

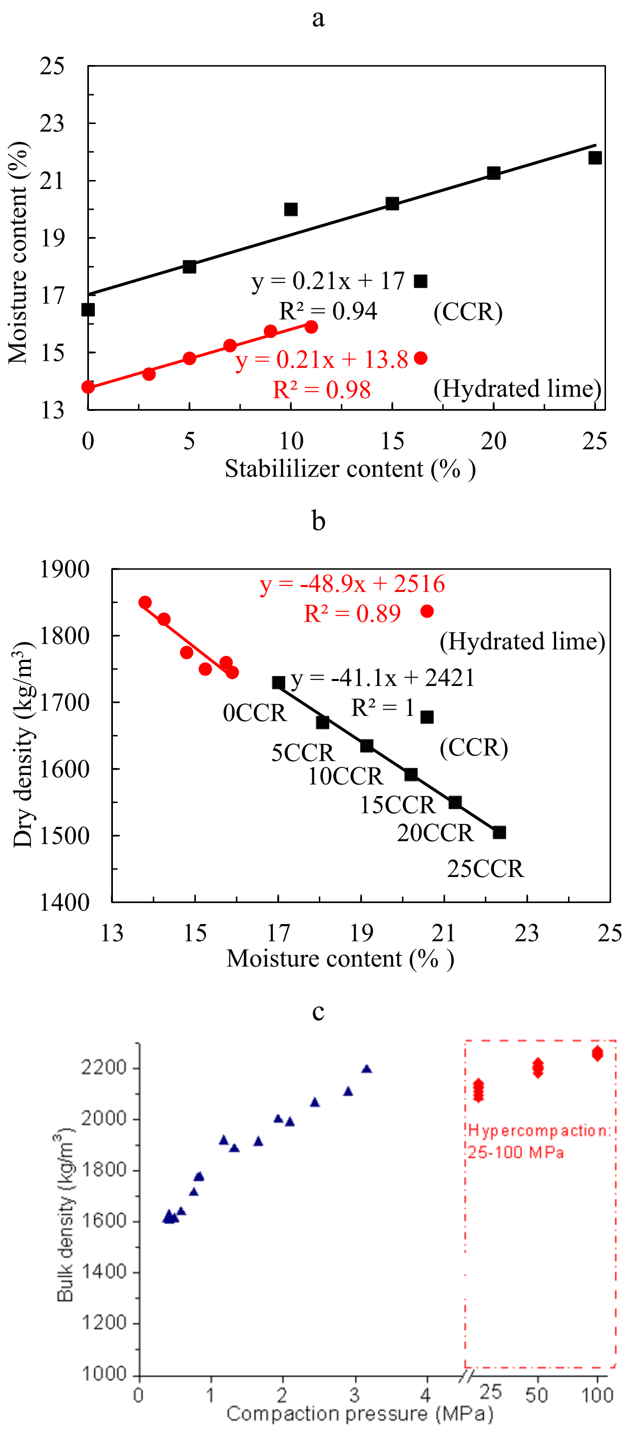

Fig. 3 **a** effect of chemical binder on the optimum moisture content (OMC) of the mixtures of earth + binder; **b** effect of OMC on the maximum dry density of the mixtures of earth + binder [3]; **c** evolution of the bulk density with compaction pressure of unstabilized CEBs [82]

were cured at 40 °C than 20 °C [66]. The curing was also accelerated, from 45 to 28 days, by partial substitution of lime with an amorphous and more reactive pozzolanic materials of RHA [60]. Moreover, geopolymer reaction in MKG stabilized CEB was improved when they were cured from 30 to 60 °C [57]. Therefore, the OMC to reach maximum compressibility and curing conditions to reach the maturity of the reaction should be assessed, depending on the composition of the mixtures and the types of binders. This gives the opportunities to process the stabilized CEB in a way that allows to control their physical and mechanical performances from controlling the production and curing process.

Bulk density and porosity

The bulk density of CEBs is affected by the composition of the earth material, and type and content of stabilizer, as well as the compaction pressure [82]. It is affected by the water demand and compressibility of the material, among other parameters (Fig. 3b), and tested referring to [87]. The stabilization of CEBs using 0–25% CCR has decreased the bulk density in the range of 1900 to 1477 kg/m^3 and increased the bulk porosity in the range of 33 to 44%, up to 90% of which was accessible by water [62, 64, 71]. By contrast, the addition of CCR with RHA (20:0 to 12:8% CCR:RHA) has kept the bulk density of CEBs quasi-constant (1578 kg/m^3); but still, lower than that of cement stabilized CEBs (1781 kg/m^3) [62]. Moreover, the bulk density of CEBs stabilized with 5–20% MKG evolved in the range 1730–1840 kg/m^3, and the water accessible porosity evolved in the range of 33–38% [57]. This is related to the increase of the OMC with the CCR and MKG (Eqs. 1a, 1b).

Equations 2, from Fig. 3b, shows that the bulk density, ρ (kg/m^3) decreases with the increase of the OMC (%); resulting from the drying of part of OMC and the creation of porosity after the curing of CEB stabilized with CCR. This can also be related to the specific density of the CCR (2.49) and RHA (2.25) which are lower than that of earth materials (2.76) and cement (3.1). Moreover, the addition of 0 to 10% shea butter residue decreased the bulk density of CEB from 1930 to 1730 kg/m^3, due to the increase of the porosity [58]. Therefore, the bulk density of CEBs can barely reach 2300 kg/m^3, even after hyper-compaction at 100 MPa (Fig. 3a). In fact, the compressibility index evolved in the range of 0.64–0.72, depicting the maximum compacity achievable by normal compaction of earth material (Table 3). It is noteworthy that more compacity would allow to reach more densification and contributing more compaction effect on the development of the strength (Sect. "Resistance to compression").

Resistance to compression

The improvement of the compressive strength is one of the most sought out effect throughout the stabilization of CEB, and tested referring to [11]. This improvement can be divided into time independent physico-mechanical effect resulting from the compaction, packing and the natural binding of clay particles in the earth material; and the time dependent chemico-mineral effect from chemical reactivity with binders [60].

The compaction and packing effects depend on the production conditions such as the packing density of the mixture, the compaction pressure, the type and content of the earth material and stabilizer, and production moisture. Equation 3, from Fig. 4b, shows that the dry compressive strength, Rc (MPa) of unstabilized CEBs increasing quasi-exponentially with the bulk density, ρ (kg/m^3) [82]

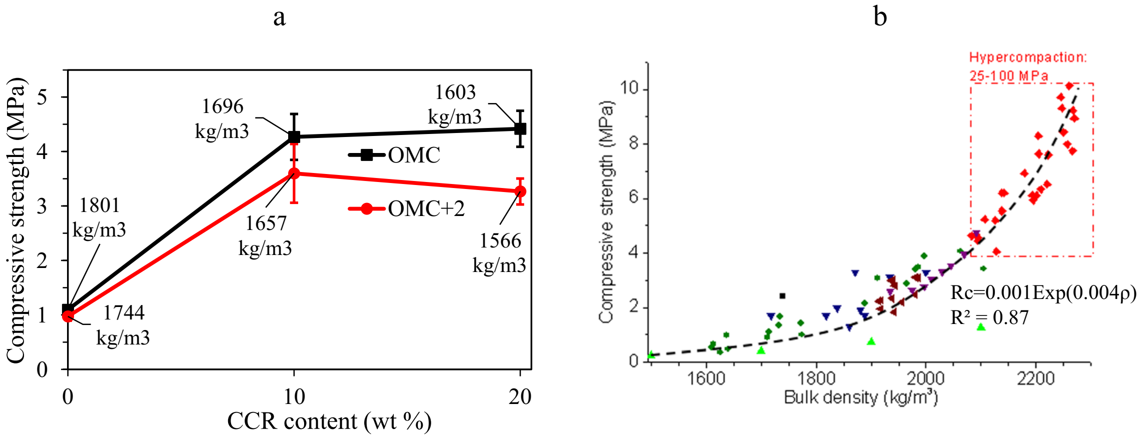

Fig. 4 **a** Effect of production moisture on the compressive strength of CCR stabilized CEB: indices are bulk density [3]; **b** evolution of the dry compressive strength (Rc) with bulk density (ρ) of unstabilized CEB [82]

$$Rc = 0.001 \times e^{0.004 \times \rho} \quad (3)$$

The binding effect rather depends on the type and reactivity of earth material, the type and content of binder, and production and curing conditions [66]. Figure 3c shows that the compressive strength of CEB, produced using their OMC, increased 0.7 times (from 1.2 MPa to 4.4 MPa); resulting from the binding effect which was positively affected by the stabilization of CEB with 20% CCR. This, therefore, counteracts the compressibility which was negatively affected (decrease of the bulk density from 1801 to 1603 kg/m^3) by the stabilization with CCR (Fig. 3b). However, the strength of CEB stabilized with 20% CCR decreased 0.3 times (from 4.4 MPa to 3.3 MPa) when they were produced using OMC + 2%, instead of the OMC (Sect. "Processing and curing conditions").

Additionally, Table 3 shows that the compressive strength of CEB in dry condition improved 10 times (0.8 to 8.3 MPa) for CEB produced from the most reactive earth materials stabilized with 20% CCR, compared to the improvement of only 2.5 times (2 to 7.1 MPa) for the least reactive materials [44]. Moreover, the compressive strength of CEB was improved when they were stabilized with up to 10% CCR (4.3 MPa), 16:4% CCR:RHA (7 MPa) [62], 20% MKG (8.95 MPa) [57]. Therefore, the CEB stabilized with alternative binders may reach comparable or even better compressive strength than CEB stabilized with 8% cement 6.2 MPa [62], 8.2 MPa [57], 6.6 MPa [59]. However, the addition of 0 to 10% shea butter residue decreased the strength from 3.8 to 1.1 MPa [58]. In fact, the stabilization indices of 2.5–10 depict the contribution of the stabilization (chemical) effect on the development of the compressive strength of CEB, depending on the reactivity of the materials and the type of binders (Table 3).

Similarly, the compressive strength of CEB in wet condition was also improved by stabilization with alternative binders, but not at the same level, depending on the earth materials and type of binder. It is usually required that the ratio of the wet compressive strength (Rcw) to the dry compressive strength (Rcd) reaches, Rcw/Rcd = 0.5, for an appropriate stability of CEB in wet environment. The wet compressive strength of CEB was improved to reach 2.7 MPa (Rcw/Rcd = 0.6) with 10% CCR, and 2.7 MPa (Rcw/Rcd = 0.4) with 16:4% CCR:RHA [62]; and 6.29 MPa (Rcw/Rcd = 0.7) with 20% MKG [57]. This obviously gives some insights that the CEB stabilized with alternative binder (MKG) may have better stability in wet environment than CEB stabilized with cement (Rcw/Rcd = 0.5) [57, 62].

However, the tensile strength of CEB is rarely assessed, given that they are rarely loaded in traction applications. Sore et al. [57] reported that the flexural strength of CEB evolved in 0.43–1.68 MPa with 0–20% MKG, compared to 2.2 MPa reported for CEB stabilized with 8% cement. These values can be considered sufficient for CEB to resist the handling during the transport and construction processes.

Therefore, the CEB stabilized with alternative binders can be useful for application in construction of wall masonry, as their dry compressive strength reaches 2, 4 or 6 MPa respectively for usage in non-load-bearing (single storey) and load-bearing (two-storey or three-storey), according to Table 2.

Resistance to abrasion

The resistance to abrasion of CEB is usually assessed based on the coefficient of resistance to abrasion (Cb) which is the ratio between the abraded surface over the weight loss, referring to [11]. The Cb was similarly improved by the stabilization using alternative binders, depending on the reactivity of earth materials. Tarmangue et al. [64] reported that the coefficient of abrasion of CEB improved from 1 to 49 cm^2/g, 9 to 66 cm^2/g, 2 to 88 cm^2/g, and 1 to 43 cm^2/g respectively for different type of earth materials stabilized with 20% CCR cured for 45 days. Another study reported that the Cb increased from 1 to 20 cm^2/g for CEBs stabilized with 20% CCR and 20 to 70 cm^2/g for CEB stabilized with 12:8% CCR:RHA [63]. The Cb of CEB stabilized with 20% geopolymer increased from 2 to 100 cm^2/g [59]. Therefore, the CEB stabilized with alternative binders may reach comparable or even better resistance to abrasion than common CEB stabilized with 8% cement 70 cm^2/g [63], 23.4 cm^2/g [59]. The stabilization of CEB using alternative binders contributes to the formation of cementitious products; which are responsible for binding earth matrix and increase not only the volumetric bulk compressive strength; but also, the surface hardness and stability of earth particles to resist abrasion.

Considerations of the structural efficiency of stabilized CEB

Structural efficiency

The stabilization of CEB offers the opportunity to improve the overall structural performance through the effects that it has on the physical and mechanical properties. In fact, the structural performance can be assessed at the material scale based on the coefficient of structural efficiency, CSE (J/kg): the ratio between the dry compressive strength, Rc (Pa), and the bulk density, ρ (kg/m^3) (Eq. 4). This can be looked as a useful paramater to evaluate the load-bearing capacity of materials. The CSE was considerably improved from 609 to 2902 J/kg for CEB stabilized with 20% CCR and 2902 to 3827 J/kg for CEB stabilized with 12:8% CCR:RHA [62]. The CSE increased from 275 to 4793 J/kg, from 1372 to

5560 J/kg, from 564 to 5526 J/kg, and from 385 to 4565 J/kg respectively for CEB produced from different type of clay earth materials and stabilized with lime [64]. The application of Eq. 4 on CEB stabilized with 20% MKG gives the CSE of 5085 J/kg [57]. In fact, a recent study confirmed that the CSE of CEB stabilized with 20% MKG is 5300 J/kg [59]. Therefore, the CEB stabilized with alternative binders may reach comparable or even better structural performances than common CEB stabilized with 8% cement 3547 J/kg [62], 4295 J/kg [57], 3500 J/kg [59].

This essentially shows the interests of giving value to these alternative materials in the construction for the improvement of structural performances of CEB. Future studies should carry out similar assessment at wall or even building scale and, look at thermal and durability efficiency and even the sustainability, reached from the use of CEB stabilized with alternative binders.

$$\mathrm{CSE} = \mathrm{Rc}/\rho \tag{4}$$

Correlations of the resistance to abrasion and resistance to compression

The processing and quality control of CEB are among the crucial factors that affect their efficient stabilization and therefore delaying their large-scale use in modern constructions [80]. The compressive strength, regarded as a technical parameter to assess both engineering and durability performances of CEB, has its shortcomings in terms of access to equipment and as a destructive test. Therefore, a more accessible less destructive, and yet robust test of abrasion may allow to overcome these challenges; by assessing the surface hardness of the samples and correlating it with the volumetric strength of CEB. Some studies have already showed the possible correlation between the coefficient of resistance to abrasion, Cb (cm^2/g), and the resistance to compressive, Rc (MPa), via a power law (Eq. 5). The parameters of correlation “A” and “B” would depend on the type of earth materials, and stabilization technique, among others. “A” and “B” were respectively reported to be 0.69–0.84, and 0.59–0.67 for CEB produced from different type of clay earth materials and stabilized with CCR [64]; 1.6 and 0.35 for CEB stabilized with CCR:RHA [63]; and 0.59 and 0.58 for CEB stabilized with MKG [59].

This clearly shows the existence of correlation between the destructive compressive test and the non-destructive abrasion test. For example, for the medium scale industry which produce CEB, as it is the case in Burkina Faso, it would be easier and more practical for the technicians to test the abrasion resistance than the compressive strength. The former would only require a wire brush to abrase the CEB and the balance to weight the mass of lost particles; while the latter would require sophisticated and more expensive equipment which are not mostly accessible by the local producers. After calculating the coefficient of abrasion following [11], they would rapidly estimate the compressive strength following Eq. 5. More types of non-destructive tests should be fully developed to serve as stepping stone to boost the development of CEB-based construction technique, in terms of the control of industrial quality of the stabilization of CEB and onsite constructions.

$$\mathrm{Rc} = \mathrm{A} \times \mathrm{Cb}^{\mathrm{B}} \tag{5}$$

Summary and ways forward

This snapshot review recommends the following considerations to be taken to ensure efficient stabilization of earth materials using alternative binders to improve the structural performances of CEB.

1. The chemical reactivity of earth materials must be considered, in addition to the geotechnical parameters, to better assess their suitability and efficient stabilization to produce stabilized CEB.
2. The processing of mixtures of earth materials and (alternative) chemical binders into CEB must also consider the water demand of the binders, in addition to the demand of raw earth materials, to reach better compressibility and binding effects which are responsible for the development of the structural performances of stabilized CEB. This will also allow to control the physical and mechanical properties of CEB.
3. The effective stabilization of CEB using alternative binders allows to improve their performances in general; and their compressive and abrasion resistance in particular. This improvement mainly results from the reactivity in the mixtures responsible for the formation of binding products which bind and ensure physical and mechanical stability of earth particles.
4. The effect of the stabilization of CEBs can also be assessed through their structural performances, at a material scale, through the improvement of their coefficient of structural efficiency.
5. The correlation can be devised from the test of surface abrasion and volumetric compression. This could further be developed into a non-destructive test to assess the performances of CEB. This correlation was established using a dataset in the range of 0 to 70 cm^2/g of the coefficient of surface abrasion.

These recommendations could therefore open the whole possibilities to design the stabilized CEB, incorporating alternative binder and/or eventually fibers, to achieve the desired physico-mechanical, eventually thermal, and acoustic performances, and sustainability. The present snapshot review showed the evolution of the physico-mechanical properties of stabilized CEB and impacts on their structural performances. The evolution of the physical properties would also affect the thermal and acoustic properties, in the sense that denser CEB would have higher conduction capacity than lighter and porous CEB and vice versa. Therefore, there would be possibilities of designing these CEB, varying the content of binders or the content of the production moisture, and eventually incorporating fibers to achieve the needed/required engineering properties. The current results qualitatively align with the sustainability goals, through the recycling of wastes; conservation of natural and depleting resources; use of alternative binders, with less energy consumption than industrial cement/lime and therefore less carbon emission.

Numbers of limitations still need to be addressed, to fully use and scale up the production of CEB stabilized with alternative binders. One of the remaining questions is not necessarily related to the technical performances, but rather to the understanding of socio-economic acceptance and viability of the CEB and its whole value chain. The availability and the quality variability of the raw earth materials, for industrial applications in the production of CEB, require dedicated studies of the most appropriate economic model, but also standardized tests. These should be applied to assess the economic and ecological viability of CEB in general and the effect on the performances of CEB stabilized with alternative binders. This should not only consider the cost related to their production/construction; but also, the cost of exploitation/maintenance, the availability of qualified manpower, and the adoption by the architects and engineers. The latter also need the tool for architectural and structural designs of the building envelope and masonry. The other point of interest would be to quantify the ecological impact of such CEB compared to other materials. This should similarly consider the direct impacts related to the production/construction as well as the indirect impacts related to air-conditioning requirements, specifically cooling in the hot and dry climatic context of Burkina Faso.

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