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Influence of Cement Content on Thermophysical and Mechanical Properties of Compacted Earth Bricks Made from Kaolinitic and Lateritic Soils: Experimental Study

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Abstract

This study explores the impact of the cement content (4%, 6%, and 8%) on the thermophysical and mechanical properties of compressed earth bricks produced from a mixture of kaolinitic (60%), lateritic (12% - 16%), and sandy (20%) soils. The results regarding thermophysical properties indicate that an increase in the cement content from 6% to 8%, combined with a 28-day curing period, leads to a gradual increase in bulk density, from 1859 to 1863 kg/m^3 (5.9%), thermal conductivity, which ranges from 0.601 to 0.690 W/m·K (14.8%); thermal effusivity, which increases from 1202 to 1328.5 $W/m^2 \cdot K \cdot S^1/^2$ (+10.5%), thermal diffusivity, which rises from 2.53 to 2.71 × 10^{-7} m^2/s (+7.1%), and a nearly constant specific heat capacity ranging from 1357.76 to 1367.54 J/kg·K (+0.7%). In contrast, thermal resistance decreased from 0.33 to 0.28 $m^2 \cdot K/W$ (−15.2%). As for mechanical properties, compressive strength increased from 1.78 to 3.51 MPa (+97%) with a 4% cement addition and curing periods of 3, 7, and 28 days; from 2.34 to 4.44 MPa (+89.74%) with a 6% cement addition and curing for 3, 7, and 28 days; and from 3.03 to 6.08 MPa (+100%) with an 8% cement addition and curing for 3, 7, and 28 days. All formulations exceed the minimum compressive strength of 2 MPa generally recommended by several standards for stabilized clay bricks. The 6% and 8% formulations meet the requirements for bricks used in load-bearing walls. The 8% formulation provides very high compressive strength and can be used in sustainable construction.

Keywords

Compressed Earth Bricks, Cement Stabilization, Thermophysical Properties,

Mechanical Properties

1. Introduction

In developing countries such as Chad, the global issue of climate change, along with spatial and demographic expansion driven by rural exodus and refugee migration, has led to the emergence of peri-urban areas where housing quality has become a major challenge. This situation has resulted in an increase in household energy consumption and, subsequently, a housing crisis. Most traditional building materials, such as concrete, are imported and expensive, making it difficult for average households to build decent housing. It is therefore necessary to find alternative construction methods using other materials, such as earth. This material, available worldwide, represents a viable option in the construction sector to meet the needs of the population.

One of the reasons for using earth in construction is its availability near the housing construction site. In addition, earth-based materials offer beneficial thermal and hydrological properties. Their high thermal inertia [1] [2], combined with a high storage capacity [3]-[5], allows for passive temperature regulation inside buildings, thereby contributing to thermal comfort.

Although rammed earth structures offer many advantages, their unstabilized nature presents some disadvantages, such as insufficient mechanical strength, inevitable cracks caused by shrinkage, and, above all, their high sensitivity to water. From ancient times to the present day, people have sought to improve the properties of earthen structures and reduce their sensitivity to water by using various soil stabilization methods. This experience has led to the emergence of various earthen construction techniques, such as adobe, rammed earth, cob, and compressed earth blocks (CEB), among others.

To address these shortcomings, the stabilization of compressed earth blocks through the addition of cement has, over time, established itself as a compromise between traditional techniques and modern requirements. Ordinary Portland cement has become the most commonly used stabilizer in most previous research on stabilized earth bricks techniques due to its ability to achieve high strength within 28 days.

According to numerous authors, including [6]-[18], the thermophysical properties of cement-stabilized compressed earth bricks tend to increase with the addition of cement, while thermal resistance tends to decrease. Regarding mechanical properties, according to studies by [8]-[11] [17] [19]-[23], the stabilization of compressed earth bricks with cement results in a gradual increase in compressive strength, generally in the range of 2 to 7 MPa, with this variation depending on the mixture composition and curing conditions.

The main objective of this article is to experimentally study the thermophysical and mechanical properties of cement-stabilized compressed earth bricks made from kaolinitic and lateritic soils, with a view to optimizing their performance for use in construction.

2. Materials and Methods

2.1. Materials Used

2.1.1. Soils

1) Location of the Study Sites

The soils examined in this study are from the city of Moundou, located in southwestern Chad, approximately 450 km from the capital, Ndjamena. The city is situated between three bodies of water: Lake Taba to the north, the Logone River to the southeast, and Lake Wey to the west. The city is situated in a flat basin on the banks of the Logone River at 8.550˚ north latitude and 16.090˚ east longitude. Temperatures in the city range from 10˚C to 31˚C, with an annual average of 27˚C. The dry season lasts approximately 5 months (from November to the end of March), but its boundaries are highly variable. The city has a Sudanian-type semi-humid tropical climate with an average annual rainfall of 1127 mm. The soil types in Moundou consist primarily of three types characteristic of the Sudanese zone [24]:

- hydromorphic soils covered with recent and ancient alluvial deposits in the floodplains. These are beige, sandy-clay and silty soils that are frequently flooded during the rainy season.

- leached ferralitic soils on the non-flooded areas, which are gray-brown in color, very sandy on the surface, and sandy loam deeper down.

- red soils, which are sandy deeper down and covered with a lateritic crust, particularly on the upper parts of plateaus.

2) Sampling

For this study, three soil varieties were selected to examine their geotechnical profiles and determine their suitability for inclusion in mixtures used to manufacture earthen bricks. The clay was sourced from the teacher training college's quarry, located at the following geographic coordinates: 8˚33'11.74"N, 16˚04'41.95"E. The laterite was extracted 80 cm below the natural ground level from the Koutou quarry, located at the northern entrance to Moundou at 8˚35'59.68"N, 16˚04'0.97"E. The sand comes from the Lac Wey quarry, located west of the city of Moundou. It was extracted from the riverbed at a depth of approximately 3 meters below the natural ground level. Its coordinates are 8˚33'14.9"N, 16˚03'10.59"E. The soil in all of these quarries has been mined for decades by local communities, primarily for the production of adobe bricks and roofing and wall coverings.

3) Geotechnical Characterization of Soils Used

Table 1 illustrates the different particle size classes of the three types of soil used in brick manufacturing.

Table 1 presents the particle size classes for three types of soil. Particles larger than 2 mm are negligible, with percentages passing through a 0.08 mm sieve of 77.08%, 45.7%, and 49.7%. All soils contain more than 35% fine particles (<80 μm)

Table 1. Different particle size classes of the three types of soil used.

Soil origin (quarries)	Apparent density ρ_a (g/cm^3)	Particle size distribution			Atterberg limits			Proctor test WOPM (%)
		Gravel (%) > 2 mm	Sand (%) 0.08 - 2 mm	Fines (%) (silt + clay) < 80 µm (%)	LL (%)	PL (%)	PI (%)	
Teacher training college's (Clay)	1.22	0.36	22.56	77.08	63.8	32.39	31.41	18
Koutou (Laterite)	1.36	3.39	50.91	45.7	33	16.55	16.45	
Lac Wey (Sand)	1.6	1.46	48.84	49.7	34.75	24.04	10.71	

and are therefore classified as fine soils according to the [25]. The soil at the teacher training college's, classified as clayey or silty (77.08% passing through the 0.08 mm sieve), is dominated by fine particles. The lateritic soil at Koutou, with 45.7% fines, is rich in sand, classifying it as sandy with fines. The soil at Lac Wey, with 49.7% fines, lies on the boundary between coarse and fine soils and is classified as coarse. Using the results of Atterberg limit tests—specifically the plasticity index and the liquid limit—the Casagrande diagram ([26] and the USCS soil classification system [27]), these soils can be classified as follows: clay soil at teacher training college's (MH), lateritic clayey sand from Koutou (SC), and silty-clayey sand from Lac Wey (SM-SC).

Knowing the nature of these three soil types, we determined the optimum moisture content using the modified Proctor test. The optimum moisture content (WOPM) is 18%.

4) Classification and Mineralogical Identification of Soils in Use

Table 2 presents the methylene blue values (MBV), the blue activity index (BAI), the specific surface area (SS), and the cation exchange capacity (CEC) of our soils.

Table 2. Classification and mineralogical identification of soils in use.

Soil origin	MBV (g/100g)	BAI (%)	SS (m^2/g)	CEC (meq/100g)	Probable mineralogical type
Teacher training college's (Clay)	5.2	0.06	108.83	13.9	Kaolinitic-silty
Koutou (Laterite)	3.3	0.07	69.06	8.82	Sandy lateritic
Lac Wey (Sand)	2.1	0.04	43.95	5.61	Silty-lateritic

Table 2 shows that the analyzed soils, characterized by medium to low plasticity, have a blue activity index (BAI) below 3, indicating their inactivity. They consist mainly of kaolinite, with less illite, and exhibit a significant cation exchange capacity (CEC) typical of kaolinite/laterite soils. The results indicate that these soils do not possess the characteristics of highly expansive soils such as smectite or montmorillonite, but rather those of tropical lateritic soils dominated by weakly active kaolinite, revealing a clear consistency in the data.

2.1.2. Cement

In our study, we used CPJ-CEM II 32.5 composite Portland cement, consisting of 65% clinker and 35% additives (limestone, slag, or fly ash). It is manufactured locally by the Société Nationale de Ciment (SONACIM).

2.1.3. Formulations and Manufacturing of Stabilized Earth Bricks

1) Formulations

The composition of the mixtures used in this study is presented in **Table 3**.

Based on these material proportions, we used three (3) formulations to manufacture cement-stabilized, compressed earth bricks. They are summarized in **Table 4**.

Table 3. Composition of the various material mixtures.

Materials	Mix proportions
S1: Soils from teacher training college's (Clay)	60%
S2: Soils from Koutou (Laterite)	16%, 14%, and 12%
S3: Soils from Lac Wey (Sand)	20%
C: Cement	4%, 6%, and 8%

Table 4. Material formulations for the manufacture of stabilized bricks.

Formulations	Compositions (%)
F1	60% S1 + 16% S2 + 20% S3+ 4% C
F2	60% S1 + 14% S2 + 20% S3 + 6% C
F3	60% S1 + 12% S2 + 20% S3 + 8% C

2) Manufacturing

As part of our study, we initially prepared masonry blocks measuring 30 × 15 × 13 cm^3 to analyze the mechanical properties of the bricks. Subsequently, in accordance with the experimental conditions for the thermal tests, we were required to modify the size of our brick samples. We therefore manufactured bricks measuring 8 × 5 × 4 cm^3. However, all test specimens (30 × 15 × 13 cm^3 and 8 × 5 × 4 cm^3) were manufactured using the same methods and formulations, with the exception of their molds, which were different. They were produced using the conventional method (mixing, compaction, and demolding). Initially, the natural clay was sun-dried, manually crushed, and then sieved before being combined with the binders (cements) in accordance with the standard [28] (**Figure 1(a)**). The materials were first mixed dry, according to the various formulations listed in **Table 4**. Subsequently, a quantity of water corresponding to the optimal water content was instantly added to the mixture, followed by mixing (**Figure 1(b)**). The required amount of mixture was weighed and placed into the mold (**Figure 1(c)**). To increase the density of the material and bring the solid grains closer together, the static compaction technique is used. For this study, we used a lightweight manual press with a pressing force of 5 to 10 metric tons and a production rate of 300 to 600 blocks per day (Figure 1(d)).

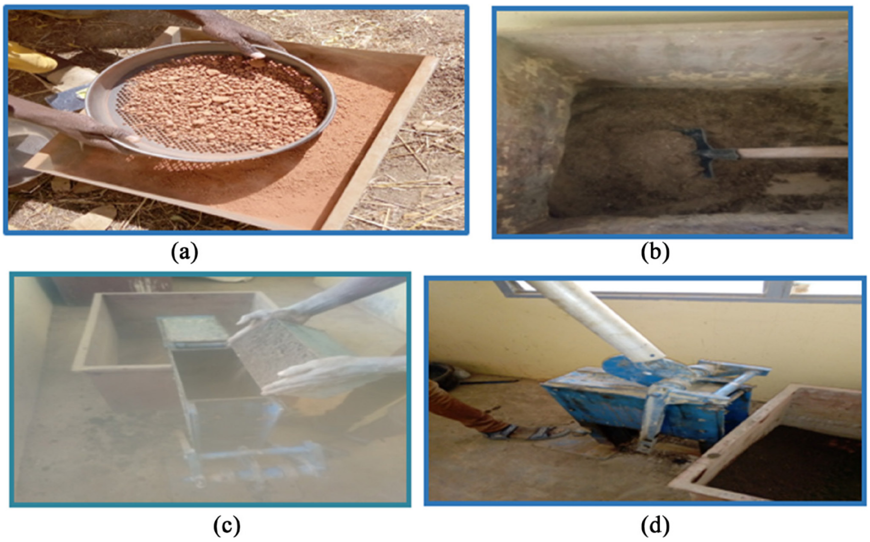


Figure 1. Test specimen preparation: (a) sieving the ground material; (b) mixing the material; (c) filling the mold with the material; (d) manual compaction press.

The maximum curing period is set at 28 days. However, for the mechanical tests, the stabilized earth bricks were tested after curing periods of 3, 7, and 28 days. In total, 18 brick samples were used for the mechanical tests (6 for the 4% cement formulation, 6 for the 6% cement formulation, and 6 for the 8% cement formulation). For the bricks used in the thermophysical measurements, the maximum curing period was set at 28 days. The samples were then dried for 24 hours in an oven to completely remove all traces of moisture. Subsequently, green sandpaper was used to sand these elements in order to obtain flat surfaces that ensure optimal contact with the heating element (Figure 2). Twelve (12) brick samples were used for the thermal tests (4 for the 4% cement formulation, 4 for the 6% cement formulation, and 4 for the 8% cement formulation).

Figure 2. Bricks that have been dried and sanded with green sandpaper.

3) Curing of the Blocks

Curing involves keeping the material in a sufficiently humid environment for a sufficient period of time to maximize chemical reactions. The use of hydraulic binders such as cement requires a curing period to allow hydration reactions to occur under optimal conditions, thereby improving the binder's effectiveness. In our case, after demolding, the manufactured blocks are kept in a humid atmosphere at room temperature in the laboratory and are covered with a curing bag made of plastic film to maintain humidity (**Figure 3(a)**). After a curing period, the test specimens are removed and stored in a temperature-controlled room at 20˚C and 50% relative humidity for drying. The maximum curing time for our test specimens is 28 days. The test specimens are then marked and subjected to various tests (**Figure 3(b)**).

(a) (b)

Figure 3. Preparation of test specimens: (a) curing using plastic wrap; (b) test specimens marked for testing.

2.2. Experimental Methods

2.2.1. Characterization of Thermophysical Properties

1) Physical Properties

a) Bulk Density

The hydrostatic weighing method, in accordance with the standard [29], was used to determine the density of the stabilized and compressed bricks. The principle involves weighing a sample that has been dried at 105˚C in an oven until a stable mass is achieved, then coating its entire outer surface with paraffin, and finally weighing it in open air. The paraffin-coated bricks are then submerged in water. Given that paraffin has a density of 0.88 g/cm³, the apparent density (ρ_a) of the dry bricks is calculated using Archimedes' principle and equation (1).

$$\rho_a = \frac{m_s}{V} \quad \text{avec} \quad V = \frac{m_p - m'_p}{\rho_w} - \frac{m_p - m_s}{\rho_p} \tag{1}$$

m_s : mass of the sample; V : volume of the sample; m_p : mass of the dry, paraffin-coated sample; m'_p : mass of the paraffin-coated sample submerged in water; ρ_w : density of water (1 g/cm³); ρ_p : density of the embedding paraffin (0.88 g/cm³).

2) Measurement of Thermal Properties

In our study, we used the hot-wire/hot-plate method under transient conditions. The hot-wire method measures thermal conductivity, while the hot-plate method determines effusivity. The goal is to generate a slight local temperature increase in the material, which is assumed to be in thermal equilibrium, and to measure this temperature increase over a very short period of time (Figure 4).

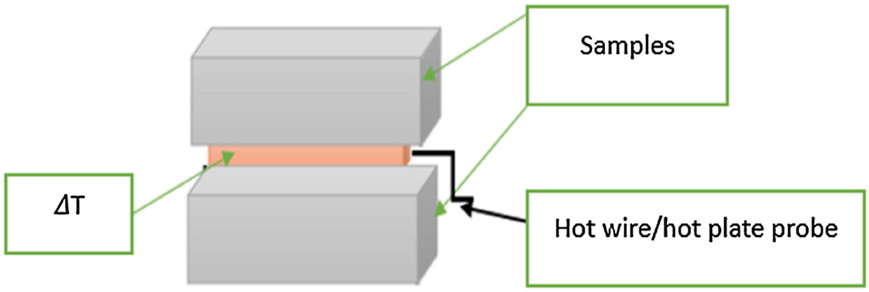
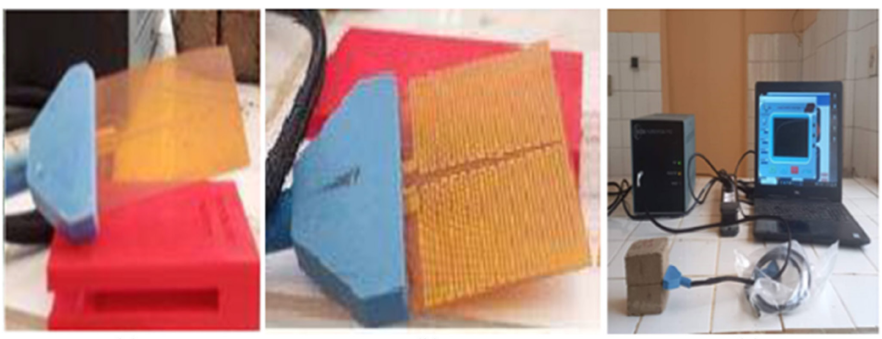


Figure 4. Illustration of the hot-wire/hot-plate technique.

The measurement system used in this study was developed by the French Scientific and Technical Center for Building (CSTB) in accordance with the standards [30] and the RILEM AAC 11 - 13 recommendation. The equipment consists of thermal shock probes (a hot-wire probe to evaluate thermal conductivity and a hot-plate probe to measure effusivity) to be positioned between the two samples of the material to be characterized (Figure 5(a) and Figure 5(b)), an electronic data acquisition system, and graphical user interface software to control the experiments and analyze the results (Figure 5(c)). The shock probe is based on the principle of locally generating a slight increase in the material's temperature (a few degrees above ambient temperature) and measuring this rise in temperature over time (over a period of a few minutes). The probe allows for measurements ranging from 20˚C to 100˚C. The temperature difference between the two sides of the sample is established using thermocouples of specific dimensions. The heat flux is measured by thermopiles in accordance with the standards [30]. Thermal conductivity is determined through mathematical signal processing integrated into the provided software. This technique offers numerous advantages, particularly its ease of implementation and the speed of the measurements. Indeed, since it is a transient method, the measurement time is consequently very short [31].



(a) (b) (c)

Figure 5. Experimental setup for the hot-wire/hot-plate method used to measure thermal properties: (a) hot-wire probe for thermal conductivity; (b) hot-plate probe for effusivity; (c) electronic data acquisition system.

Furthermore, it can be used not only for solids but also for liquids and other materials [32].

- **Thermal Conductivity**

Thermal conductivity refers to a material's ability to transfer heat by conduction when subjected to a temperature difference [33]. The method involves generating a slight local increase in temperature within the material (which is then considered to be at thermal equilibrium) and observing the rise in temperature over a very short period of time [34].

The following equation establishes a relationship between thermal conductivity and the change in temperature over time:

$$\Delta T = \frac{q}{4\pi\lambda} * \left(\ln(t) + c\right) \tag{2}$$

where: λ: Thermal conductivity in $W \cdot m^{-1} \cdot K^{-1}$; q: the applied heat flux in W/m; ΔT: the temperature difference in K; t: the test duration in s and c: constant.

- **Thermal Effusivity**

Thermal effusivity represents the rate at which a material's surface temperature changes (the sensation of cold or heat when touched). It describes how quickly a material absorbs heat. A lower effusivity coefficient results in faster heating of the material's surface [33].

The equation below relates effusivity to temperature and time:

$$\Delta T = q\left(R_t - \frac{Cs}{Eff^2} + 2\frac{\sqrt{t}}{Eff\sqrt{\pi}}\right) \tag{3}$$

where Eff: thermal effusivity in $w/m^2 \cdot K \cdot S^{1/2}$; T: temperature in K; q: injected flux density in $W \cdot m^{-2}$; t: time in s; R_t: total resistance, *i.e.*, the resistance of the probe and the contact resistance in $K \cdot m^2 \cdot W^{-1}$ and Cs is an intrinsic characteristic of the probe in $w \cdot K^{-1} \cdot m^{-2}$.

- **Thermal Diffusivity**

Thermal diffusivity characterizes the rate at which heat propagates through the mass of a material. The lower this value, the longer it takes for the heat front to travel through the thickness of the material [33].

It is expressed by the following equation:

$$a = D = \frac{\lambda}{\rho * C_p} \quad (\text{in } m^2/s) \tag{4}$$

where λ is thermal conductivity in $W \cdot m^{-1} \cdot K^{-1}$; ρ is density in kg/m^3; C_p is specific heat in J/kg·K.

- **Specific Heat**

Specific heat measures the amount of energy required to raise the temperature of 1 kg of a material by 1 K.

It is determined by the formula:

$$C_p = \frac{Q}{m\Delta T} \tag{5}$$

where C_p is the specific heat (J/kg·K); Q is the amount of heat absorbed; m is the mass of the sample; and ΔT is the change in temperature.

- **Thermal Resistance**

The thermal resistance (R_{th}) of a wall depends on the thermal conductivity (λ) of the materials used and the thickness (e) of the layers of each material.

It is calculated as follows:

$$R_{th} = \frac{e}{\lambda} \quad (\text{in m}^2\cdot\text{K/W}) \tag{6}$$

with $e = 20$ cm, the standard wall thickness. In fact, the thermal conductivity λ was measured on test specimens measuring 8 × 5 × 4 cm. Therefore, the 4-cm-thick test specimen is used solely to measure λ, which is an intrinsic property of the material. Thermal resistance R was then calculated for a standard wall thickness of 20 cm, in accordance with standard practice in civil engineering, to reflect the actual performance of the bricks in use, since this value allows for a comparison of the insulating performance of the different formulations under real construction conditions.

2.2.2. Dry Compressive Strength Test

After drying, a batch of test specimens is subjected to a simple compression test to determine their compressive strength in the dry state. The compressive strength of cement-stabilized blocks is measured either on a masonry unit (block and joint), on a half-block, or on a whole block [20]. In this study, compressive strength was measured according to the method developed by [35] on a whole block. The procedure involves placing a block on a compression press and loading it until failure in accordance with the standard [36] (**Figure 6**). The maximum load reached is recorded, and the compressive strength is determined using Equation 7.

$$R_c = \frac{F}{A_c} \tag{7}$$

R_c: Compressive strength (MPa); F: compressive failure force (N); and A_c: area over which the force is applied (mm²).

Figure 6. Compression test setup.

3. Results

3.1. Thermophysical Properties

The thermophysical results for 12 samples of cement-stabilized earth bricks are presented in Table 5 and Table 6.

Table 5. Thermophysical parameters of cement-stabilized earth bricks.

Numb.	Formulations	Vol. (cm^3)	dry weight (g)	ρ_a (kg/m^3)	C_p (J/kg·K)	λ (W/m·K)	*Eff* (W/m^2·K·S$^{1/2}$)	D (m^2/S)	e (m)	S (m^2)	R_{th} (m^{2}K/W)
1	F_1 (4% cement)	160	283	1768.75	1359.152886	0.6	1201	2.49584E−07	0.2	0.008	0.333333333
2		160	281	1756.25	1353.121521	0.61	1204	2.56689E−07	0.2	0.008	0.327868852
3		160	283	1768.75	1313.119799	0.62	1200	2.66944E−07	0.2	0.008	0.322580645
4		160	279.2	1745.00	1405.67141	0.59	1203	2.40532E−07	0.2	0.008	0.338983051
1	F_2 (6% cement)	160	291	1818.75	1371.0314	0.655	1278	2.62676E−07	0.2	0.008	0.305343511
2		160	293	1831.25	1329.007994	0.669	1276	2.74885E−07	0.2	0.008	0.298953662
3		160	294	1837.50	1301.020408	0.68	1275	2.84444E−07	0.2	0.008	0.294117647
4		160	289	1806.25	1437.549075	0.63	1279	2.42627E−07	0.2	0.008	0.317460317
1	F_3 (8% cement)	160	299	1868.75	1365.65673	0.69	1327	2.70369E−07	0.2	0.008	0.289855072
2		160	300.4	1877.50	1379.281742	0.68	1327	2.62589E−07	0.2	0.008	0.294117647
3		160	297	1856.25	1357.255604	0.7	1328	2.77843E−07	0.2	0.008	0.285714286
4		160	296	1850.00	1368.000772	0.7	1331	2.76592E−07	0.2	0.008	0.285714286

The average thermal parameters are summarized in the following table:

Table 6. Average values of the thermophysical properties of cement-stabilized earth bricks.

Thermal properties	F_1 (4% cement)	F_2 (6% cement)	F_3 (8% cement)	Variation (F4→F8)
bulk densities ρ_a (kg/m^3)	1759	1823	1863	+5.9%
Thermal conductivity λ (W/m·K)	0.601	0.651	0.690	+14.8%
Thermal effusivity *Eff* (W/m^2·K·S$^{1/2}$)	1202	1277	1328.25	+10.5%
Thermal diffusivity D (m^2/s)	2.53E−7	2.66E−7	2.71E−7	+7.1%
Specific heat C_p (J/kg·K)	1357.76	1359.65	1367.54	+0.7%
Thermal resistance R_{th} (m^2·K/W)	0.33	0.30	0.28	−15.2%

3.2. Mechanical Properties (Dry Compressive Strength)

Table 7 and Table 8 show the dry compressive strengths R_c (in MPa) as a function of different mixtures (in % cement) and curing time (days).

Table 7. Values of the dry compressive strengths of cement-stabilized earth bricks.

Formulations	Ages	Block n°	Compressive failure force F(N)	Area (mm^2)	Compressive strength R_c (Mpa)	Average
F_1 (4% cement)	3 days	1	80,000	42,774	1.87	1.78
		2	72,000	42,774	1.68	
	7 days	1	100,000	42,774	2.34	2.48
		2	112,000	42,774	2.62	
	28 days	1	120,000	42,774	2.81	3.51
		2	180,000	42,774	4.21	
F_2 (6% cement)	3 days	1	100,000	42,774	2.34	2.34
		2	100,000	42,774	2.34	
	7 days	1	120,000	42,774	2.81	2.82
		2	121,000	42,774	2.83	
	28 days	1	160,000	42,774	3.74	4.44
		2	220,000	42,774	5.14	
F_3 (8% cement)	3 days	1	128,000	42,774	2.99	3.03
		2	132,000	42,774	3.09	
	7 days	1	135,000	42,774	3.16	3.21
		2	140,000	42,774	3.27	
	28 days	1	240,000	42,774	5.61	6.08
		2	280,000	42,774	6.55	

Table 8. Average values of the dry compressive strengths of cement-stabilized earth bricks.

Curing time (age)	Formulations		
	F_1 (4% cement)	F_2 (6% cement)	F_3 (8% cement)
3 days	1.78	2.48	3.51
7 days	2.34	2.82	4.44
28 days	3.03	3.21	6.08

4. Discussion

4.1. Effect of Cement on Thermophysical Properties

- The bulk density increases with the cement content, rising from 1859 to 1863 kg/m^3, representing a 5.9% increase when the cement content ranges from 4% to 8%. In fact, when cement comes into contact with water, it undergoes a hydration reaction that produces calcium silicate hydrates (C-S-H) and portlandite. These hydration products have two effects:

  - They fill the interstitial voids between the clay, sand, and laterite particles.

- They coat the particles, creating a denser matrix.

It is this pore-filling mechanism that explains the increase in density: Indeed, bulk density and porosity are inversely related:

$$\text{bulk } \rho = \text{solid } \rho \times (1 - \text{porosity})$$

When cement hydrates and fills the pores, porosity decreases, which mechanically leads to an increase in bulk density.

The bulk density results obtained in this study (1759 - 1863 kg/m^3) are largely consistent with those reported in the literature for stabilized soil blocks, which generally range between 1700 and 2100 kg/m^3 [6] [7] [10].

- Thermal conductivity (λ) increases significantly with the cement content, rising from 0.601 to 0.690 W/m·K, which corresponds to a 14.8% increase between 4% and 8% cement.

This result is fully consistent with the scientific literature. Several studies demonstrate that increasing the percentage of cement in stabilized earth bricks leads to an increase in thermal conductivity [11]-[15]. This trend can be explained by two main mechanisms:

1) Densification of the matrix: cement hydration products (hydrated calcium silicates, C-S-H) fill the interstitial voids, reducing porosity and thus the air content (an excellent insulator, $\lambda \approx 0.026$ W/m·K) in favor of a more conductive solid phase [11]-[13].

2) Replacement of laterite: Laterite has lower thermal conductivity than cement hydrates [16], and its proportion decreases from 16% to 12% in formulations F4 through F8.

- Thermal effusivity (*Eff*) increases with the cement content, rising from 1202 to 1328.5 w/m^2·K·S^1/^{2} (+10.5%). Effusivity characterizes a material's ability to exchange heat with its environment under transient conditions. High effusivity indicates greater thermal inertia: the material absorbs more heat during the day and releases it at night.

Furthermore, research on cement-stabilized, compressed earth bricks reports a similar trend, with an increase in effusivity from 800 to 1500 w/m^2·K·S$^{1/2}$ [17]; [18].

- Thermal diffusivity (*D*), which characterizes the rate at which a heat front propagates, increases slightly from 2.53 to 2.71 × 10^{-7} m^2/s (+7.1%). This increase is consistent with the rise in thermal conductivity, which outweighs the slight change in specific heat.

Furthermore, our results are consistent with the values for compressed and stabilized earth bricks, particularly those reported in the studies by [17] and [6], which range from 1.5 to 3 × 10^{-7} m^2/s.

- The specific heat remains virtually constant (1357.76 to 1367.54 J/kg·K) (+0.7%). This increase remains small due to the small variation in cement content (4% to 8%) and the high proportion of clay fraction (60%) in the formulations. A material with high specific heat capacity is equivalent to a material with good thermal inertia capable of improving thermal comfort in buildings. The following parameters influence the increase in specific heat capacity:

a- Densification

An increase in the cement content contributes to the densification of the matrix and to an increase in thermal storage capacity.

b- Mineralogy

Cement hydration products possess significant heat capacity, contributing to a slight increase in specific heat. However, this increase remains moderate due to the relatively low variation in cement content (4% to 8%) and the largely constant clay content (60%).

c- The clay fraction

Clay materials naturally possess high thermal inertia and good heat storage capacity, which limits the increase in specific heat.

Our results are consistent with the findings of [10] [17], who obtained specific heat values ranging from 800 to 1,500 J/kg·K.

- The thermal resistance (R_{th}) decreases from 0.33 to 0.28 m^2·K/W (−15.2%), due to the increase in thermal conductivity λ ($R_{th} = e/\lambda$). A lower thermal resistance indicates poorer insulating performance of the brick.

It should be noted that the thermal resistance R_{th} was calculated for a standard wall thickness of 20 cm, in order to reflect the actual performance of the bricks in a real-world application. This value allows for a comparison of the insulating performance of the different formulations under real construction conditions. Meanwhile, the thermal conductivity λ was measured on an 8 × 5 × 4 cm^3 test specimen—that is, for a thickness of 4 cm—since λ is an intrinsic property of the material.

Furthermore, our results are consistent with those of [17] and [10], which show that cement stabilization of compressed earth bricks improves their mechanical properties but reduces their thermal insulation performance.

4.2. Effect of Cement on Dry Compressive Strength

The results in **Table 7** and **Table 8** show a gradual increase in dry compressive strength as a function of cement content and curing time. This increase in strength between 3 and 28 days is primarily due to the ongoing cement hydration reactions, which lead to the formation of a cementitious matrix (C-S-H) responsible for the densification of the material. Two effects are observed in these results. First, the compressive strength R_c increases with the cement content (R_c 8% > R_c 6% > R_c 4%). Second, the compressive strength R_c increases with curing time (R_c 28 days > R_c 7 days > R_c 3 days).

<u>Analysis of the trend (resistance gain)</u>

Gain from 3 to 28 days (R_c 4% → R_c 8%)

- 4% cement:

  1.78 → 3.51 MPa (+97%)
- 6% cement:

  2.34 → 4.44 MPa (+89.74%)
- 8% cement:

3.03 → 6.08 MPa (+100%)

The material's strength nearly doubles between 3 and 28 days

Overview of Selected Standards and Studies on the Classification of Stabilized Clay Bricks

In the field of stabilized clay bricks, several reference standards are used to classify these bricks based on whether they meet minimum construction requirements and whether they can be used for load-bearing walls (Table 9-11). The following tables summarize these classifications.

Table 9. Classification according to the CraTerre recommendation [37].

Use	Minimum strength
Non-load-bearing wall	2 MPa
Load-bearing wall	4 To 5 MPa

Table 10. Classification based on selected African studies ([37]-[40]).

Types of concrete	Minimum strengths
Simple stabilized concrete	2 MPa
Load-bearing concrete	≥4 MPa
High-performance concrete	≥5 MPa

Table 11. Classification according to the ASTM standard [37].

Classification	Strengths
Low strength	<2 MPa
Medium strength	2 - 4 MPa
High strength	>4 MPa

Changes in the Standards for our cement-stabilized earth bricks

a. Changes Based on Treatment Duration

- **At 3 days**

Formulations	Interpretation
F_1 (4% cement)	Insufficient for structural use
F_2 (6% cement)	Acceptable for light loads
F_3 (8% cement)	Close to code requirements

The cement hydration is still incomplete; therefore, the strengths remain low.

- **At 7 days**

Formulation B (4% cement) has already reached the minimum threshold for several stabilized earth bricks;

- **At 28 days**

All formulations meet the requirements of the standards cited above.

b. Changes Based on Mechanical Strength

Formulations	28-Day strength	Standard classification	Recommended uses
F_1 (4% cement)	3.51	Stabilized earth bricks (medium strength)	Non-load-bearing walls
F_2 (6% cement)	4.44	Load-bearing compressed earth brick	Low-rise houses
F_3 (8% cement)	6.08	high performance compressed earth brick	Load-bearing walls

- All formulations exceed the minimum compressive strength of 2 MPa generally recommended by several standards for stabilized clay bricks;
- The 6% and 8% formulations meet the requirements for bricks used in load-bearing walls;
- The 8% formulation provides very high compressive strength and can be used in sustainable construction.

4.3. Correlation of Thermophysical and Mechanical Properties

Cement	Mechanical effect	Thermal effect
Strength ↑	✓ improvement	
Density ↑	✓ improvement	Conductivity ↑
Isulation ↓		Thermal resistance ↓

Improving mechanical strength comes at the expense of thermal insulation.

5. Conclusion

The experimental study on the influence of cement content on the thermophysical and mechanical properties of compressed earth bricks made from maolonitic and lateritic soils shows that the cement content has a significant influence on the thermophysical and mechanical performance of the bricks. Indeed, the incorporation of cement into compressed earth bricks increases compressive strength while simultaneously increasing thermal conductivity and reducing insulating properties. However, all the brick formulations tested exceed the minimum threshold of 2 MPa, which is generally recommended by several standards for stabilized earth bricks. The 6% and 8% stabilized formulations meet the requirements for bricks used in load-bearing walls. The 8% formulation provides very high compressive strength and can be used insustainable construction.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Brambilla, A. and Jusselme, T. (2017) Preventing Overheating in Offices through Thermal Inertial Properties of Compressed Earth Bricks: A Study on a Real Scale Prototype. *Energy and Buildings*, **156**, 281-292. https://doi.org/10.1016/j.enbuild.2017.09.070

[2] Meukam, P. (2004) Utilization of Stabilized Soil for Thermal Insulation in Buildings. Ph.D. Thesis, University of Yaoundé I, 140 p.

[3] Collet, F., Serres, L., Miriel, J. and Bart, M. (2006) Study of Thermal Behaviour of Clay Wall Facing South. *Building and Environment*, **41**, 307-315. https://doi.org/10.1016/j.buildenv.2005.01.024

[4] Soudani, L., Woloszyn, M., Fabbri, A., Morel, J. and Grillet, A. (2017) Energy Evaluation of Rammed Earth Walls Using Long Term *In-Situ* Measurements. *Solar Energy*, **141**, 70-80. https://doi.org/10.1016/j.solener.2016.11.002

[5] Taylor, P. and Luther, M.B. (2004) Evaluating Rammed Earth Walls: A Case Study. *Solar Energy*, **76**, 79-84. https://doi.org/10.1016/j.solener.2003.08.026

[6] Zhang, L., Gustavsen, A., Jelle, B.P., Yang, L., Gao, T. and Wang, Y. (2017) Thermal Conductivity of Cement Stabilized Earth Blocks. *Construction and Building Materials*, **151**, 504-511. https://doi.org/10.1016/j.conbuildmat.2017.06.047

[7] Turco, C., Paula Junior, A.C., Teixeira, E.R. and Mateus, R. (2021) Optimisation of Compressed Earth Blocks (CEBs) Using Natural Origin Materials: A Systematic Literature Review. *Construction and Building Materials*, **309**, Article ID: 125140. https://doi.org/10.1016/j.conbuildmat.2021.125140

[8] Walker, P., Keable, R., Martin, J. and Maniatidis, V. (2005) Rammed Earth: Design and Construction Guidelines. BRE Bookshop.

[9] Camara, M., Vianou, A. and Keita, M. (2005) Mesure de la conductivité termique de la boue rouge stabilisée au ciment et à l'argile. *Journal des Sciences Pour l'Ingénieur*, **5**, 40-45. https://doi.org/10.4314/jspi.v5i1.30018

[10] Cagnon, H., Aubert, J.E., Coutand, M. and Magniont, C. (2014) Hygrothermal Properties of Earth Bricks. *Energy and Buildings*, **80**, 208-217. https://doi.org/10.1016/j.enbuild.2014.05.024

[11] Nshimiyimana, P., Messan, A. and Courard, L. (2020) Physico-Mechanical and Hygro-Thermal Properties of Compressed Earth Blocks Stabilized with Industrial and Agro by-Product Binders. *Materials*, **13**, Article 3769. https://doi.org/10.3390/ma13173769

[12] Ouedraogo, M., Dao, K., Millogo, Y., Aubert, J., Messan, A., Seynou, M., *et al.* (2019) Physical, Thermal and Mechanical Properties of Adobes Stabilized with Fonio (Digitaria Exilis) Straw. *Journal of Building Engineering*, **23**, 250-258. https://doi.org/10.1016/j.jobe.2019.02.005

[13] Boffoue, M.O., Kouadio, K.C., Kouakou, C.H., Assande, A.A., Dauscher, A., Lenoir, B. and Emeruwa, E. (2015) Effect of Cement Content on the Thermo-Mechanical Properties of Compressed and Stabilized Clay Blocks. *Afrique Science*, **11**, 35-43.

[14] Adam, E.A. and Agib, A.R.A. (2001) Compressed Stabilised Earth Block Manufacture in Sudan. The United Nations Educational, Scientific and Cultural Organization, UNESCO, 11 p.

[15] Bakari, R., Samaouali, A., Kanibou, F., Ouaazizi, K. and Arbaoui, A. (2025) Temperature and Cement Content Effect on Thermophysical Properties of Compressed White Earth Bricks. *Emergent Materials*, **8**, 3301-3312. https://doi.org/10.1007/s42247-025-01022-x

[16] Zakham, N., El Rhaffari, Y., Ammari, A., Cherraj, M., Bouabid, H., Gueraoui, K., *et al.* (2018) Influence of Cement Content on the Thermal Properties of Compressed Earth Blocks (CEB) in the Dry State. *MATEC Web of Conferences*, **149**, Article ID: 01059. https://doi.org/10.1051/matecconf/201814901059

[17] Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C. and Bertron, A. (2016) Earth-Based Materials for Construction: An Insight on Mechanical Properties and Durability. *Construction and Building Materials*, **102**, 170-180.

[18] Khoukhi, M. (2018) The Combined Effect of Heat and Moisture Transfer Dependent Thermal Conductivity of Polystyrene Insulation Material: Impact on Building Energy Performance. *Energy and Buildings*, **169**, 228-235. https://doi.org/10.1016/j.enbuild.2018.03.055

[19] Alavéz-Ramírez, R., Montes-García, P., Martínez-Reyes, J., Altamirano-Juárez, D.C. and Gochi-Ponce, Y. (2012) The Use of Sugarcane Bagasse Ash and Lime to Improve the Durability and Mechanical Properties of Compacted Soil Blocks. *Construction and Building Materials*, **34**, 296-305. https://doi.org/10.1016/j.conbuildmat.2012.02.072

[20] Morel, J., Pkla, A. and Walker, P. (2007) Compressive Strength Testing of Compressed Earth Blocks. *Construction and Building Materials*, **21**, 303-309. https://doi.org/10.1016/j.conbuildmat.2005.08.021

[21] Bahar, R., Benazzoug, M. and Kenai, S. (2004) Performance of Compacted Cement-Stabilised Soil. *Cement and Concrete Composites*, **26**, 811-820. https://doi.org/10.1016/j.cemconcomp.2004.01.003

[22] Taallah, B. (2014) Study of the Physical and Mechanical Behavior of Compressed Earth Blocks Reinforced with Fibers. Ph.D. Thesis, Université Mohamed Khider Biskra, 202 p.

[23] Karka, B.R., Ouinra, K. and Fulbert, T.N. (2020) Comparative Study of the Mechanical Characteristics of Sand Mortar and Compressed Lateritic Bricks Stabilized with Cement. *International Journal of Innovation and Applied Studies*, **28**, 438-451.

[24] PUR, Urban Master Plan for the City of Moundou (2011) Urban Development Support Project (PADUR). Ministry of Land Use Planning, Urban Planning, and Housing of Chad, STUDI International, 65 p.

[25] NF P11-300 (1992) Classification of Materials for Use in the Construction of Embankments and Subgrades for Road Infrastructure. AFNOR, 21 p.

[26] Casagrande, A. (1932) Research on the Atterberg Limits of Soils. *Public Roads*, **13**, 121-136.

[27] ASTM D2487 (1998) Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Society for Testing and Materials, 10 p.

[28] NF XP P 13-901 (2001) Compressed Earth Blocks for Walls and Partitions. Nor 01. French Standards Association, AFNOR, 35 p.

[29] NF P 94-064 (1993) Identification and Testing: Dry Density of a Rock Sample-Hydrostatic Weighing Method. AFNOR, 6 p.

[30] ASTM D5930 (1997) Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique. ASTM, 5 p.

[31] Aghahadi, M. (2019) Experimental Study and Physical Modeling of Coupled Heat and Moisture Transfer in a Bio-Based Insulation Material. Ph.D. Thesis, University of Bourgogne Franche-Comté, 147 p.

[32] Abakar, A. (2018) Mechanical and Thermal Characterization of Clay Stabilized with

Gum Arabic and Reinforced with Rice Straw. Ph.D. Thesis, University of Lorraine, 204 p.

[33] El Fgaier, F. (2013) Design, Production, and Qualification of Fired and Unfired Clay Bricks. Ph.D. Thesis, Ecole Centrale de Lille, 121 p.

[34] Sophie, C. (2018) Experimental and Numerical Study of Solutions Based on Eco-Materials for the Thermal Renovation of Urban Built Heritage. Ph.D. Thesis, University of Toulouse, 166 p.

[35] Walker, P.J. (2000) Strength and Durability Testing of Earth Blocks. 6*th International Seminar on Structural Masonry for Developing Countries*, Bangalore, October 2000, 110-118.

[36] NF EN 12390-3 (2003) Part 3. Compressive Strength of Test Specimens, AFNOR, 17 p.

[37] Zakaria, M.M., Karka, B.R., Moungache, A., Barka, M. and Halawlaw, Y.I. (2025) Combined Litho- and Cement Stabilization of Earth Bricks: Experimental Study of Compressive Strength. *Open Journal of Applied Sciences*, **15**, 2344-2359. https://doi.org/10.4236/ojapps.2025.158157

[38] Raheem, A.A., Bello, O.A. and Makinde, O.A. (2010) A Comparative Study of Cement and Lime Stabilized Lateritic Interlocking Blocks. *The Pacific Journal of Science and Technology*, **11**, 27-34. http://www.akamaiuniversity.us/PJST.htm

[39] Chinenye E, O. (2020) Strength Property of Laterite Blocks Made with Different Pozzolanic Materials. *NIPES Journal of Science and Technology Research*, **2**, 152-157. https://doi.org/10.37933/nipes/2.2.2020.15

[40] Wade, M., Thiam, M., Ba, M. and Ndiaye, M. (2025) Influence of Sand on the Mechanical Strengths of Compressed Earth Blocks Based on Sindia Laterite Stabilized with Cement. *American Journal of Civil Engineering and Architecture*, **13**, 1-4. https://doi.org/10.12691/ajcea-13-1-1