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Research Article

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Thermophysical properties of Balkuy clay associated with slaked lime to improve the energy efficiency of buildings in the Sahelian zone

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Abstract As part of sustainable buildings' construction and the valorization of local building materials, clay can be stabilized by adding small mass percentages of lime, thus improving some of its properties. Clay from the Balkuy deposit was used to illustrate these improvements. We firstly studied the particle granulometry and Atterberg limits, which both meet the criteria for good lime stabilization. Among other important results, we note that the variation of the mechanical resistance as a function of the lime rate shows a maximum of 2.72 MPa at 6% lime, which proves that this material can be interesting from a mechanical point of view. On the other hand, thermal conductivity has a minimum value of 0.42 W.m-1.K-1 at 6% lime. It appears from these results that the optimal dosage of lime is 6%. Lime stabilization meets mechanical and thermal specifications from a sustainable development perspective.

Keywords Clay, Lime, Stabilization, Compressive strength, Conductivity

Nomenclature
Symbols:
Latin letters:
A: Surface area (m^2)
C: Heat loss constant ($W.K^{-1}$)
C : Mass capacity, ($J.kg^{-1}.K^{-1}$)
e: Thickness (m)
IP: Plasticity index (%)
P: Maximum crushing load (N)
$\dot{Q}$: Heat flux (W)
$\dot{Q}_1$: Power dissipated by Joule effect in the heating resistor (W)
$\dot{Q}_2$: Lateral losses between the inside of box B, temperature T_B, and the outside environment, temperature T_A (W)
R : Electrical resistance (Ω)
Rc: Compressive strength (Pa)
S: Compressive area (m^2)
T : Temperature (K)
t : Time (s)
V : Electrical voltage (V)

WL: Liquid limit (%)
WP: Plasticity limit (%)
λ : Thermal conductivity, (W.m^{-1}.K^{-1})
ρ : Density (kg.m-3)

1. Introduction

The history of soil stabilization for the improvement of construction works of buildings and roads is quite long. In developing countries, the high cost of these materials represents a serious handicap for the sustainable construction of these infrastructures.

Several studies [1-2] have shown that each type of soil has its own stabilizer. Cement compared to sand is a better stabilizer than the latter. Sand, in addition to its high purchase price, is often transported to the construction site, thereby increasing costs.

However, clay is abundant in the earth's crust, particularly in Burkina Faso, and one of its best stabilizers is lime. For the construction of buildings, the use of clays stabilized with lime has proven to be a competitive and sustainable solution. Our study focuses on the lime stabilization of Baskuy clay (located in Ouagadougou) as a construction material. The choice of this clay is based on its known chemical composition [3]. The use of such a material in the buildings' construction requires a thermomechanical study because a building must offer its occupants good safety and thermal comfort. Earth construction has attracted the interest of several researchers [4-5].

It can be stabilized in various ways (binder, mineral or vegetable matter, etc.). According to [6], as soon as clay is mixed with lime, two phenomena always occur: firstly, its plasticity decreases and the clay becomes more manageable; and secondly, the lime reacts with the aluminas and silicas of the laterite. The compressive strength is highest between 5 and 6%, with a value of 3.7 MPa. F. G. Bell [7] also noted in his study that all clays react with lime at an optimal dosage of about 4 %. Some such as quartz (4 MPa) are suitable for stabilization, while montmorillonite (0.8 MPa) and kaolinite (1.5 Pa) perform less well. Part of the laterite is stabilized with cement (8%) to reach 2.5 MPa [8], a value already sufficient for the compressive strength of the walls.

Our study focuses on the mass production of lime-stabilized earth bricks with high mechanical and thermal performance. This contributes to the valorization of local construction materials. To achieve this, we first formulated the stabilization in accordance with the state of the art, then presented the mechanical and thermal measurement methods.

2. Study methodology

Samples for mechanical and thermal testing will have characteristics that depend directly on the formulations developed.

2.1 Formulation

Most clays have a fixation point between 1 and 3%, point above which the material can be stabilized [9]. A complementary study on dosage proportions was carried out by Ingle [10], who found that the correct mass dosage of lime is 1% compared to that of clay grains. When 1% quicklime is added to the soil, the exothermic hydration reaction dries the soil, removing approximately 0.5 to 1 % of water, while adding 2 to 3 % quicklime immediately reduces the plasticity of the soil and destroys clods: this reaction is known as the limestone fixation point [11]. Beyond this dose, the compressive strength can considerably increase. For this reason and for mechanical and thermal test purposes, we used doses of 0 to 10 % of lime, in steps of 2 with respect to the mass of dry clay. All samples are shade cured within 28 days to avoid rapid shrinkage, which may lead to cracking.

2.2 Principle of mechanical measurement

Before designing a structure, it is necessary to know how it will respond to the different mechanical constraints that will be applied to it, such as compressive, tensile constraints, etc. Materials based on lime-stabilized mortar will be used for the partitions and possibly the load-bearing walls; the latter will be essentially subjected to compressive resistance, the bricks being superimposed on one another.

2.2.1. Compressive strength test principle

Compressive strength is measured by the axial compression of a straight cylinder of revolution of section S and height twice the diameter (Fig. 1).

Figure 1: Compressive strength test

$$R_c = \frac{P}{S} \qquad (1)$$

The specimens measure 4×4×16 cm3. The measurement is carried out on 3 test pieces and the curing time is 28 days. We then take the arithmetic average of the three values, which allows us to estimate the compressive strength (Rc) given by equation (1).

2.2.2. Description of measurement and equipment used

The testing device is a hydraulic press meeting the requirements of the ASTM E4 standard, Verification of Testing Machines. The test is performed according to Canadian standard CAN-A23.2-M77, paragraph A23.2-9C. The test pieces are removed from the curing place shortly before the test. They are then centered between the press plates and loaded continuously at an average speed of 5 kN/s. With the maximum load (P) applied, we determine the compressive strength.

2.3 Thermal conductivity measurement method

Measuring the thermophysical properties of materials used in building construction is of great importance for thermal comfort. Thermal conductivity is one of the most important parameters.

2.3.1. Device description

The EI700 measuring cell (Fig. 2.) is composed of the following elements [12]:

- An isothermal capacity (A) with external dimensions of 200x100x50 cm3. At its base it contains an exchanger which is supplied by a fluid (glycol water) whose temperature is regulated by a cryostat (K). This capacity plays the role of the cold environment.
- Two identical and independent measuring boxes (B) in styrodur, allowing simultaneous measurements. Each of the boxes is provided with a heating film on the internal part of its upper face and has an open face. The interior of each box plays the role of hot environment. The heating element is a resistor cut from a flexel film, supplied with current by a variable autotransformer. The power output is determined by measuring the potential difference across the resistor and its value.
- The sample (E), with a parallelepipedic shape of 27 cm side and variable thickness of 4 to 7 cm, is placed between the two environments.
- The temperature sensors are placed on both sides of the sample, in the atmosphere of the box and in the experimental room.
- All the wiring for the temperature sensors and the power supply to the heating element leads to a terminal block which can be linked either to a datalogger or to a recorder connected to a computer.

2.3.2. Measurement of thermal conductivity

To measure this quantity, we used the box method, which consists of subjecting the sample to a heat flow and subsequently measuring either a temperature profile or a radial flow. When the steady state is established, the heat flux passing through the sample can be written as:

$$\dot{Q} = \frac{\lambda}{e}(T_C - T_F)A \;=\; \dot{Q}_1 - \dot{Q}_2 \qquad (2)$$

$$\dot{Q}_1 = \frac{V^2}{R} \tag{3}$$

$$\dot{Q}_2 = C(T_B - T_A) \tag{4}$$

Conductivity can be deduced from equality (3-4) by $\lambda = \frac{e}{A(T_C - T_F)}\left[\frac{V^2}{R} - C(T_B - T_A)\right]$ (5)

Thermal conductivity is determined by the average value: $T_m = \frac{(T_C + T_F)}{2}$

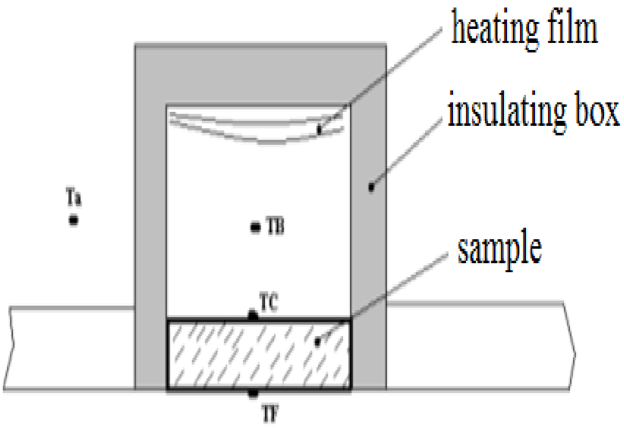

Figure 2: Principle of thermal conductivity measurement

2.3.3. Determining the cell constant C

The constant C can be determined experimentally in two different ways:

- By choosing a reference sample whose thermal conductivity and dimensions are known. At equilibrium, we evaluate C by the relation (6).

We obtain: $$C = \frac{1}{(T_B - T_A)}\left[\frac{V^2}{R} - \frac{\lambda A}{e}(T_C - T_F)\right] \tag{6}$$

- By taking a sample of unknown thermal conductivity (thermal insulator), then studying their two equilibria.

By making two conductivity measurements with two different flows and,

We will obtain: $$\frac{1}{(T_C - T_F)_3}\left[\frac{V_3}{R} - c(T_B - T_A)_3\right] = \frac{1}{(T_C - T_F)_4}\left[\frac{V_4}{R} - c(T_B - T_A)\right] \tag{7}$$

Indices 3 and 4 correspond to the first and second measurements, respectively.

All quantities in this equation can be measured experimentally, so the constant C can be derived from equation (6). The choice of this method is based on the fact that it is available in our working laboratory and that their precision is comparable to that of other methods. This method will also allow us to present some mechanical and thermal experimental results.

3. Experimental results

3.1 Geotechnical results

3.1.1. Chemical results

Table 1: Chemical results for Balkuy clay [3].

Clay	61.10	19.45	5.15	0.02	0.95	0.75	0.55	1.85	0.85	0.08	9.95
Dosed Oxides (%)	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	P.F.

We note that Balkuy clay has a fairly high percentage of silicon and aluminum oxides (80.55%). This result already shows that, from a chemical point of view, Balkuy clay is well suited for lime stabilization.

3.1.2. Granulometric results

Figure 4 shows the particle size results for Balkuy clay.

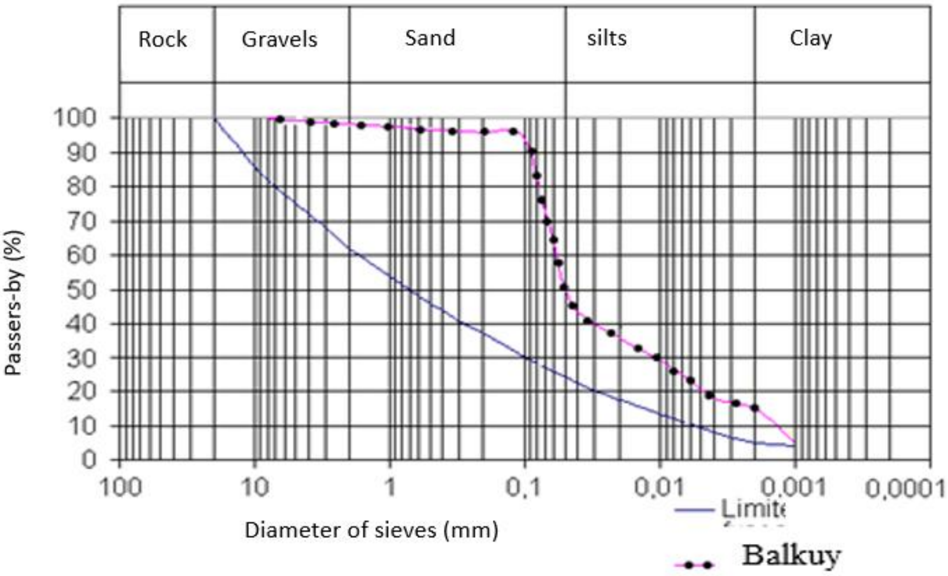

Figure 3: Granularity of Balkuy clays

Figure 4 shows that the clay is contained within the grain size spindle. It is practically parallel to the spindle boundary curve at the level of the silts. This curve shows that, from a particle size point of view, this clay can be stabilized with lime. However, the particle size condition, while necessary, is not sufficient to ensure that the clay can be lime-stabilized. It is thus necessary to check the plasticity condition.

3.1.3. Plasticity results

Table 2 shows the results of the Atterberg limits.

Table 2: Atterberg limits of Balkuy clay

Clay	**Liquidity Limit WL (%)**	**Plasticity Limit W_P (%)**	**Plasticity Index: PI (%) $I_P = W_L - W_P$**
Baskuy	52	20	32

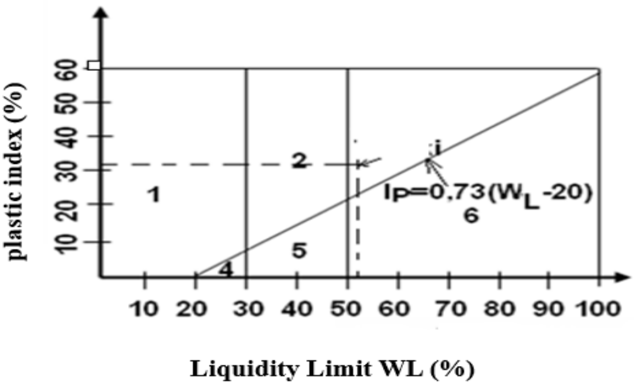

Figure 4: Casagrande diagram

We note that the Balkuy clay is located in the zone of mineral clays with high plasticity, suitable for lime stabilization. It should be remembered that organic matter is detrimental to stabilization in general and to stabilization by lime in particular [13, 14]. This clay meets all the necessary conditions for lime stabilization for good mechanical strength.

3.2. Mechanical results

For mechanical tests purpose, we prepared test specimens measuring 4x4x16 cm3 with a mass percentage of lime from 0 to 10% (in steps of 2). For each dosage we prepared 3 test tubes. This result confirms what we saw in the Casagrande diagram.

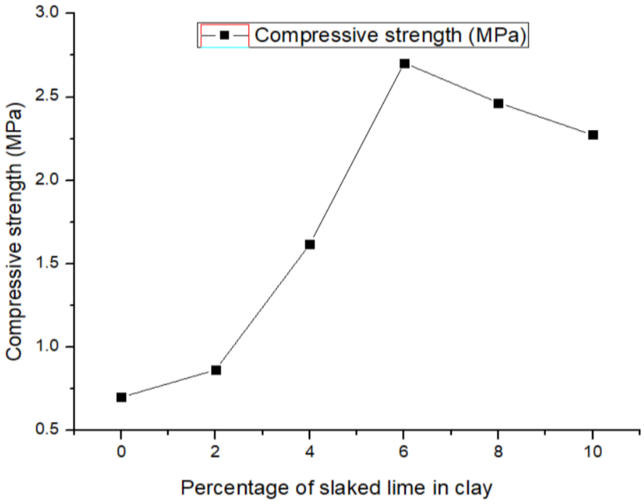

Figure 5: Compressive strength as a function of the percentage of lime at 28 days

It can be seen that the compressive strength increases significantly up to 6%. Above this value, any reduction in the mass of clay in favor of that of lime results in a slight drop in strength. This type of variation has already been noted in the literature, notably by F.G. BELL [7]. The increase in compressive strength between 0 and 6% is due to the increase in the potential for exchangeable calcium cations provided by the lime. The slight decrease in compressive strength could be due to the reduction in cohesion and plasticity of the clay under the effect of lime. The highest compressive strength is obtained at 6% and is of the order of 2.736 MPa, or 4 times higher than the initial clay which is 0.702 MPa. Additionally, the minimum Swiss standard requirement for a brick in a single-story load-bearing wall is 1.830 MPa for compressive strength. We have compressive strength much higher than the target value, so our material can be used not only in partition walls, but also in load-bearing walls. On the other hand, the cement bricks used in the wall mass have a compressive strength of between 3 and 6 MPa [15]. The first building safety criterion is met by the use of this lime-stabilized material.

3.3. Thermal performance

The thermal aspect is becoming increasingly important in the building's construction, as energy consumption to ensure thermal comfort depends on it.

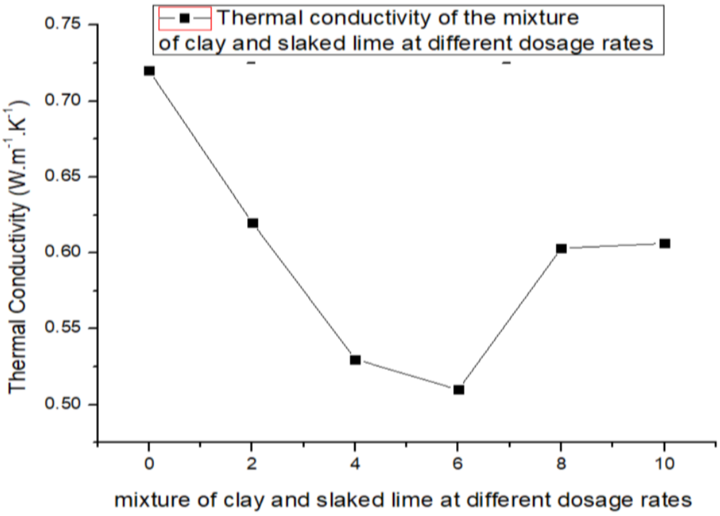

Figure 6: Thermal conductivity as a function of the percentage of lime

We note that the thermal conductivity drops from 0.72 W.m^{-1}.K^{-1} to more or less 0.46 W.m^{-1}.K^{-1} depending on the percentage of lime used. The evolution of thermal conductivity follows the opposite direction to that of compressive strength. The drop in conductivity is due to the hydration of the lime, which dries the mortar by reducing the mass of water. The volume of air increases and since air is more insulating than water, conductivity decreases. According to the thermal regulations of 2000, concrete has a thermal conductivity of around 1.25 W.m^{-1}.K^{-1}.

Our values are below these, and the value that interests us most is the optimal value of 0.42 W.m^{-1}.K^{-1}. This becomes very interesting because we took into account mechanical and thermal aspects in our study.

4. Conclusion

The aim of our study was to investigate the thermomechanical characteristics of lime-stabilised earth used in building construction.

The first result concerns the criteria for suitability for lime stabilization. Through granulometric and plasticity studies, we showed that the soil used met the stabilization criteria. With quicklime, we increased the mechanical compressive strength of the earth from 702 kPa to 2736 kPa corresponding to 6% lime. This initial resistance is almost quadrupled at 6% by weight of lime. This geo-concrete can be used both in partition walls and in the load-bearing walls of single-storey buildings.

Thermal conductivity, the most important thermophysical quantity, decreased from 0.72 W/m. K to 0.42 W/m.K., proof that energy consumption to ensure thermal comfort can be reduced. With the significant inertia of the walls, this material makes it possible to create bioclimatic architecture. Since the lime-stabilized earth bricks are not cooked but dried in the sun, we avoid fuel consumption, in addition to the material that can be recovered on site, we save fossil energy. The improvement in compressive strength and conductivity through lime, in addition to its competitive price, shows that it is in our interest to use this material. Modern construction standards can be applied to this type of material.

Today we are experiencing systematic stabilization with cement which, certainly, offers good safety, but is expensive and the comfort that this stabilization offers needs to be improved. This is why it is necessary to carry out studies to identify suitable soils for different stabilizers in general and lime in particular. In our next study, we will determine the impact of lime-stabilized earth on the energy consumed using a dynamic simulation tool (EnergyPlus).

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