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Durability and stability performance of compressed earth blocks (CEB) made with sediment and FA

Mohamedou Brahim, Khadim Ndiaye and Salima Aggoun
Laboratoire L2MGC, CY Cergy Paris Universite, Neuville-sur-Oise, France

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Abstract

Purpose – This study aims to evaluate the mechanical behavior and durability of sediment-based compressed earth blocks (CEB), linking the evaluation to the ability of CEB to resist weathering and physical attack while retaining the desired mechanical properties through compressive strength tests, behavior under drying-wetting cycles and the evolution of drying shrinkage.

Design/methodology/approach – The stabilization was achieved by partial substitution of sediments for fly ash (FA) with six different percentages 0, 10, 20, 30, 40 and 50% of the sediment by volume. The curing temperatures of all the mixtures were at 50°C for 7 days in an autogenous condition. All the CEB samples were characterized in terms of mechanical and durability properties.

Findings – The results show that the dosage of sediment-FA has a significant impact on CEB properties, as the FA dosage increased, the porosity decreased and the compressive strength increased. When the FA dosage increased from 0 to 50%, the CEB drying shrinkage decreased by 67%. The CEB containing at least 20% FA are well adapted to load-bearing wall applications in buildings in terms of mechanical performance, thermos-hydric stability, volumetric stability and environmental acceptability.

Originality/value – Dredged sediments without binders generally have poor mechanical properties. In order to improve the geotechnical characteristics and mechanical performance of these sediments, the addition of a geopolymeric binder “stabilizer” based on sodium hydroxide (NaOH)-activated FA is an effective solution. This geopolymeric binder improves cohesion between sediment grains by means of a chemical effect, involving the hydration of FA and a physical effect, reducing voids to obtain lower compressibility and better mechanical strength as well as durability.

Keywords Sediment, Fly ash, Compressed earth bricks, Durability

Paper type Research paper

1. Introduction

This article focuses on concerns related to sustainable development. The question of finding new construction materials reveals that research is focusing on the possibilities of reusing industrial and natural wastes as an alternative to the materials currently in use, which are becoming increasingly rare over time. River sediments in dams are an environmental and economic concern. The large quantities generated by the siltation leave the authorities at a loss as to how to manage it (Alloul *et al.*, 2023). A series of studies have shown that the use of sediments in civil engineering offers several promising opportunities. These studies have

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highlighted several advantageous applications for dredged sediments in concrete production (Safhi *et al*., 2020), road (Belayali *et al*., 2023), cement manufacturing (Alujas Diaz *et al*., 2022; Benzerzour *et al*., 2017) and as an alternative to traditional aggregates in brick production (Brahim *et al*., 2022). Nevertheless, the recovery of dredged sediments is conditioned by several parameters, including mineral composition, particle size distribution and particle characteristics (Amar *et al*., 2018). In addition to these elements, several scientific challenges remain to be resolved. These include the potential content of inorganic contaminants such as heavy metals (lead, copper, chromium, etc.), salts, cyanides, etc., as well as organic hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and tributyltin (TBT) (Couvidat *et al*., 2020).

This context has led to the development of environmentally-friendly sediment-based construction materials that are, above all, suited to the type of construction. Compressed earth bricks are a serious candidate. The disadvantages of CEB technology can be remedied, of course, by a combined chemical and mechanical action, technically known as soil stabilization. An additional binder, such as cement, lime can be included to stabilize the mixture.

In order to reduce cement use in construction materials, alkali-activated products such as geopolymers are emerging as alternative binders. An alternative solution could potentially replace Portland cement in the manufacture of compressed earth bricks. Geopolymer binders are energy efficient as they reduce carbon emissions compared to Portland cement production (Karam *et al*., 2021; McLellan *et al*., 2011).

The results of Manvendra Verma’s (Verma *et al*., 2022) research on geopolymer binders show that the latter offers a superior alternative to ordinary Portland cement by demonstrating increased strength, durability and effectively reducing the carbon footprint through the use of solid industrial waste such as fly ash (FA) and slag, which also reduces production costs, and exhibiting excellent resistance to extreme environmental conditions, including acid and sulphate attack, making it suitable for a variety of construction applications such as bricks.

In another study, Verma *et al*. (2022) reveal that the mix with a 75/25 ratio of FA/blast furnace slag has a higher mechanical strength than the other mixes, and replacing the blast furnace slag with FA increases the strength of the mix design.

Samples cured in an oven at 80 °C have a higher strength than samples cured in ambient air.

The main indicators cited in various literature studies to evaluate the durability of CEB are water absorption, dry/wet compressive strength index, erosion resistance and mass loss after drying-wetting cycles (Muntohar, 2011; Panagiotou *et al*., 2022). An 8 mol sodium hydroxide (NaOH) alkaline activator solution was used in the samples for all mix-design. Compressive strength results of all samples were higher than 2 MPa in dry conditions, with water absorption results lower than 20 g/cm min $^{1/2}$ at 28 days for stabilized CEB. Islam *et al*., (2020) tested CEB stabilized with a mixture of FA and cement. Their results show that using cement contents of 7–8% and FA contents of 15–20% by weight of soil provides compressive strength and durability concerning water absorption.

The NBR 13554 durability test (soil and cement wetting and drying cycles) (“ABNT, Brazilian Association of Technical Standards NBR 13554: Soil-Cement - Wetting and Drying Durability Test - Test Method, ABNT, Rio de Janeiro, Brazil (2012),” n.d.) has been carried out by researchers to assess the durability of CEB (Siqueira *et al*., 2016; Souza *et al*., 2021). The research revealed that CEB properties are dependent on clay mineral type and content, plasticity index, free swelling index, water content, cracking, degree of compaction and dry density. However, shrinkage cracking appears when CEB is exposed to moisture loss in the environment (Biswal *et al*., 2019). Chompoorat and Likitlersuang (2016) have shown that replacing Ordinary Portland Cement with FA in a cement-stabilized clay containing 15% additions leads to a considerable reduction in drying shrinkage. The addition of FA impacts the ion exchange between soil particles and water surface tension.

In the previous study (Brahim *et al*., 2022), the optimization of using sediment as a base material and FA for stabilizing compressed earth blocks (CEB) was achieved. However, the issue of durability remains to be examined. Brahim *et al*., (2022) reported the use of FA to stabilize sediment in CEB. FA replaced sediment mass at rates of 10%, 20%, 30%, 40% and 50%, respectively. An 8 mol NaOH alkaline activator solution was used for all mix designs. The compressive strength results of all samples were higher than 2 MPa in dry conditions, with water absorption results lower than 20 g/cm min $^{1/2}$ at 28 days for stabilized CEB.

This article evaluates the mechanical behavior and durability of sediment-based CEB, linking the evaluation to the ability of CEB to resist weathering and physical attack while retaining the desired mechanical properties through compressive strength tests, behavior under drying-wetting cycles and the evolution of drying shrinkage, with the objective of developing a methodology for assessing the durability of CEB stabilized with FA and other stabilizers through rigorous testing to measure compressive strength, water absorption and dimensional stability under various environmental conditions.

2. Materials and methods

2.1 Sediment

The sediment used in this study to produce CEB was extracted from the storm water basins of the Lille European Metropolis (MEL). This work is part of a scientific and industrial approach to study the most suitable recovery methods for sediments extracted from storm water basins, while at the same time responding to development work. The sediment was subjected to the following geotechnical experiments, in accordance with the Association Française de Normalisation (AFNOR) (French Association AFNOR for technical standards) and following the guide prepared by CRAterre-EAG: The distribution of grain size (XP P13-901 (2001)), liquidity and plasticity limits, and specific mass (n.d.). The results in Figure 1 demonstrate that the sediment satisfies the XP P13-901, 2001, specifications for soils used in the manufacture of CEB, although part of the granulometry curve falls outside the recommended zone, showing a slight deficit of fines. Indeed, the French standard sets no limits for clay, silt, sand or gravel content, only that 100% of the particles have to pass through the 5 mm sieve. This sediment

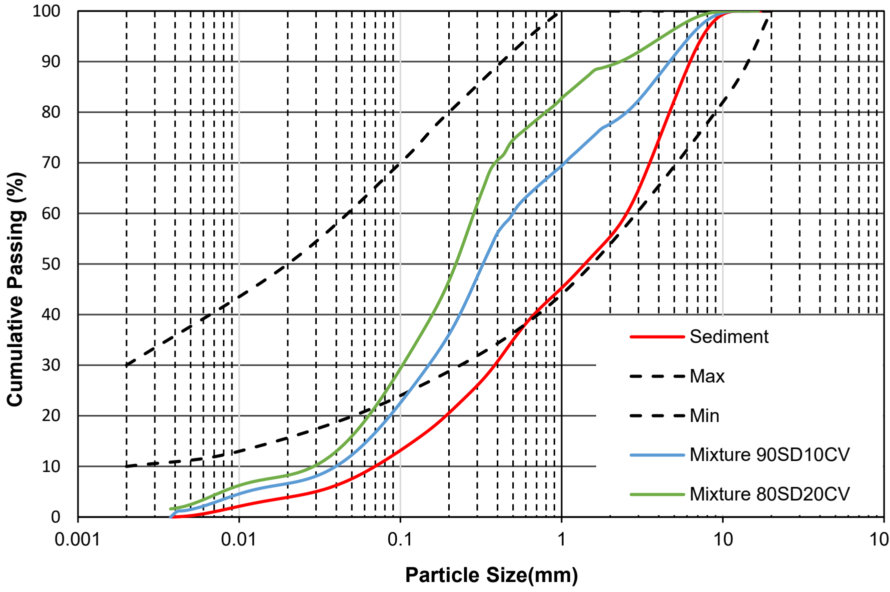

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Figure 1. Particle size distribution of sediment and corrective mixtures

also presents a plasticity index (14.4%) due to the large presence of organic matter, which is valued at 13%.

The effects of FA on the mixture's liquid limit, plastic limit and plasticity index are shown in Figure 2. The results show that the liquid limit and plasticity index are reduced with the addition of FA. This drop is found to be more with increasing amounts of FA up to 20%. The MEL sediment can be considered non-plastic with the addition of around 20% of FA. This change in sediment classification is attributable to the fact that when FA is mixed with sediment and water, a series of reactions leads to the dissociation of the lime (CaO) present in the FA, the free lime pozzolanic reactivity with the clay including ion exchange and associated flocculation, this reaction reduces the plasticity of the sediment (National Cooperative Highway Research Program *et al.*, 2009). In addition, it is attributable to the formation of cementitious and pozzolanic gels (Tastan *et al.*, 2011).

The chemical composition of the sediment was determined by using a BRUCKER S4 wavelength-dispersive X-ray fluorescence spectrometer. The results of the dredged sediment analyses are presented in Table 1. The latter gives the main constituent oxides of sediment. The ratio of SiO_2 to Al_2O_3 is high (>3), in line with recommendations for CEB ("Towards sustainable bricks production: An overview - ScienceDirect," n.d.). All components of dredged sediments are generally considered to be relatively inert and non-reactive.

The mineralogical composition was determined by BRUCKER AXS D8 ADVANCE X-ray diffraction using CuKα radiation. The anticathode is copper (hence $\lambda = 1.5406$ Å). The device is fitted with a Lynxeye XE-T type fast detector. Acceleration voltage and current are 40 kV and 40 mA respectively. X-ray diffraction was used to determine the crystalline phases of the sediments. Figure 3 shows that one of the main constituents of sediment is quartz (SiO_2) with a higher peak. In addition to quartz, the diagrams show that the sediment also contains clay phases: kaolinite, illite, and calcite.

Environmental analysis of sediments mainly concerns heavy metals, PCBs and PAHs. For this study, and depending on the type of reclamation envisaged, the environmental impact of raw sediment was assessed using the NF EN 12457–2 leaching test ("NF-EN-12457–2,

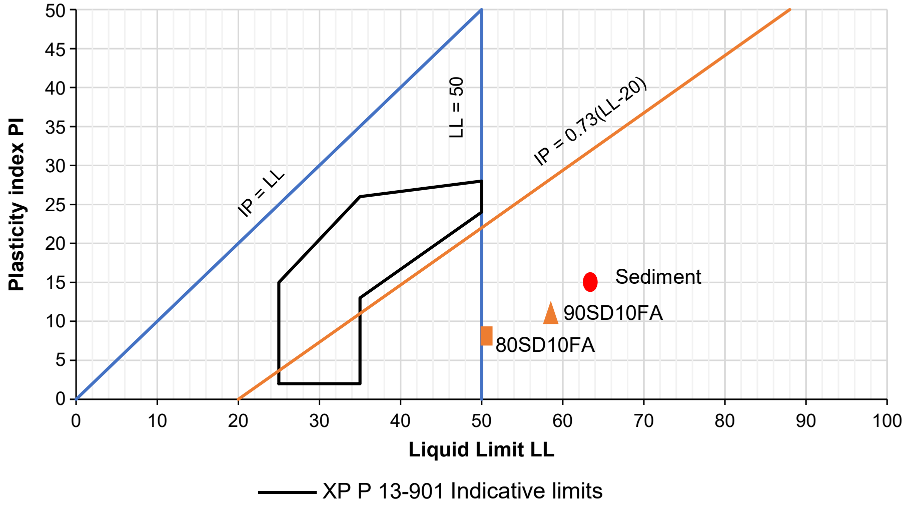

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Figure 2. Sediment and corrective mixtures Atterberg limits and recommendation range

Table 1. Chemical composition of sediment

Oxide	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	K_2O	MgO	MnO_2	TiO_2
Sediment	51.95	11.15	13.29	4.72	0.67	3.84	1.66	0.08	0.50

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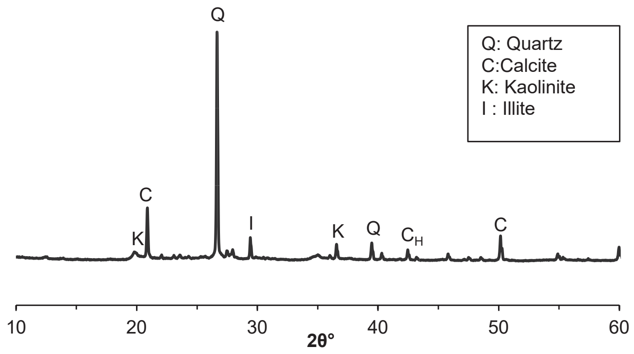

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Figure 3. X-ray diffraction pattern of the sediment

2002"). The reference thresholds used were defined in accordance with the recommendations of the SETRA guide (territoires *et.al*., 2020). The results of the leaching tests are presented in Table 2. The environmental balance sheet for the sediments shows that the concentrations of heavy metals do not exceed the thresholds for the material to be used in compressed earth bricks. The high PCB values classify the sediments as non-hazardous non-inert waste, in accordance with European Decision 2003/33/EC.

2.2 Fly ash

Dredged sediments generally have poor mechanical properties. To improve the granular compactness and the cohesion of sediment grains, the addition of physico-chemical stabilizers should be envisaged. To achieve these benefits, another waste product, FA, which is becoming increasingly abundant, has been valorized and added to sediments for the formulation of CEB. The Class F FA used to stabilize CEB comes from a thermoelectric power plant and is supplied by SURSCHISTE (Lens, France). The particle size distribution of FA is presented in Figure 4. The FA has an absolute density of 2.39 g/cm^3 with a Blaine fineness ranging from 2,300 to 5,000 g/cm^2.

The FA is composed mainly of the following elements SiO_2 (50%), Al_2O_3 (20%) and Fe_2O_3 (8%). The mineral phases present in FA include quartz (SiO_2), maghemite (U-Fe_2O_3), mullite ($Al_6O_{13}Si_2$) and hematite (α-Fe_2O_3). Fly ash properties are presented in Table 3.

A commercial NaOH of 99% purity was used to activate the FA. The concentration of the NaOH solution was set at 8 mol for all mixtures. To avoid uncontrolled reaction temperature, the solution was prepared one day in advance. On contact with the alkaline NaOH solution, Class F FA dissolves in the alkaline solution via exothermic chemical reactions.

2.3 Optimum moisture content determination

The optimum moisture content of the different dry mixtures was obtained by the method of Proctor standard compaction test (NF P 94–093, 1999). The principle of this test is to compact

Table 2. Environmental analysis of sediment and the recommended limits

Environmental analysis (leaching test NF EN 12–457–2) Elements	Sediment MEL (mg/kg.ms)	Limits (mg/kg.ms)
Arsenic (As)	0.05	0.5
Barium (Ba)	0.35	20
Cadmium (Cd)	0.004	0.04
Chromium (Cr)	0.012	0.5
Copper (Cu)	0.4	2
Mercury (Hg)	0.0005	0.01
Lead (Pb)	0.1	0.5
Molybdenum (Mo)	0.063	0.5
Nickel (Ni)	0.1	0.4
Selenium (Se)	0.039	0.1
Zinc (Zn)	0.21	4
Chloride (Cl)	24	800
Sulfate (S)	554	1,000
Soluble fraction	2,320	4,000
pH	7.4	5.5–13
Electrical conductivity (µS/cm)	404	–
COT	73,000	30,000
BTEX	0.25	6
PCBs	46	1
PAHs	20	50

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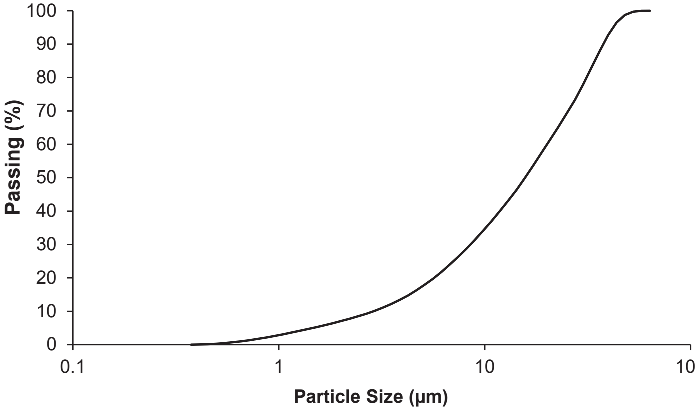

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Figure 4. Particle size distribution of FA

Table 3. Chemical composition of FA

Oxide	SiO_2	Al_2O_3	CaO	Fe_2O_3	Na_2O	K_2O	MgO	MnO_2	TiO_2
Fly ash (%)	55	22	3	8.55	0.62	2	3	0.52	1

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the material at different water contents using a given process and energy. For each moisture content, the wet density is measured and the dry density of the material is determined. From the relationship established between water content and dry density, the compaction characteristics (dry density and optimum water content) are determined. The results are shown in Figure 5. The increase in FA content resulted in a higher optimum water content and lower density, due to the lower density of FA compared to sediment. This optimum moisture content will be used to formulate the CEB. The CEB mixtures had dry densities ranging from 1.6 g/cm^3 to 1.71 g/cm^3.

2.4 Preparation of bricks

The preparation of the mixture to produce CEB was carried out in two stages, using a standardized mixer to homogenize the mixes. After homogenizing the dry material (sediment with and FA) for 7 min at slow speed, the wet mix was processed by adding the alkali solution prepared with the moisture content corresponding to the optimum Proctor and 8 M NaOH for 3 min at slow speed. The obtained mixtures are compacted by an INSTRON press (INSTRON-3369) under static compaction with a pressure of 40 bars. All the tests and experimental procedures are shown in Figure 6. The cylindrical metal molds used were equipped with 3 wedges of varying heights. Compacting was carried out in 3 stages, with a system of progressively smaller metal compression wedges employed at each phase. This procedure enabled the final dimension of the sample to be obtained progressively, in accordance with standard NF P 94–100 ("NF P 94–100 Sols, n.d.). Once the sample had been compressed, the pressure was maintained for 10 s, then the CEB specimens were demolded by using a piston. This procedure enabled the final dimension of the sample, 5 cm in diameter and 10 cm in height.

Details of the mixture compositions used in the CEB manufacturing are shown in Table 4.

2.5 Testing methods

2.5.1 Porosity investigation. The porosity of CEB samples was determined. According to the equations in the NF-EN 1936 standard (NF-EN 1936).

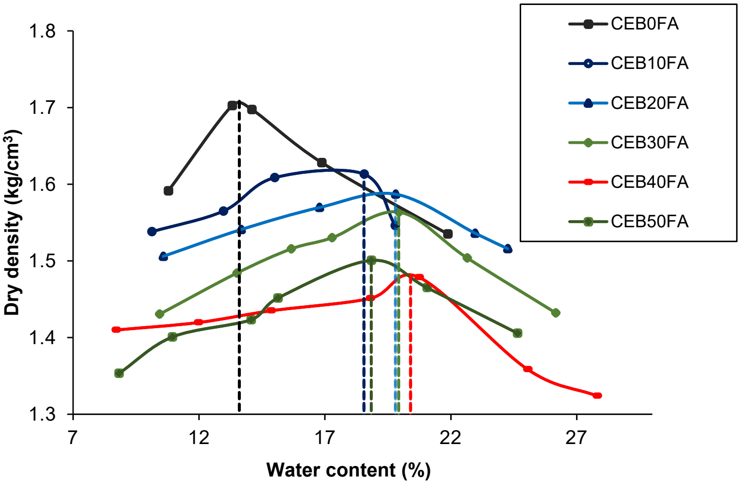

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Figure 5. Proctor compaction curves for the different mixtures

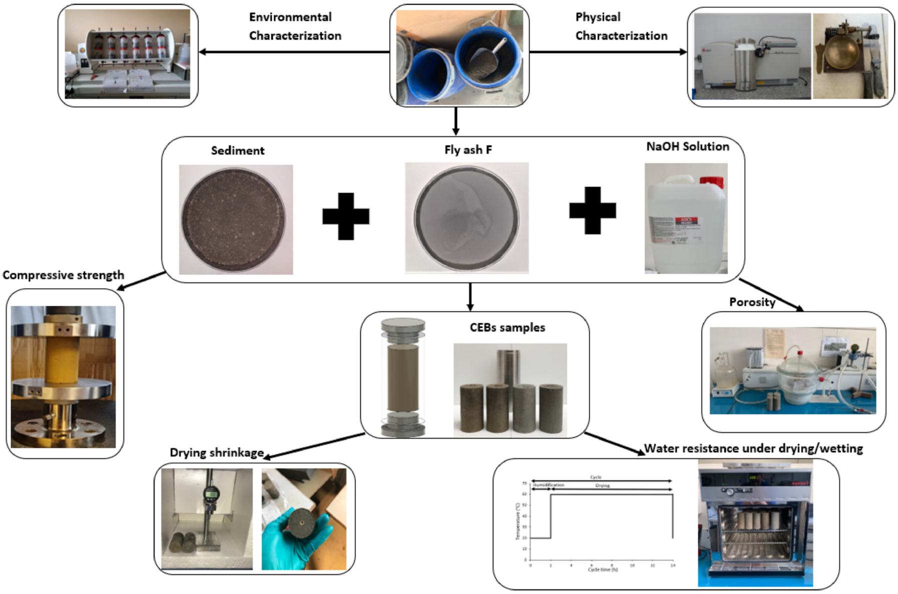

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Figure 6. Steps for the experimental study

Table 4. Composition of CEB mix-designs

Materials	CEB0FA	CEB10FA	CEB20FA	CEB30FA	CEB40FA	CEB50FA
Sediment (%)	100	90	80	70	60	50
Fly ash (%)	0	10	20	30	40	50
Water*/dry material (%)	0.1409	0.1855	0.2187	0.1993	0.207	0.1884
NaOH concentration (Mol/L)	8	8	8	8	8	8

Note(s): *Water content (%)
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$$Ɛ = \left(\frac{M_{sat.air} - M_{Dry}}{M_{sat.air} - M_{sat,eth}} \right) \times 100$$

Ɛ: total porosity accessible to ethanol (%)

$M_{sat.air}$: saturated mass, weighed in air (g)

M_{dry}: constant dry mass of the CEB samples (g)

$M_{sat.eth}$: saturated mass, weighed in ethanol (g)

2.5.2 Compressive strength. Compressive strengths were determined following standard XP P13-901, 2001. The tests were performed by a hydraulic press with a load capacity of 30 kN, operated at a loading speed of 0.15 kN/s. At each test, three cylindrical samples of dimensions 100 × 50 (50 mm diameter and 100 mm height) were tested, to determine their minimum characteristics under the most unfavorable conditions. This test is identical to the dry compressive strength test, except that the samples are first saturated with water for 2 h. They are then removed and wiped dry with a slightly damp towel.

2.5.3 Water capillary absorption. The capillary absorption of the blocks was measured in accordance with standard XP P13-901, 2001. Dry samples were initially weighed and then immersed in a thin layer of water (5 mm) for 10 min. The mass of the sample was measured during the absorption test. The water absorption coefficient (C_b) was calculated according to equation (1):

$$C_b = \frac{100 \times (P_1 - P_0)}{s\sqrt{t}} \tag{1}$$

C_b: coefficient of resistance to capillary ($g/cm^2.min^{1/2}$)

P_0: mass of sample before immersion in water (g)

P_1: Sample mass after immersion in water (g)

S: immersed block surface (cm^2)

t: block immersion time in water (min)

2.5.4 Wetting-drying cycles. The wetting-drying tests were carried out according to ASTM D559-89 (ASTM D559,1989), which is the only recommendation in terms of durability for soil-binder mixtures (Bianchi *et al.*, 2010). Three specimens for each formulation were subjected to wetting-drying cycles, while the other three were used as control specimens and kept under the same curing conditions without undergoing the cycles. A wetting-drying cycle is divided into two phases: the first phase involves placing the specimen in water for 2 h at room temperature (at a temperature of 25 °C and a relative humidity of 50% ± 5%), while the second phase involves placing the specimens in an oven at 60 °C for 12 h and cooling them for at least 3 h at room temperature. Samples are tested after 1, 2, 4 and 6 cycles of wetting-drying. Once the target number of cycles has been reached, compressive strength tests and mass tracking measurements were carried out.

2.5.5 Drying shrinkage. The hardening of CEB is mainly subject to two types of shrinkage: shrinkage due to the self-dessication linked to the hydration reaction, and desiccation shrinkage due to the drying of the sample (Lirer *et al.*, 2017). In both cases, material shrinkage is due to a decrease in relative humidity in the material, either internal (autogenous) or external (drying). The two shrinkage phenomena coincide and lead to deformations which, in turn, can result in cracks, reducing the performance of CEB and making it more vulnerable to various external aggressions. A standard deformometer was used to measure CEB length variations. This device consists of a support plate to hold the specimen (dimensions), a calibration rod (100 mm) and a comparator with an accuracy of 0.001 mm. Furthermore, steel measuring inserts are inserted into the CEB samples during the compaction stage to aid in measuring linear shrinkage.

2.5.6 Batch leaching test. To identify the environmental impact of CEB, leaching tests on different CEB were carried out following the French standard (NF-EN-12457–2, 2002). The various CEB mixtures were crushed, sieved <4 mm and then leached with distilled water. The mixture was stirred for 24 h at room temperature. After filtration, the concentrations of the most important heavy metals (As, Ba, Cd, Cr, Cu, Hg, Ni, Mo, Pb, Sb, Se and Zn) were assessed by using ICP spectrometry.

3. Results and discussion

3.1 Mechanical properties

FA replaced sediment mass by 10%, 20%, 30%, 40% and 50%, respectively. An 8 mol NaOH alkaline activator solution was used for all mix-design. The compressive strength test revealed that CEB produced using different sediment and FA contents exhibited varying levels of strength (Figure 7). Average compressive strength ranged from 2.4 MPa to 11.6 MPa, with the highest strength values observed in blocks made with sediments featuring a finer particle size distribution and higher FA content. These results presented in Figure 7 indicate that the choice of sediment composition and the amount of FA significantly influence the compressive strength of CEB. This enhanced mechanical performance is due to the formation of binding phases between sediment particles, making the bricks more compact and resistant. These phases result from an amorphous geopolymeric gel formed by the chemical reaction between aluminosilicate fly ash (FA) and an alkaline solution of NaOH 8 M. The FA eventually dissolved within the NaOH solution, releasing large quantities of SiO(OH)$^{3-}$ as well as Al (OH)$^{4-}$ compounds (Lirer *et al.*, 2017; Rifaai *et al.*, 2019; Izquierdo *et al.*, 2009). As a consequence of the elevated concentration of the alkaline solution, the formed gels form a three-dimensional aluminosilicate structure that links the sediment particles together. The quantity of gels formed depends on the amount of FA and the NaOH contents. This partly explains why the highest mechanical strengths correspond to the highest FA proportions (CEB40FA and CEB50FA). All CEB with a FA content of at least 20% have a compressive strength over 4 MPa, in line with the recommendation of standard XP13-901 (XP P13-901, 2001). Nevertheless, a significant reduction in compressive strength was observed when exposed to moisture, compared with its dry strength of around 50%. Determining the compressive strength of unstabilized CEB (CEB0FA) in wet conditions proved unfeasible because the blocks disintegrated upon immersion in water for 2 h.

Standard (XP P13-901, 2001) classifies compressed earth bricks in two categories: bricks with a compressive strength between 2 and 4 MPa, designed for non-load-bearing walls, in contrast to bricks with a compressive strength greater than 4 MPa, suitable for load-bearing walls. Based on dry and wet compressive strengths, CEB stabilized with a minimum of 20% FA is appropriate for load-bearing walls, while CEB stabilized with 10% FA is suitable for non-load-bearing walls.

The porosity determines the mechanical behavior of compressed earth bricks ("The Porosity of Stabilized Earth Blocks with the Addition of Plant Fibers of the Date Palm | Idder | Civil Engineering Journal," n.d.). By examining Figure 8, we can observe the results of the porosity analysis of manufactured CEB. It is important to note that porosity is directly induced by the presence of FA. Thus, as FA content increases, porosity decreases linearly. This relationship can be explained by the alkaline activation process of FA, which leads to the formation of particle-bound gels, and also by the fact that the presence of fine

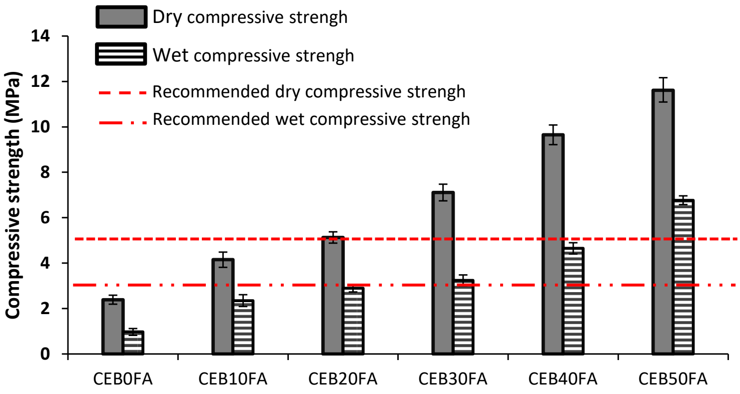

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Figure 7. Dry and wet compressive strength of CEB after 28 days

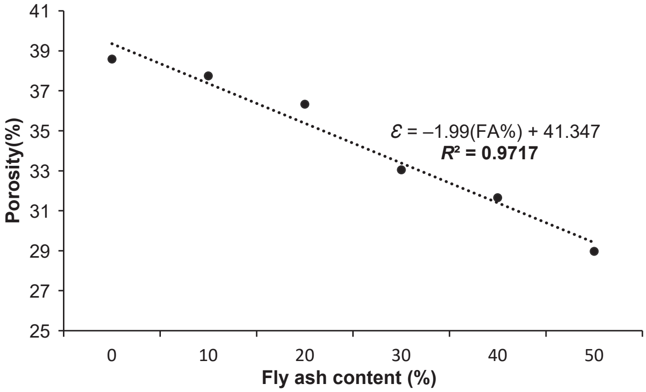

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Figure 8. Porosity of CEB samples as a function of FA content

particles of unreacted FA fills the inter-granular voids with more sediment (which improves granule compactness).

3.2 Absorption properties

The durability of bricks is greatly enhanced by their low water absorption capacity. Bricks with low absorption capacity are more resistant and durable to weathering. The results of absorption test, presented in Figure 9, revealed a water absorption variant ranging from 18.08 to 8.23 g/cm^2 min$^{1/2}$ for stabilized CEB. However, unstabilized CEB (CEB0FA) shows a coefficient of water absorption of 21.46 g/cm^2 min$^{1/2}$. In general, the water absorption coefficient decreases with increasing geopolymer content. This justifies the 13% difference between unstabilized CEB0FA bricks and CEB50FA bricks.

The evolution of water absorption coefficients shows that stabilized CEB bricks, with low water absorption coefficients, reach stability after partial immersion for more than 2 h. According to standard XP P13 901, all the CEB manufactured in this research showed water absorption coefficients below 40 g/cm^2 min$^{1/2}$, which classifies them as slightly-absorbing

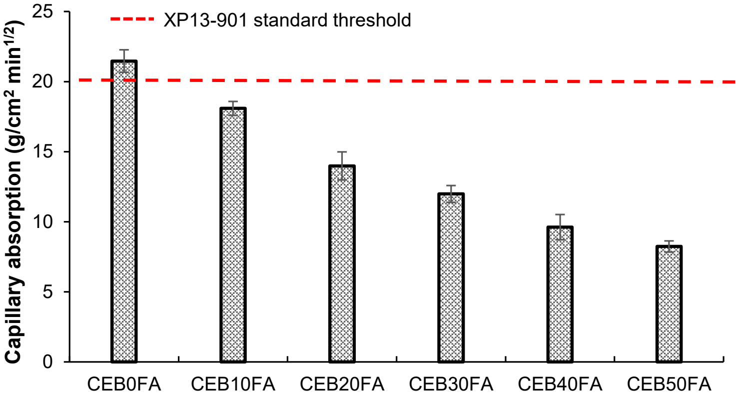

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Figure 9. Capillary water absorption coefficient of different CEB

capillary bricks. Furthermore, all stabilized CEB can fail as low-capillary bricks, with values below 20 g/cm^2 min$^{1/2}$. Consequently, the stabilized CEB prepared in this study meet the requirements for application in exterior wall construction.

3.3 Water resistance

The bricks durability is strongly dependent on water absorption capacity (Gencel *et al.*, 2021). Indeed, the CEB with a low absorption capacity are more durable and resistant to weathering (Benlalla *et al.*, 2015). To examine the hydric behavior of bricks, Figure 10 shows the aspects of different CEB after a 24-h immersion underwater. The underwater behavior of CEB samples was assessed visually. These results provide an initial assessment of the water resistance of CEB. Unstabilized bricks (CEB0FA) disintegrated after immersion in water, unlike bricks stabilized by the addition of FA. However, among the stabilized CEB, water coloring lightened with FA content between 10% and 50%. The dark appearance of the water was due to unreacted FA particles leaching (dissolving) into the water. The leachate from the unstabilized brick (CEB0FA) remained clear despite its dislocation, as there was no FA. In contrast, the water in CEB10FA was darker among the samples, signifying less cohesion compared to CEB20FA, CEB40FA and CEB50FA. The latter is likely to contain more geopolymer gels binding the sediment grains, giving good cohesion and less porosity in the samples. The geopolymerization rate of CEB10FA would be inferior to that of other samples with a high presence of anhydrous (FA).

3.4 Water resistance under drying/wetting cycles

According to ASTM 1989b (ASTM D559, 1989), cyclic drying-wetting tests were used to evaluate the durability of CEB. Evaluation of test results was based on compressive strength about initial dry compressive strength and on mass loss in relation to initial dry weight. CEB samples underwent 6 cycles of 2 h immersion, then 12 h drying. However, the test could not be carried out for unstabilized CEB (CEB0FA), which degraded on contact with water. On the other hand, CEB samples stabilized with FA showed minimal mechanical resistance. Figure 11

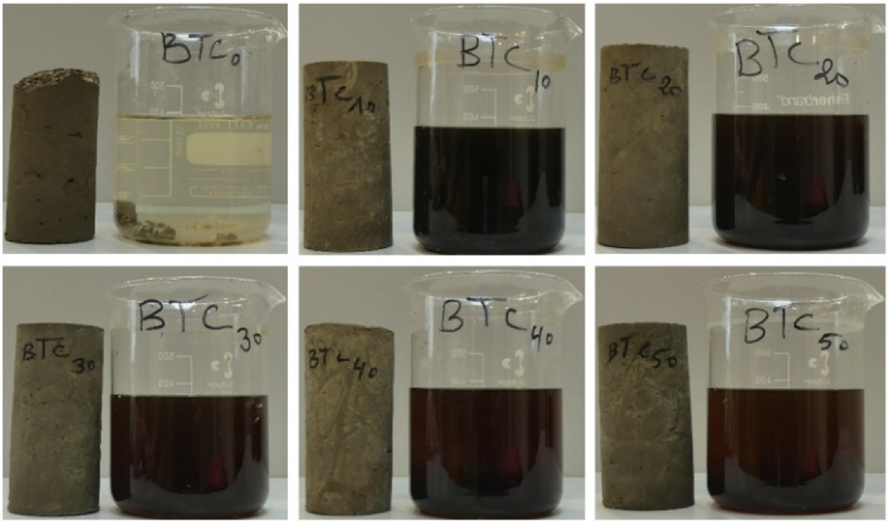

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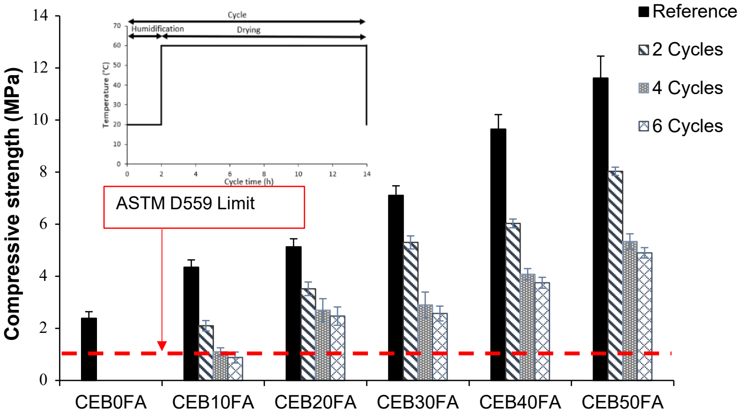
Figure 10. CEB water sensitivity (24 h of immersion)

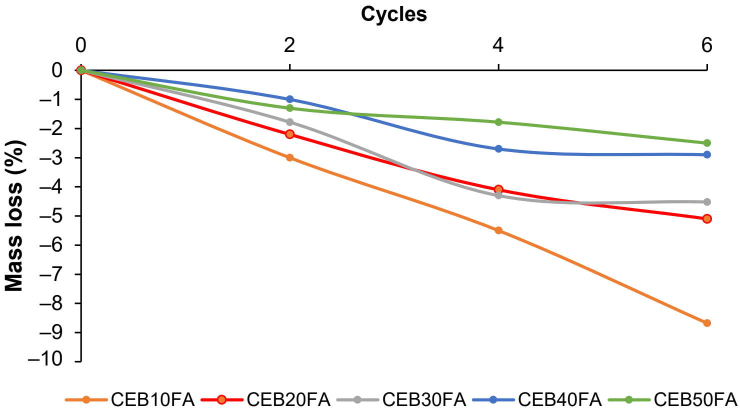


Source(s): Authors' own work

Figure 11. Effects of wetting-drying cycles on compressive strength

shows that the percentage loss of strength over drying-wetting cycles varied between 30 and 70% depending on the FA dosage. The compressive strength after 6 cycles of samples stabilized with at least 20% FA exceeded the regulatory strength of 1.6 MPa. This suggests that BEC should be stabilized with at least 20% FA to maintain long-term performance.

It is important to note that during the drying-wetting evaluation tests, all samples showed a loss of mass. Taking this into account during the tests enabled us to better assess the performance of CEB under the effect of the wetting-drying cycles. Figure 12 suggests that the loss of mass was due to the detachment of soil particles by pore water pressure after immersion. In addition, the higher water absorption of CEB0FA induced greater swelling/shrinkage during wetting-drying, resulting in greater mass loss compared with the other stabilized CEB. CEB0FA continues to lose mass, whereas the other formulations remain stable after 4 cycles. This is why the loss of strength is low between 4 and 6 cycles. CEB stabilized with more than 20% FA meets the durability criteria, because the loss of mass of these CEBs is well below the 7% loss of mass permitted by the standard.



Source(s): Authors' own work

Figure 12. CEB weight loss under wetting-drying cycles

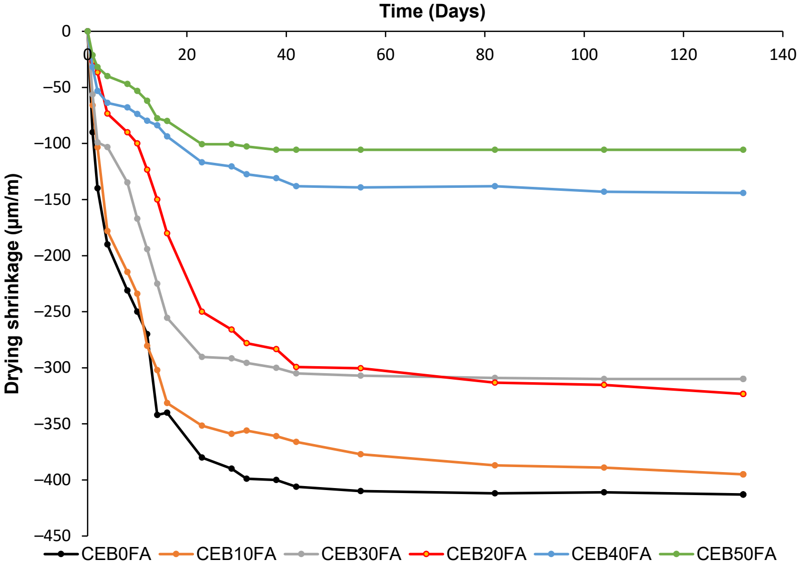
This behavior in water was confirmed by Kumar *et al.* (2022). The geopolymer samples showed better durability in seawater, with a mass loss of 8.1% and retained compressive strength of 56% after 24 weeks, compared with a mass loss of 14.2% and retained strength of 32% for conventional concrete. In addition, after 90 wetting and drying cycles, the geopolymer samples retained their compressive strength.

3.5 Drying shrinkage

The shrinkage of the CEB is a critical factor that determines its application, as excessive shrinkage leads to cracking and renders the blocks inappropriate for construction. Figure 13 shows that stabilization with FA significantly reduces the drying shrinkage of CEB, by increasing the FA content between 0 and 50%, the degree of shrinkage was reduced by 67%. The results showed that the shrinkage is primarily due to the shrinkage stress generated by the capillary pore water loss. Consequently, as the curing age increases, shrinkage initially increases quickly, then becomes progressively more stable at 20 days, as sample moisture tends to equilibrate with the external environment. CEB0FA, by contrast, is characterized by high free water content and, consequently, higher shrinkage.

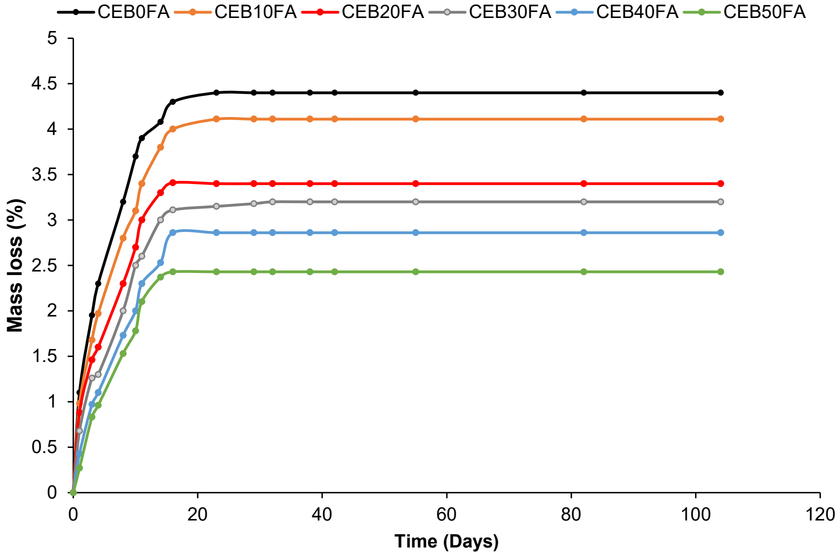
For a more detailed study of drying shrinkage, we also carried out mass tracking tests to quantify water exchange. The curves in Figure 14 show that mass losses are in line with shrinkage evolution, with almost identical values from day one for all CEB. All curves begin with a linear section whose slope decreases with time. In the intermediate zone, the curves are highly non-linear, which explains a reduction to low values due to evaporation. After 20 days, mass losses begin to decrease very slightly and are lower for stabilized CEB than for the reference CEB0FA. The more FA is added, the more water is consumed by the geopolymerization reaction. There is therefore less loss of free water.

The linear correlation between shrinkage and mass loss of BEC stabilized with FA is clearly observed, Figure 15. The curves show that mass loss and shrinkage evolve similarly, with almost identical values from day one. Initially, the curves are linear, then they become non-



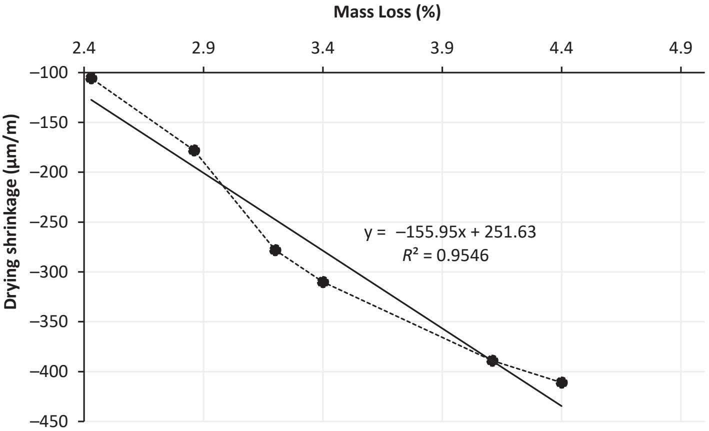
Source(s): Authors’ own work

Figure 13. Drying shrinkage of CEB



Source(s): Authors' own work

Figure 14. Weight loss of CEB



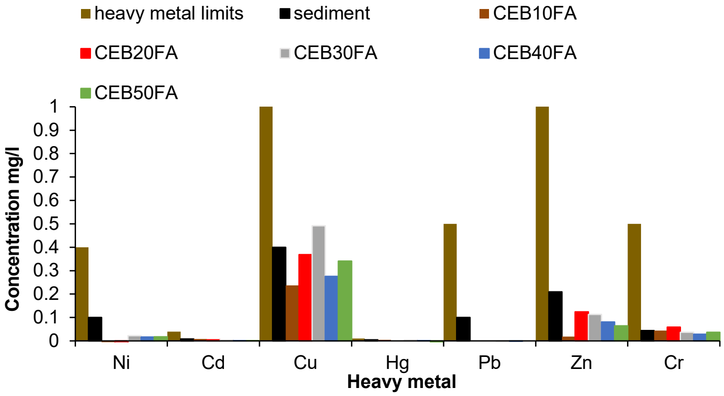
Source(s): Authors' own work

Figure 15. The linear correlation between shrinkage and mass loss of BEC

linear due to continuous evaporation, and after 20 days, mass losses decrease slightly. The addition of FA reduces the amount of free water by promoting geopolymerization, which reduces shrinkage. The higher the FA content, the less mass loss and shrinkage.

3.6 Batch leaching of heavy metals

The leaching of heavy metals from sediments is the main environmental impact of sediment-based bricks (Cusidó and Cremades, 2012). To identify the environmental impact of CEB, leaching tests on different CEB were carried out following the French standard NF EN 12457–2 (NF-EN-12457–2, 2002). The results of heavy metals leaching are shown in Figure 16.



Source(s): Authors' own work

Figure 16. Histogram of concentrations of various heavy metals leachates

The results indicate that the heavy metal concentrations are well below the leaching thresholds for inert waste required for inert waste in accordance with French directive 0,289 published on December 14, 201 (NF-EN-12457–2, 2002). None of the CEB formulations would have a dangerous impact on the environment. Given these results, these sediment-based bricks could be used for construction applications. Figure 16 shows a decrease in heavy metal concentrations in leachate with the addition of FA. This verifies that the addition of FA to sediments immobilizes contaminants, as reported in recent studies (Izquierdo *et al.*, 2009).

4. Conclusions

The experimental study on CEB presented in this research provides valuable insights into the durability and stability of CEB produced using different sediment-FA contents. The results emphasize the importance of careful selection of sediment characteristics, appropriate mix design and the potential benefits of incorporating FA in enhancing CEB performance.

Over time, CEB must withstand various stresses and strains (physical, mechanical, chemical), the loads to which it is subjected, as well as actions such as wind, rain, cold, heat and the ambient environment, while retaining its aesthetic appeal. The CEB produced has been subjected to several durability tests (water resistance, resistance to drying-wetting cycles, shrinkage).

(1) The CEB containing at least 20% FA are well adapted to load-bearing wall applications in buildings in terms of mechanical performance

(2) The drying-wetting cycle test shows that the addition of 20% FA satisfies the prescribed limit of less than 7% cumulative mass loss after 6 cycles according to standard (ASTM D559, 1989). A compression test was performed on CEB samples capable of withstanding multiple drying-wetting cycles, and strength was maintained at levels ranging from 30% to 70% depending on FA content.

(3) The CEB containing a higher dosage of FA showed lower drying shrinkage given their micro-filling benefits and pozzolanic properties, by increasing the content of FA from 0 to 50% drying, shrinkage was reduced by 67%.

(4) The leaching tests carried out on the bricks showed that heavy metal concentrations in the leachate were well below regulatory limits according to the standard (NF-EN-12457–2, 2002). Additionally, the addition of FA results in lower concentrations of heavy metals, suggesting that FA is a promising technology for pollution control. In fact, CEB could be considered an environmentally-friendly product.

Following on from these results, we propose to develop a prototype masonry wall in order to assess its mechanical, thermal and hydric stability under conditions close to reality. This multi-scale analysis should start at the insulated brick scale and progress to the wall scale, providing a comprehensive overview of the application and performance of CEB with FA stabilization in the practical application.

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Corresponding author

Mohamedou Brahim can be contacted at: mohamedou.brahim@cyu.fr