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An Experimental Study to Evaluate the Properties of a Clayey Silt Treated with Lime for the Manufacture of Mud Bricks

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This work involved evaluating the properties of *Cubitermes* sp termite mound soil treated with 3 - 9% lime for the manufacture of adobe mud bricks and compressed earth bricks CEBs. X-Ray Diffraction and other geotechnical methods for soil characterisation were used to analyse the selected material samples. The results show that the soil is a class A-2 clayey silt with a low organic content, composed of 19.18% clay, 47.20% silt and a sand content of 23.62%. The addition of lime reduces the clay and silt content, while the sand content increases and improves the granulometry, which incorporates spindles (adobes and CEBs) with lime contents ranging from 5%

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to 9%. The clay content of both the raw soil and the mixes is below the 30% maximum, while the sand content of the mixes is above the 30% minimum permitted by most standards. The specific surface area SSA and cation exchange capacity CEC decrease with the addition of lime, and the mechanical properties of the material improve. Raw soil and mixes have good moulding properties and a compressive strength of CS (3.89 - 5.95 MPa) suitable for the manufacture of adobe bricks and CEBs. The microstructure shows that the soil in the *Cubitermes sp* termite mound is composed of kaolinite, illite, smectite, quartz, calcite and iron oxide (haematite). Kaolinite is important for making solid bricks and illite helps the soil to sinter at a relatively low temperature.

Keywords: Earth bricks; Cubitermes sp termite mound soil; adobes; clay; granulometry.

1. INTRODUCTION

Earth has been the most widely used material for building sustainable, cost-effective homes for thousands of years in countries around the world, taking advantage of its abundant availability. Even today, 2/3 of buildings in Africa, Asia and the Middle East are made of earth, and 1/3 of the world's population lives in them [1,2]. For earth houses to last, the physical characteristics of earth bricks, such as strength and durability, must be respected. Buildings using local materials cost around 20% less than other permanent structures, and can be more aesthetically pleasing and better adapted to the climate [3]. With a global housing deficit looming, with one in four people lacking access to adequate and appropriate housing [4], there is an urgent need for an affordable solution. In Africa south of the Sahara, in rural areas with sandy savannahs, earth from termite mounds is used as a building material. However, in large cities, mud bricks have all but disappeared from the new-build sector in favour of modern materials (cement blocks, reinforced concrete foundations). Moreover, the production of these conventional building materials contributes to environmental problems such as resource depletion and environmental degradation, and consumes a lot of resources and energy [4]. For example, the manufacture of compressed earth blocks (CEBs) reduces greenhouse gas emissions compared with fired clay bricks or cement concrete blocks. This type of construction is considered to be more solid and easier to install and maintain [5,6], but it is noted that air humidity is not evenly distributed [3]. Developed countries over the last century have replaced conventional earth construction with modern materials. Today, these countries are interested in earth materials because of their economic, social and environmental advantages. Indeed, there is renewed interest in earth construction, particularly in the context of sustainable development, due to climate change and the depletion of natural resources. The texture, mineralogy and structure of the soil, as well as its porosity, are essential elements in the behaviour of earth bricks in relation to air humidity and the direct action of rain [7]. However, one of the main limitations of rammed earth is its inherent lack of strength and durability. As the earth is not watertight, the house needs a good stone foundation to prevent the bricks from crumbling underneath. The stone base protects the walls from rainwater. Next, the roof must be laid with a wide overhang to keep run-off water away, so that the bricks can be laid from the inside, protecting them from the main cause of deterioration, i.e. water [8]. The large-scale use of compressed earth blocks (CEBs) as a building material is justified for reasons of ecology, fire resistance, local availability, cost-effectiveness and increasingly popular durability. To achieve this, it is necessary to take into account not only the technical requirements and direct cost of construction, but also the environmental and social impacts. In this context, the use of local non-conventional recycled or natural materials remains a topical issue [9]. In order to use the soil from cubitermes sp termite mounds to make bricks, it is first necessary to determine its geotechnical and mineralogical properties and its interaction with the local environment. In sandy savannahs, where the soil of cubitermes sp termites is the only building material available, the question arises as to whether it can be used on a large scale to make mud bricks. In other words, are the geotechnical characteristics of this soil suitable for the manufacture of compressed earth bricks or adobes ? If not, propose an alternative solution to the widespread use of cubitermes sp termite mound soils for the manufacture of adobe or compressed earth bricks. Several studies have shown, among other things, that the hardness, strength and bearing capacity of soils can be improved by using hydraulic binders [10,11,12]. However, hydrated lime is the least harmful binder for personnel and the environment, the least costly for construction and the most effective for treating fine soils, compared with cement. Despite the diversity of studies on the manufacture of bricks treated with hydraulic binders, they have not exhausted the subject. It will always be important to carry out the necessary tests for each soil-binder combination [13]. To our knowledge, the manufacture of bricks from cubitermes sp termite mound earth, whether raw or treated with hydraulic binders, has not yet been reported. The aim of this work is to characterise the soil from the cubitermes sp termite mound with a view to its use in the manufacture of raw earth bricks (adobes and CEB) and, if the material does not meet current standards, to improve the mechanical properties of the soil by adding a hydraulic binder. To do this, the mineralogy, geotechnical properties, specific surface area and cation exchange capacity of the raw soil and the mixtures will be determined.

2. MATERIALS AND METHODOLOGY

The soil of the cubiterme sp termite mound was sampled on the Ngo - Mpouya road, in the Plateaux department, Republic of Congo, following the geographical coordinates 150 45' E and 20 29' S. The lime used was Pascal "CL 90-S" hydrated lime, purchased on a local market.

The soil-lime mixture was made by mixing the chosen proportions of lime (3%, 5%, 6%, 7% and 9%) with the soil until a homogeneous mixture was obtained. The tests were carried out in accordance with current standards. The granulometric distribution (grain size) and sedimentation of the soil for grains smaller than 80 µm were determined in accordance with the respective standards NF P94-056 [14] and NF P94-057 [15]. The particle size fraction is deduced from the recommendations of the particle size nomograms, which consider clays as particles smaller than <0.002 mm, silt 0.002-0.06 mm and sand 0.06-2 mm. The plasticity of the soil was estimated using the Atterberg limits (plasticity limit, liquidity limit and plasticity index) determined in accordance with standard NF P 94-051 [16] and the SBV soil blue value in accordance with standard NF P94-068 [17]. Soil activity is defined as the ratio between the plasticity index PI and the clay fraction CF < 0.002 mm, and is used to help distinguish the different minerals contained in natural soil (Ac = PI/CF). Specific surface area (SSA) and cation exchange capacity (CEC) are fundamental properties that dominate the behavior of fine soils, and are defined by the respective formulae SSA(m2/g) = 20.93*SBV, CEC (meq/100g) = SBV*1000/374). The maximum dry density, which is an indication of brick strength, and the optimum water content for brick manufacture were determined using the modified Proctor test in accordance with standard NF P94-093[18]. The results of the laboratory tests were analyzed on the basis of AFNOR standards and technical documents reported by Delgado M. C. J., Guerrero J. C., 2007 [19].

Fig. 1. The cubiterme sp termite mound soil

Table 1. Standards and technical documents according to particle size fraction (clay, silt, sand) for the manufacture of adobes and CEB

Technical	Documents	Clay	Silt	Sand
Adobe	NTE E 080 (2000) [20]	10 -20	15 – 25	55 - 70
Adobe, CEB	Smith et Austin [21]	4–15	40	60–80

Table 2. Normative recommendations and technical documents on the manufacture of Adobe and CEB according to the liquidity limit and plasticity index

Technical	Documents	Liquidity limit (LL)	Plasticity index (PI)
Adobe	Houben et Guillaud [22]	31 - 50	16 - 33
Compressed	Houben et Guillaud [22]	25 - 51	2 - 31
earth blocks	ARSO (1996) [23]	25 - 50	2,5 - 29
(CEBs)	XP P 13-901 (2001) [24]	25 - 50	2,5 - 29

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Identification of raw cubitermes sp termite mound soil and mixtures

In order to improve the particle size distribution to within the normative ranges, the soil from the *Cubitermes* sp termite mound was treated with lime. The particle size curves of the mixtures showed very marked improvements, sensitive to particle size for all modifier contents for a curing time of 48 hours. The sand, silt and clay contents deduced from these curves are shown in Table 1. However, for use in adobe and CEB, the standards recommend an average clay content of CF (10 - 30%) and a sand content of at least 30%.

According to Houben and Guillaud (1989) [1], raw soil and mixes are suitable for the manufacture of adobe bricks on the basis of their liquidity limit LL (31-50%) and plasticity index PI (16-33%). However, for the manufacture of CEBs, all the normative documents specify the liquidity limits LL (25-50%) and the plasticity index PI (2-30%).

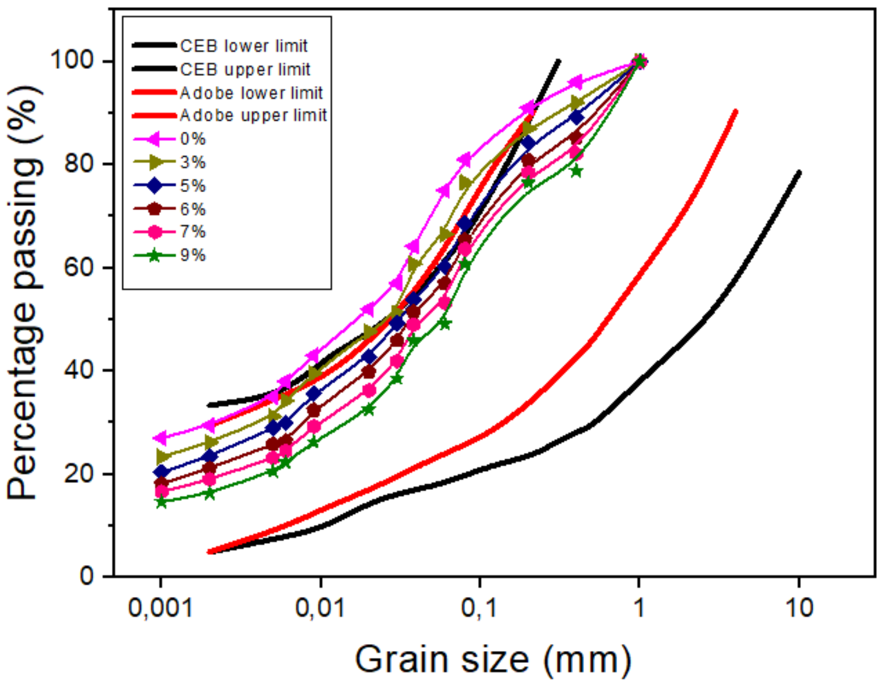

Fig. 2. Sieve size curves for raw soil and mixes with 3%, 5%, 6%, 7% and 9% lime, based on the normative ranges for Adobes and compressed earth bricks (CEB) [19]

Table 3. Properties of raw soil and mixtures

Lime (%)	CF (%)	SiF (%)	SaF (%)	LL (%)	PL (%)	PI (%)	MDD T/m^3	OMC (%)	SBV (%)	Ac	SSA (m^2/g)	CEC (meq/100g)
0	29.45	45,12	25,43	36.20	18.44	17.76	1,62	20	0.5	0.603	3.09	1.337
3	26.14	40,39	33.47	35.75	18.83	16.92	1,6	21,5	0.37	0.647	2.09	0.989
5	23.45	36,98	39,57	35.55	18.95	16.6	1,55	21,98	0.33	0.708	1.63	0.882
6	21.14	36,28	42,58	35.44	19.06	16.38	1,5	22,1	0.29	0.775	1.29	0.775
7	18.78	35.4	45,82	35.4	19.10	16.3	1,458	24,5	0.28	0.824	1.16	0.749
9	16.29	33,55	50,16	35.25	19.15	16.1	1,36	24,8	0.25	0.988	0.91	0.668

CF – Clay fraction, LL – Liquidity limit, PL - Plasticity limit, PI - Plasticity index, SBV – soil blue value, SSA - specific surface area, CEC – Cation exchange capacity, Ac - activity, MDD - maximum dry density, OMC - optimum moisture conte

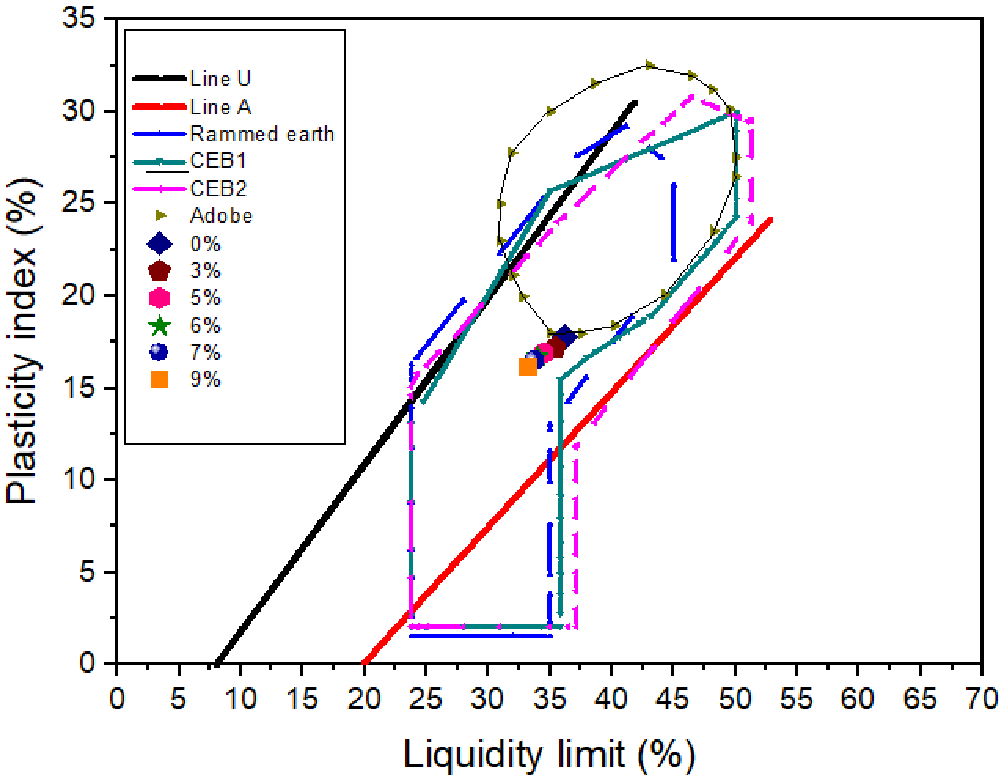

Fig. 3. Atterberg soil limits with recommended ranges for adobe and CEB according to delgado M.C.J., Guerrero I.C. 2007 [19]

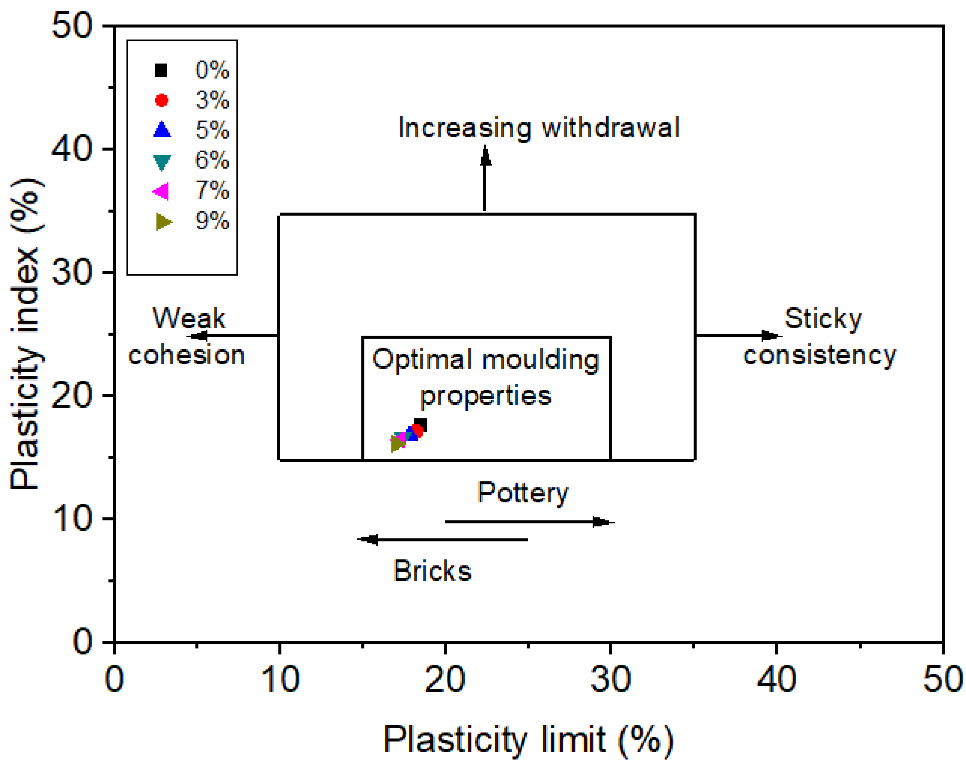

Fig. 4. Casagrande plasticity diagram showing the moulding properties of soils as a function of their Atterberg limit

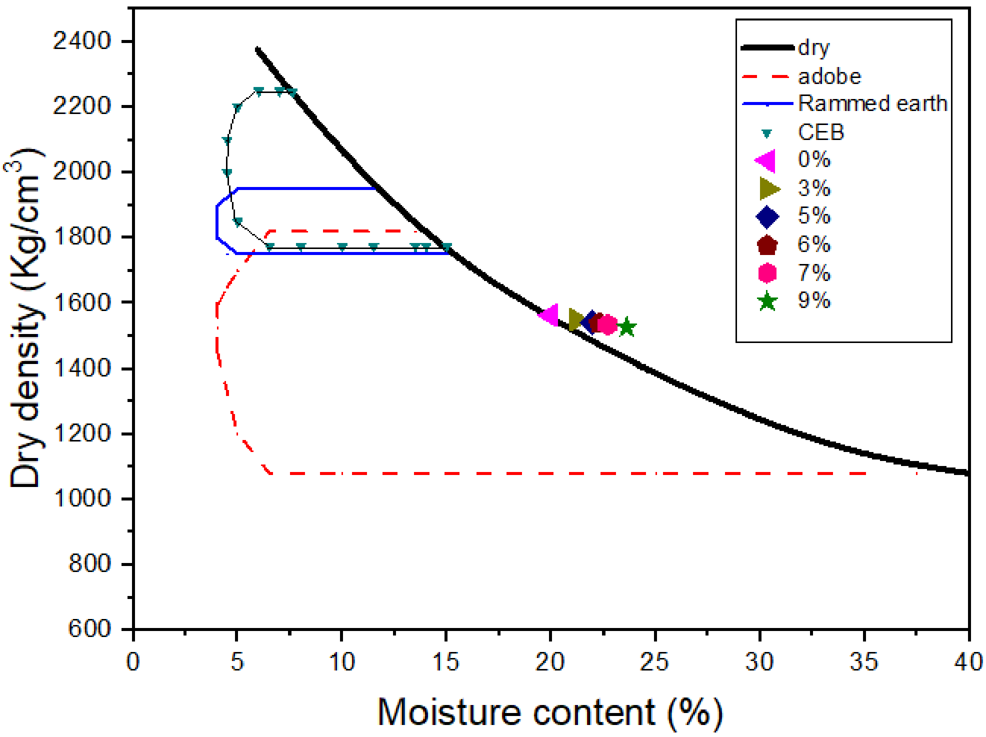

Fig. 5. Dry density based on optimum soil moisture content and recommended surfaces for CEB, Rammed earth and Adobe according to Delgado M.C.J., Guerrero I.C. 2007 [19].

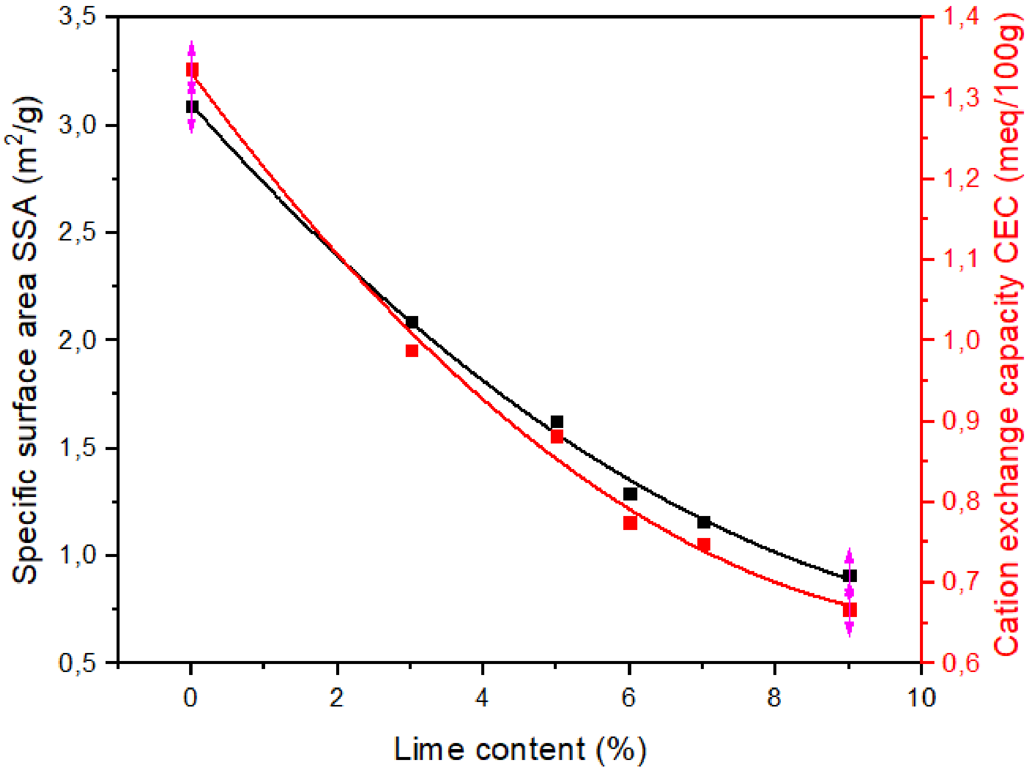

Fig. 6. Changes in the specific surface area and cation exchange capacity of soil as a function of lime content

The CEB area complies with French standard XP P13-901 [24] and that of the African Regional Standards Organisation (ARSO) [23].

Fig. 4 shows the evolution of the plasticity index as a function of the plastic limit after the addition of lime. Both the raw soil and the mixes have optimal moulding properties, an important parameter in brick manufacture.

Fig. 5 shows the evolution of the compaction energy as a function of the water content of the raw soil and those of the mixes. The raw soil has a water content close to the water saturation curve, as a function of its clay fraction of 29.45%. Incorporating lime into a clay soil reduces the maximum dry density and increases the optimum water content [25]. The decrease in dry density is explained by the reorganisation of clay particles caused by flocculation. The intensity of the changes depends on the addition of lime; the higher the lime content, the more the optimum water content shifts towards the higher water contents and the more the maximum dry density decreases. In addition, the increase in optimum water content after the addition of lime depends on pozzolanic reactions, as lime is hydrophilic.

In Fig. 6 the specific surface area (SSA) and the cation exchange capacity (CEC) (two intrinsic properties that characterize the behavior of the clay fraction of the soil) decrease with the addition of lime. The flocculation of clay particles is responsible for the decrease in specific surface area (SSA) and cation exchange capacity (CEC).

Fig. 7 shows that the compressive strengths obtained are consistent with the manufacture of adobe, CEB and rammed earth bricks. The standards require respective compressive strengths CS (2-5 MPa) for adobe. For adobe and CEB, the permitted compressive strength is CS (2.4 MPa). The compressive strengths obtained are well above the recommended minimums of 2 MPa and 2.4 MPa for adobe, rammed earth and CEB bricks.

3.2 Mineralogy of Cubitermes Sp Termite Mound Soil

The vibration observed at 778 cm^{-1} explains the presence of the Fe(II)-OH bond [26]. Those observed at 914.42 cm^{-1} and 1005 cm^{-1} reflect not only the vibration of the Si-O-Si bond characteristic of quartz, but also the presence of hematites and the hydroxyl bond of $Al(OH)_3$ [27]. The bands appearing at 1024 cm^{-1} and 1420 cm^{-1} are due to the vibration of the Si-O bond in kaolinite and calcite respectively. The band appearing at 1628 cm^{-1} is characteristic of carboxylates and/or illite. Those appearing at 3422 cm^{-1} and 3693 cm^{-1} characterize the 0-H vibration of kaolinite. On the other hand, the bands appearing at 3619 cm^{-1} and 3693 cm^{-1} express not only the presence of the O-H bond of $Al_2(OH)_3$ in smectites and kaolinite respectively, but also the presence of the hydroxyl group of the water molecule [26].

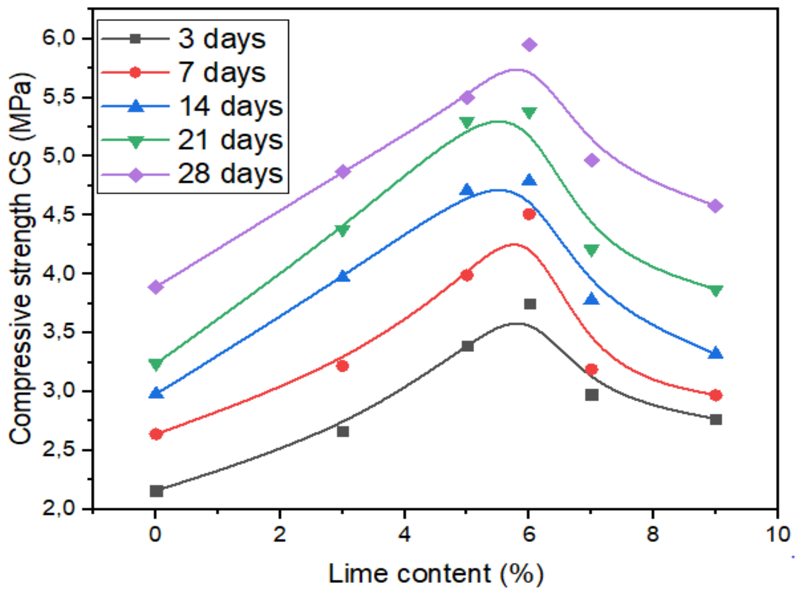

Fig. 7. Changes in compressive strength as a function of lime content

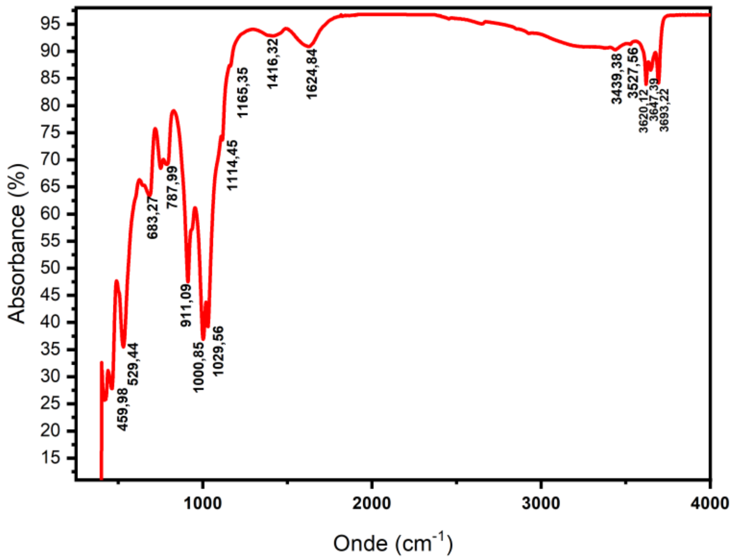

Fig. 8. Infrared spectrum of the cubitermes sp termite mound soil

4. DISCUSSION

Fig. 2. shows the grain size distribution of the raw soil, which does not include the normative spindles for adobe and CEB bricks [19]. The granulometry of the raw soil shows that the grain size is outside the normative spindles for CEB and adobe for grain sizes of 0.005 to 0.222 mm. The grain size distributions of the mixes treated with 5%, 6%, 7% and 9% lime fully integrate the normative spindle for adobe and CEB. These grain sizes are spread out, which is characteristic of materials with variable grain sizes.

The soil of the *Cubitermes* sp termite mound is a clayey silt. The mixtures treated with 3%, 5%, 6% and 7% lime are silts and the mixture treated with 9% lime is a sandy silt. All these changes in the mixtures are due to the cementing of the fines, which results in a reduction in the clayey and silt fractions, offset by an increase in the sand fraction, thus changing the nature of the raw soil. According to Table 3. the use of raw earth in the manufacture of adobes, CEB and rammed earth does not comply with the recommendations of the technical documents [21] and with standard NTE E80 [20]. In fact, the raw earth has a clayey content of 29.45%, higher than the maximum of 20% [20,19] and its sand content of 25.60% is lower than the recommended minimum of 55% [20]. The raw soil and the mixtures (3%, 5%, 6%, 7%, 9%) have liquidity limits LL (33.1-36.2%), higher than the minimum of 25%, but lower than the maximum of 50%. The PI plasticity indices (17.76-16.1%) are higher than the minimum of 2%, but lower than the maximum of 30%. These two parameters (LL and PI) are compliant for the manufacture of adobes and CEBs [2, 23, 24].

In Fig. 5. the addition of lime (3-9%) to the raw soil results in a decrease in its dry density and the optimum water contents of the mixes move towards higher water contents, above the saturation water content. The increase in water content is justified by the presence of lime, which is a hydrophilic binder. Despite the decrease in dry density, lime improves the compaction of the materials. The increase in optimum water content after the addition of lime is due to the additional water required for pozzolanic reactions and the increase in the sand fraction of the mixes. Compaction essentially consists of reducing the porosity of the material by compacting the particles. The effects of compaction are reduced permeability, compressibility, water absorption and swelling [28].

According to Fig. 6, the change in cation exchange capacity (CEC) causes clayey particles to agglomerate into stable blocks, which improves compressive strengths up to the point of lime fixation [28]. According to Fig. 7, the compressive strength of raw materials and mixes increases by CS (3.89-5.95 MPa) up to a lime content of 6%, i.e. an increase of 52.96%. Above

6%, i.e. between 7% and 9% lime, the compressive strength no longer improves, but decreases by CS (4.97-4.58 MPa), i.e. a reduction of 7.85%. In fact, the 6% lime content can be considered as the lime fixation point.

According to Fig. 8, the presence of kaolinite in this soil is of great importance, especially for the manufacture of solid bricks. Clay is known for its crystallising properties, i.e. its ability to act as a mortar, particularly when the soil contains organic matter [24]. This can improve the mechanical strength of raw and mixed soils. Illite (like smectites) is one of the important minerals in the composition of soils, particularly for terracotta (bricks, tiles and pottery), as it favours sintering at a relatively low temperature [29]. The presence of these minerals in higher concentrations in natural soil leads us to believe that it could also be used as a base material for the manufacture of ceramic products.

5. CONCLUSION

The geotechnical properties of raw soil and mixes with lime contents of 3-9% for the manufacture of bricks (Adobes and CEB) were defined and compared with the relevant standards. The results show that the addition of lime improves the physical and mechanical properties of the mixes. The raw soil is a clayey silt, the mixtures with 3-7% lime are silts and the 9% mixture is a sandy silt. The clay fractions of the raw soil and mixtures CF (29.45-16.29%) are below the maximum of 30% recommended by most standards. The sand fraction of the raw soil SaF (23.6) is less than the minimum 30% recommended by the standards and those of the 3-9% lime mixtures, SaF (33.47-50.16) comply with the standard. Clayey silt is a compressible soil which is at the lower limit of lime-treatable soils. However, clayey silt and lime mixtures have a plasticity suitable for making mud bricks. Furthermore, according to the Casagrande plasticity diagram, clayey silt and mixtures have good moulding properties. Despite the decrease in dry density and the increase in optimum water content, moulding properties improve. Compressive strengths increase for lime contents of 0-6% by 52.96% and for 7-9% lime, compressive strength decreases by 7.85%. Adding lime above the 6% level no longer improves compressive strength, and the 6% level is considered to be the lime fixation point. The compressive strengths obtained are greater than 2 MPa, i.e., suitable for the manufacture of adobes, rammed earth and compressed earth bricks.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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