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Original Research Article

Evaluation of the Geotechnical Properties of *Cubitermes sp* and *Macrotermes sp* Termite Mound Soils for the Manufacture of Earth Bricks

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Abstract

The use of local materials in construction contributes to solving the deficit of sustainable housing in some developing countries. Earth constructions have a low ecological impact and are among the cheapest, especially in rural areas. The durability of earthen buildings depends on the geotechnical properties of the soil used and the respect of basic architectural rules. Evaluation of the geotechnical properties of soils contributes to the choice of the appropriate technique to use them. The *macrotermes sp* and *cubitermes sp* termite mound soils are widespread and commonly used in construction in some regions of the world. The results obtained from the 27 samples showed that the clay content of some soils is higher than the maximum permitted of 30% and that other soils have a sand content lower than the minimum of 30% permitted by most standards for the manufacture of mud bricks. Some soils have good molding properties and a plasticity suitable for making mud bricks. To correct excess clay and limit the risk of cracking during drying, lime, plant fibers or sand could be incorporated into these soils. The *cubitermes sp* termite mound soils are composed of kaolinite and illite and the *macrotermes sp* termite mound soils of kaolinite, illite and montmorillonite. Soils containing kaolinite or illite are suitable for the manufacture of CEB, adobes, rammed earth and in the manufacture of tiles or pottery.

Keywords: Termite Mound Soil *Cubitermes Sp.* Granulometry, Geotechnical Properties, Compressed Earth Bricks (CEB), Adobes, Rammed Earth.

1. INTRODUCTION

Housing is a basic human need and access to a viable home is increasingly difficult for the vast majority of people in some parts of the world. The UN-Habitat report indicates that by 2030, approximately 3 billion people worldwide will be in need of housing [1]. Indeed, the housing deficit in some countries can be linked to poor land policy, uncoordinated rural-urban migration, population growth and the high cost of building materials [2]. Earthen construction is the traditional form of housing used by about 1/3 of the population in developing countries [3, 4]. Earth is a widely available raw material with low extraction costs, renewable and recyclable. Earth materials have been used in construction around the world for thousands of years, and have adapted to changing construction techniques and environmental conditions [5]. Today, in the West, the need to conserve natural resources and combat climate change has given earth materials a renewed interest [6]. Soil is used not only for structural materials such as CEB, adobes, rammed earth, but also for filling materials such as cob, plaster and straw earth. These uses are justified by the good performance of earth in housing (thermal and acoustic comfort, fire resistance, etc.). For example, compressed earth bricks provide good moisture regulation and have a low environmental impact. New earthen houses are built with a modern design and all amenities [7]. The geological structure of the building soil is composed of clay, silt and sand. Soil selection criteria are distinguished by texture (grain size), plasticity (clay content and nature) and less frequently by compactness. The type of soil used depends on the climate and the type of construction (Adobe, Compressed earth brick, Rammed earth, cob, fired brick, cement-stabilized brick, lime-stabilized brick...). [6]. As earthen products are not watertight, it is important to provide the house with good foundations to limit crumbling from below. To do this, you need a stone base to protect the walls from rainwater. Then the roof (with a wide overhang to prevent water run-off, so that the bricks can be placed from the inside), to protect the walls from the main factor in deterioration, which is water [7]. The texture, structure and porosity of the soil are essential elements that characterize its behavior in relation to air humidity and the direct action of rain. In most sub-Saharan African countries, mud bricks are made from natural clay soils or termite mound soils. The decision to use termite mound soils for the production of mud bricks is justified by their clay content, which is often higher than that of the surrounding soils (particularly in sandy regions). Unlike natural soils, which are the result of the weathering of a parent rock and the transport of the weathering product, termite mounds are soils reconstituted by termites to provide shelter from the vagaries of the climate and to protect them from predators. To build their nests, termites can dig into soil grains up to ten meters deep, modifying the structure and content of the clays present by concentrating certain minerals [8]. The *macrotermes sp* termite mound soils are commonly used in the manufacture of mud bricks and pottery because of their particular physic-chemical properties and their abundance. The *cubitermes sp* termite mound soils are used for wall plaster coatings in traditional houses and as surfacing material for earth roads. The particle size distribution of a soil is one of the determining factors used to classify soils and define standards for their use in geotechnical engineering. The behavior of a material depends not only on its particle size, but also on its mineralogy. Despite the diversity of studies on termite mound soils, these have not exhausted the subject. To our knowledge, the evaluation of the geotechnical properties of the *cubitermes sp* termite mound soils for the production of mud bricks has not yet been reported.

The aim of this work is to make a comparative assessment of the geotechnical properties of 27 soil samples from *cubitermes sp* [14] and *macrotermes sp* [13] termite mounds for the production of earth bricks, according to the standards in force in certain countries. Where applicable, indicate the appropriate technique for using the soil and/or the modifications required to comply with it.

Table 1: Location and sampling of *cubitermes sp* and *macrotermes sp* termite mound soils

Soils	Locality	Sampling	Place of collection
Cubitermes sp termite mound soils	BARA	CBARA	15°54'E; 1°04'S
	BOKOSONGHO	CBOKS	13°35'E; 4°25'S
	BRAZZAVILLE	CBRAZ	15°17'E; 4°16'S
	GAMBOMA	CGAMB	15°51'E; 1°52'S
	LOUIGUI	CLOUI	14°45′ E; 4°28′ S
	LOUTETE	CLOUT	13°50'E; 4°17'S
	MBE-NGABE	CMBEN	for the northern area
	MPOUYA	CMPOU	16°11'E; 2°37'S
	NGO-CENTRE	CNGOC	15°45'E; 2°29'S
	NGO-NORD	CNGON	15°45'E; 2°29'S
	NTOMBO M.	CNTOM	-4.86 S ;14.40 E
	ODZIBA-MBE	CODZM	for the northern area
	OLLOMBO	COLLO	15°55'E; 1°15'S
	YENGOLA	CYENG	4°20'25"S; 13°52'25"E
Macrotermes sp termite mound soils	BARA	MBARA	15°54'E; 1°04'S
	BOKOSONGHO	MBOKS	13°35'E; 4°25'S
	BRAZZAVILLE	MBRAZ	15°17'E; 4°16'S
	GAMBOMA	MGAMB	15°51'E; 1°52'S
	LEKANA	MLEKA	15°48'E; 1°54'S
	LOUTETE	MLOUT	13°50'E; 4°17'S
	MPOUYA	MMPOU	16°11'E; 2°37'S
	NGO-CENTRE	MNGOC	15°45'E; 2°29'S
	NGO-NORD	MNGON	15°45'E; 2°29'S
	NGO-SUD	MNGOS	15°45'E; 2°29'S
	ODZIBA-MBE	MODZM	for the northern area
	OLLOMBO	MOLLO	15°55'E; 1°15'S
	YENGOLA	MYENG	4°20'25"S; 13°52'25"E

2. METHODS

The laboratory analyses were carried out after crushing the termite mound soil and passing it through a 2 mm sieve.

The granulometric analysis was carried out by sieving, for grains larger than 80 µm, and by sedimentation for the fine fraction, in accordance with standards NF P94-056 [9] and NF P94-068 [10] respectively. The granulometric fraction is deduced from the recommendations of the granularity nomograms, which consider clays as particles smaller than <0.002 mm, silts from 0.002-0.06 mm and sands from 0.06-2 mm.

The plasticity limit (PL), the liquidity limit (LL) and the plasticity index were determined using the Casagrande cup in accordance with standard NF P94-051 [11].

The optimum moisture content (OMC) and the maximum dry density (MDD) were measured using the Proctor test modified according to standard NF P94-093 [12].

The specific surface area (SSA) and the cation exchange capacity (CEC) are two fundamental properties that characterize the behavior of fine soils, defined by the respective formulae SSA = 20.93*BVS and CEC (meq/100) = BVS*1000/374.

The analysis of the results of the laboratory tests was based on the relevant standards: XP P 13-901 (2001) [13], NTE E 080 (2000) [14], ARSO (1996) [15], SAZS 724 (2001) [16], HB 195 (2002) [17], MOPT (1992) [18], IETcc (1971) [19] and technical documents: Rigassi V (195) [20], Houben and Guillaud (1994) [21] reported by Delgado and Guerrero (2007) [22], which are used in several countries for the production of CEB, adobes, rammed earth.

Fig.1. Cubitermes sp (A) and Macrotermes sp (B) termite mound soils

Macrotermes sp termite mound soil color ranged from gray to yellow, while *cubiterme sp* termite mound soil color ranged from black to yellowish-gray.

3. RESULTS

3.1 Grain size distribution of *cubitermes sp* and *macrotermes sp* termite mound soils.

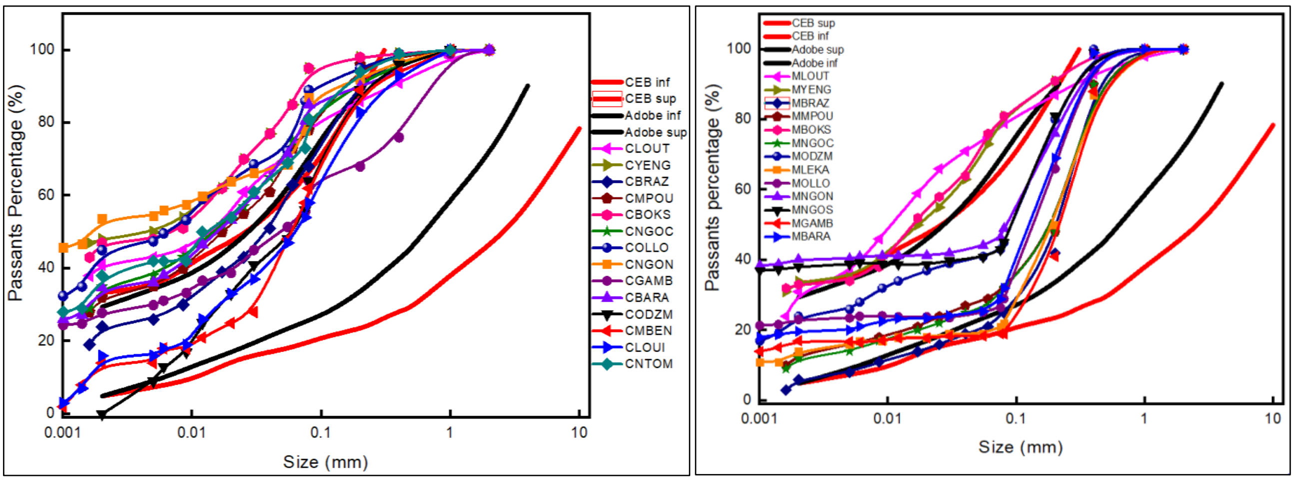

Fig. 2: Grain size distribution of *cubiterme sp* (a) and *macroterme sp* (b) termite mound soils.

Figure 2 shows the particle size distribution of the different soils and the normative spacing for adobe and CEB bricks [21]. It shows that the *cubitermes sp* and *macrotermes sp* termite mound soils (CNGON, CBOKS, CYENG, CLOUT, MNGON, MNGOS) have clay contents above the maximum permitted for the production of adobe and CEB bricks. The *cubitermes sp* and *macrotermes sp* termite mound soils (CLOUI, CMBEN, CBRAZ, CGAMB, MODZM, MOLLO, MBARA, MNGOC) are fully integrated into the spindles suitable for the manufacture of adobe and CEB bricks.

The grain diameters of the different soils are taken from Figure 2 and presented in Figure 3.

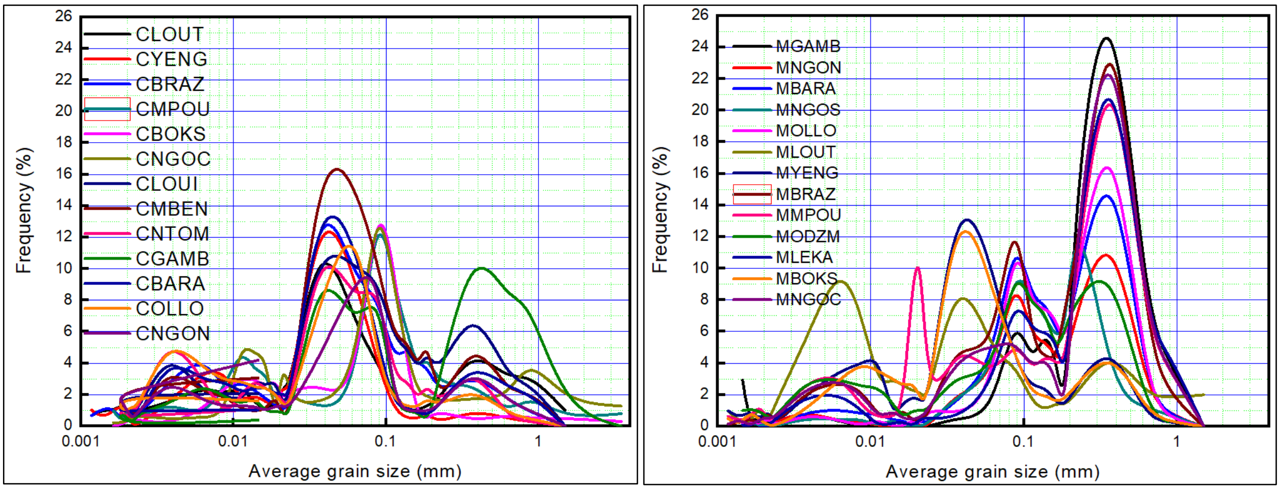

Fig. 3: Evolution of the frequency of grain diameters of *cubitermes sp* and *macrotermes Sp* termite mound soils.

The *cubitermes sp* and *macrotermes sp* termite mound soil has curves that evolve at polymodal frequencies. These soils have three main modes with diameters between 0.1-1 mm, 0.01-0.1 mm and 0.001-0.01 mm. In the case of *cubitermes sp* termite mound soils, the frequency modes of the granulometric fraction are spread out. In the *macrotermes sp* termite mound soils, the modes are closely grouped around a mean value and the granulometric fraction as a whole has a mean diameter of 0.1-1 mm. Whereas in the *cubitermes sp* termite mound soils, the predominant particles have mean diameters of between 0.02-0.1 mm and 0.002-0.02 mm.

The clay, silt and sand contents deduced from these curves are reported in Table 2.

Table 2: Geotechnical characteristics of the cubitermes sp and macrotermes sp termite mound soils.

Soil	Sand (%)	Silt (%)	Clay (%)		Soil	Sand (%)	Silt (%)	Clay (%)	
CBARA	23	48	29		MBARA	73	8	19	
CBOKS	13	44	43		MBOKS	24	45	31	
CBRAZ	37	44	19		MBRAZ	77	19	04	
CGAMB	47	28	25		MGAMB	81	5	14	
CLOUI	40	37	23		MLEKA	79	8	13	
CLOUT	27	37	36		MLOUT	24	51	25	
CMBEN	41	32	27		MMPOU	88	2	10	
CMPOU	26	46	28		MNGOC	73	17	10	
CNGOC	24	46	30		MNGON	55	7	38	
CNGON	29	23	48		MNGOS	58	5	37	
CNTOM	63	4	33		MODZM	58	23	19	
CODZM	39	38	23		MOLLO	74	5	21	
COLLO	25	38	37		MYENG	26	43	31	
CYENG	50	4	46						

Knowing the texture of a soil is essential for adapting brick-making techniques. Clay soil is made up of clay, silt and sand. However, sand retains water poorly, while silt is frequently subject to the formation of a crust that renders the clay impermeable.

Classification of the 27 *cubitermes sp* and *macrotermes sp* termite mound soils samples according to Taylor's triangular diagram identified 9 subclasses. These are: Silty loam (CBARA, CMPOU, MLOUT), Silty clay (CBOKS), Silt (CBRAZ, CLOUI, CMBEN, CODZM), Clayey loam (CLOUT, CNGOC, COLLO, MBOKS, MYENG), Sandy loam (CGAMB, MBARA, MODZM, MOLLO), clay (CNGON), sandy clay loam (CNTOM, MNGOS), sandy clay (CYENG, MNGON) and silty sand (MBRAZ, MGAMB, MLEKA, MNGOC, MMPOU).

Table 3: Geotechnical characteristics of *cubiterme sp* and *macroterme sp* termite mound soils.

Soil	PL (%)	LL (%)	PI (%)	OMC (%)	MDD (T/m^3)	SSA (m^2/g)	CEC (meq/100g)	BVS (g/100g)
CBARA	17	30.5	13,4	16,8	1,64	8.58	1.096	0.41
CBOKS	23,6	50.8	27,2	21,5	1,68	16.95	2.166	0.81
CBRAZ	19,9	32.9	12,6	17,5	1,71	7.74	0.989	0.37
CGAMB	2,1	11.6	9,5	15,2	1,72	5.65	0.722	0.27
CLOUI	14,8	26.4	11,6	14	1,79	6.91	0.882	0.33
CLOUT	23,1	48.2	25,1	16	1,73	14.86	1.898	0.71
CMBEN	19,6	27.1	7,5	14	1,75	4.81	0.615	0.23
CMPOU	18,7	41.4	22,7	24,2	1,46	14.23	1.818	0.68
CNGOC	19,8	40.7	20,9	24,4	1,47	12.77	1.631	0.61
CNGON	12	45	33	20,4	1,57	20.51	2.620	0.98
CNTOM	16,1	32.2	18,6	18,8	1,66	11.72	1.497	0.56
CODZM	20,7	41.4	12,1	22,1	1,52	7.33	0.936	0.35
COLLO	20	40	18	17	1,62	10.67	1.364	0.51
CYENG	22,7	45.4	26,2	21,5	1,68	15.49	1.979	0.74
MBARA	0	15.9	15,9	8,2	1,95	11.51	1.471	0.55
MBOKS	19,9	42	22,1	17,6	1,9	15.28	1.951	0.73
MBRAZ	13,6	18.5	4,9	10,2	1,92	4.40	0.561	0.21
MGAMB	8,4	21.2	12,8	6,8	1,98	9.42	1.203	0.45
MLEKA	0	15.5	15,5	8,7	2,09	11.30	1.444	0.54
MLOUT	27,5	38	10,5	23,7	1,47	8.163	1.043	0.39
MMPOU	13,6	23.4	10,4	12,6	1,89	7.53	0.963	0.36
MNGOC	13,6	24	9,8	11,1	2,054	7.74	0.989	0.37
MNGON	12	23.2	14,4	11,7	1,91	8.91	1.133	0.43
MNGOS	11,4	19.6	11,8	11,3	1,95	8.16	1.043	0.39
MODZM	9	27.9	10,6	10	1,97	9.42	1.203	0.45
MOLLO	14,9	41.3	13	8,2	1,95	14.65	1.872	0.7
MYENG	20,1	26.4	21,2	19,2	1,86	10.26	1.310	0.49

PL - plasticity limit, LL - liquidity limit, PI - plasticity index, OMC - optimum moisture content, MDD - maximum dry density, BVS - blue value of the soil, SSA - specific surface area, CEC - cation exchange capacity.

Table 3 shows the Atterberg limits (a measure of plasticity), maximum dry density, optimum water content, specific surface area and cation exchange capacity of *cubitermes sp* and *macrotermes sp* termite mound soils.

Table 4 shows the adaptation of *cubitermes sp* and *macrotermes sp* termite mound soils according to the standards and technical documents used in several countries for the production of CEB, Adobes and Rammed earth.

A: deduced from the recommendations in the granularity nomograms considering clays as particles under <0.002 mm.
a Clay <0.002 mm; silt 0.002-0.06 mm; sand 0.06-2mm; fine gravel 2-6 mm.
b Clay <0.002 mm; silt 0.002-0.06 mm; sand 0.06-2mm; fine gravel 2-20 mm.
c Only there are indications for the strengthened rammed earth.
d Clay <0.002 mm; silt 0.002-0.05 mm; sand 0.5-5 mm; fine gravel 5-20 mm.

Table 4: Manufacturing techniques for Adobes, Compressed Earth Bricks CEB and Rammed earth according to NTE E 080 (2000), HB 195 (2002), XP P13-9001 (2001), ARSO (1996), SAZS 724 (2001), IETcc (1971) i.e., MOPT (1992) and the technical documents Rigassi V (1995), A. Houben and Guillaud (1994) [13-22].

Nature of soils	Techniques	Adobe			Compressed earth blocks							Rammed earth		
	Soil samples Standards	NTE E 080(2000)	HB 195 (2002)	A Houben and Guillaud (1994)	A XP P 13-901 (2001)	A ARSO (1996)	HB 195 (2002)	A MOPT (1992)	A Houben and Guillaud (1994)	Rigassi V (1995) a	A Rigassi V (1995) b	SAZS 724 (2001)	A MOPT (1992)	IETcc (1971) c,d
Cubitermes sp termite mound soils	COLLO		x				x			x	x	x		x
	CNGON		x				x			x				
	CGAMB	X	x	x	x	x	x	x		x			x	
	CBARA				x	x	x	x		x				x
	CLOUT		x				x							x
	CYENG													x
	CBRAZ	X	x	x	x	x	x	x	x	x	x		x	x
	CMPOU		x	x	x	x	x	x		x				x
	CBOKS													x
	CNGOC		x	x	x	x	x	x		x				x
	CNTOM							x						x
	CMBEN			x		x		x	x	x	x		x	
	CODZM			x	x	x		x			x		x	x
	CLOUI			x		x		x	x	x	x		x	
Macrotermes sp termite mound soils	MOLLO			x	x	x		x	x	x	x		x	
	MNGON		x				x							
	MNGOS		x				x							
	MGAMB			x	x	x		x	x		x		x	
	MBARA			x	x	x		x	x	x	x		x	
	MLOUT			x	x	x		x		x			x	x
	MYENG		x				x	x	x					x
	MBRAZ									x				
	MMPOU	X	x	x	x	x	x	x	x	x	x	x	x	
	MBOKS		x				x	x						x
	MNGOC		x	x			x	x	x	x	x	x	x	
	MLEKA			x	x	x		x	x		x		x	
	MODZM	X	x	x	x	x	x	x	x	x	x	x	x	x

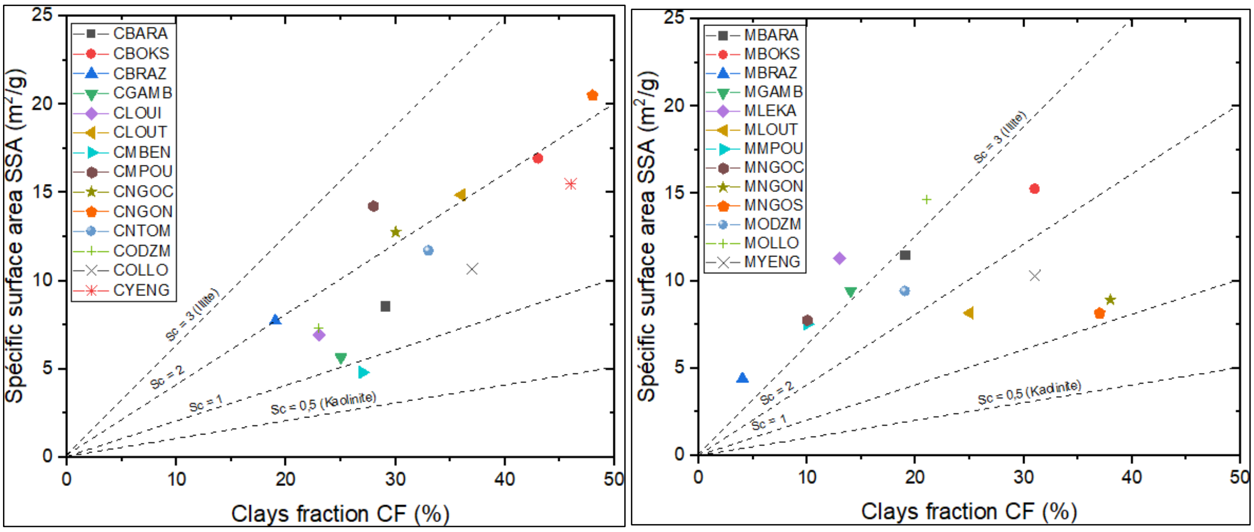

Fig. 4: Surface activity of *cubitermes sp* and *macrotermes sp* termite mound soils

Sc - are directing coefficients of the straight lines delimiting the areas of the mineralogical formations (kaolinite, illite).

The correlation between specific surface area and clay fraction is used to define the activity values of the soils studied. Figures 4 and 5 show the minerals contained in the soils on the basis of their intrinsic properties in relation to their clay fractions. Most soils with mixed mineral layers fall between the Sc surface activity and CECA cation exchange capacity activity coefficients.

Despite the fact that the soil samples come from a very wide geographical area, the *cubitermes sp* termite mound soils have a Sc surface activity greater than 0.50, but less than Sc = 3. All fourteen soils contain kaolinite and their specific surface area SSA (4.81-20.51 m^2/g).

Seven *macrotermes sp* termite mound soils (MNGOS, MNGON, MLOUT, MYENG, MBOKS, MODZM, MBARA) have a surface activity Sc greater than 1, but less than Sc = 3. These soils contain kaolinite with specific surface areas SSA (8.16-15.28 m^2/g). Six *macrotermes sp* termite mound soils (MOLLO, MGAMB, MLEKA, MBRAZ, MMPOU, MNGOC) have a surface activity greater than Sc = 3, they contain illite and have a specific surface area SSA (4.40-14.65 m^2/g).

Figure 4 shows that the *cubitermes sp* and *macrotermes sp* termite mound soils (CBOKS, CLOUT, CMPOU, CNGOC, CNGON, CNTOM, COLLO, CYENG, MBARA, MBOKS, MLEKA, MOLLO, MYENG) have specific surface areas SSA (10.26-20.51 m^2/g) [23]. Secondly, the *cubitermes sp* and *macrotermes sp* termite mound soils (CBOKO, CLOUT, CNGON, CYENG, MBOKS) have an SSA varying from 15-20.51 m2/g [24].

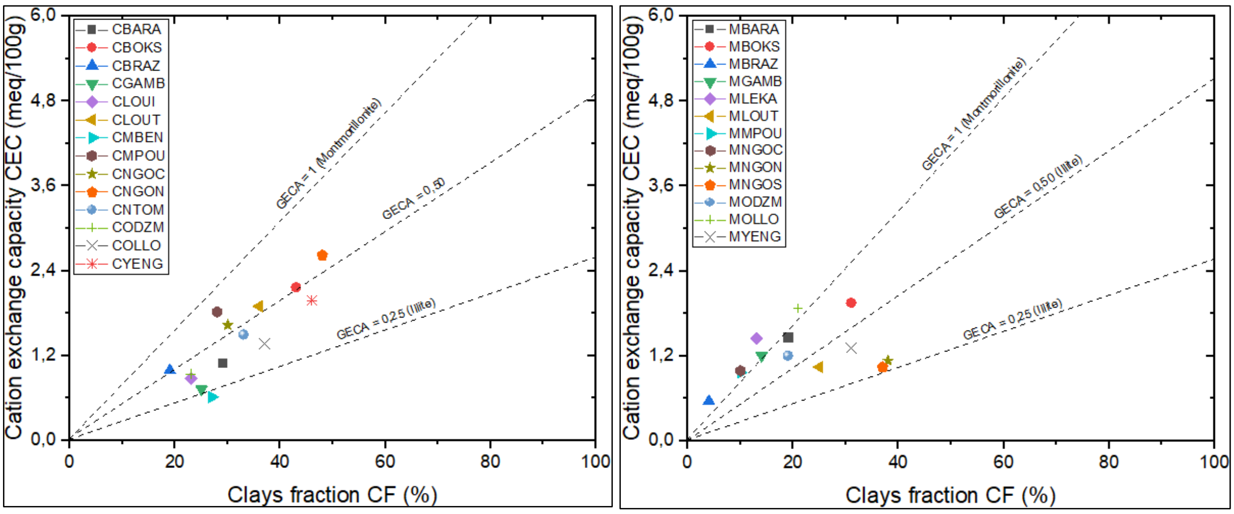

Fig. 5: Cation exchange capacity activity CECA of *cubitermes sp.* and *macrotermes sp* termite mound soils.

CECA - are the directing coefficients of the straight lines delimiting the areas of the mineralogical formations (illite, montmorillonite).

In Figure 4-5, except for the *cubitermes sp* termite mound soil CMBEN which contains exclusively kaolinite, the thirteen others are composed of kaolinite and illite. Six *macrotermes sp* termite mound soils (MBRAZ, MNGOC, MMPOU, MLEKA, MGAMB, MOLLO) contain illite and montmorillonite. Seven soils (MBARA, MODZM, MBOKS, MLOUT, MYENG, MNGON, MNGOS) contain kaolinite and illite.

Figures 4 and 5 show that for a given clay fraction, the specific surface area and cation exchange capacity are proportional to the mineralogy in the order kaolinite - illite - montmorillonite [25].

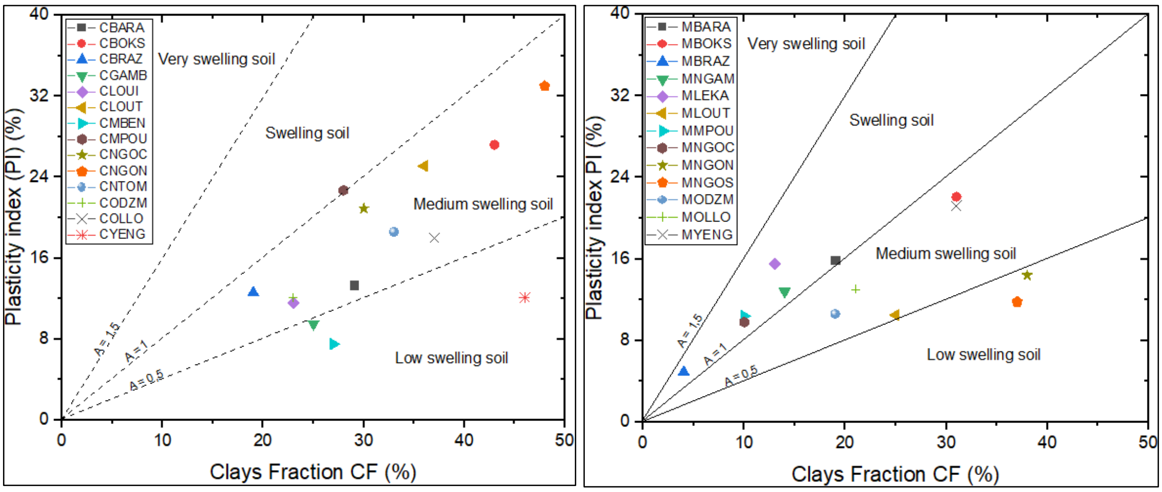

Fig. 6: Swelling potential of termite mound soils *cubiterms sp* and *macroterms sp.*

A - directing coefficients of the straight lines delimiting the areas of low, medium, high and high swelling soils.

According to figure 5, the swelling potential (variation in brick dimensions due to water absorption or evaporation) of CMBEN and CGAMB soils is low despite clay contents of 25-27%. Eleven *cubitermes sp* termite mound soils (CNGON, CYENG, CBOKS, CLOUI, COLLO, CNTOM, CBARA, CNGOC, CBRAZ, CLOUT, CODZM) are moderately swelling, despite clay contents of 19-48%. The CMPOU soil is at the lower limit of swelling soils and the upper limit of moderately swelling soils, with a clay content of 28%.

The moderately swelling soils (CBARA, CBOKS, CLOUT, CNGOC, CNTOM, COLLO, CYENG) have clay contents of 29-46%. All *cubitermes sp* termite mound soils contain kaolinite and illite despite variations in their clay content. The *macrotermes sp* termite mound soils (MODZM, MOLLO, MLOUT, MBARA, MYENG, MBOKS, MGAMB) are moderately swollen, with clay contents of 19-31%. The MOLLO soil contains exclusively illite and the other five are composed of kaolinite and illite. The swelling soils (MNGOC, MMPOU, MLEKA, MBRAZ, MGAM) composed of illite and montmorillonite have clay contents of 4-14%.

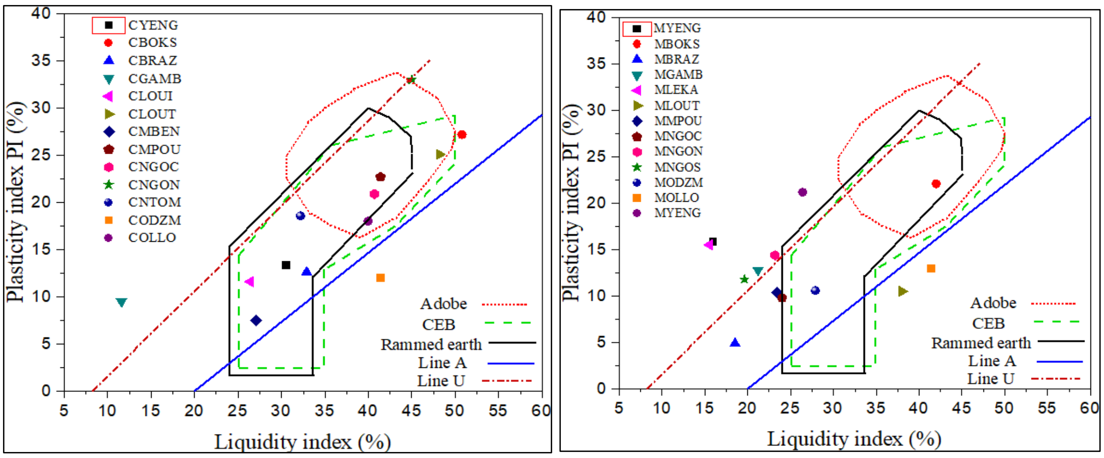

Fig. 7: Atterberg limits of soils with recommended ranges for adobe, CEB and Rammed earth according to Houben and Guillaud (1994) [21]. The CEB area is in accordance with the French standard XP P 13-901 [13] and the African Regional Standards Organization - ARSO (1996) [15].

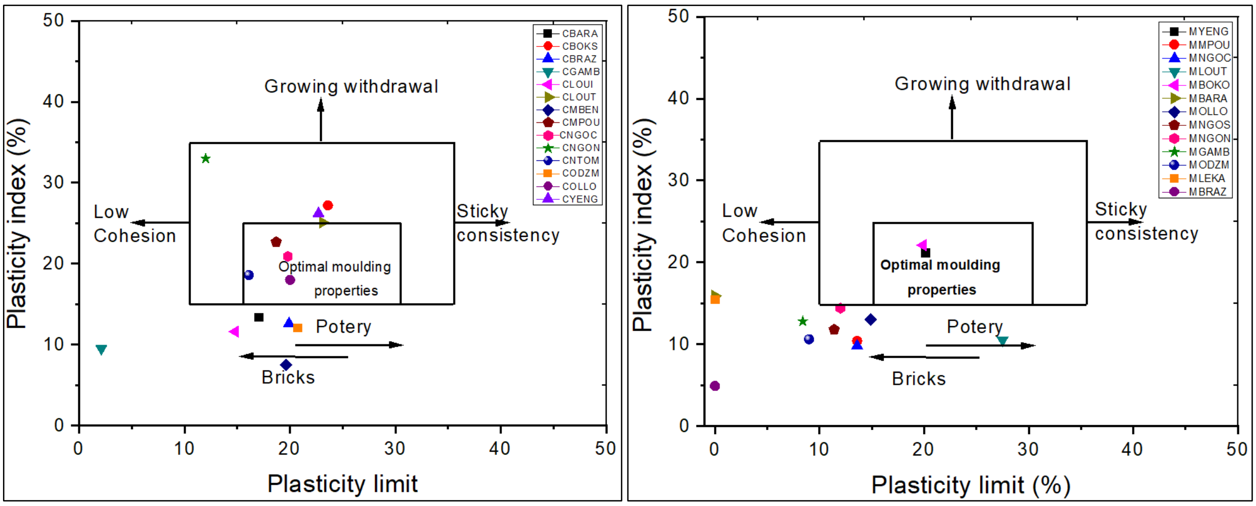

Fig. 8: Molding properties of soils as a function of the Atterberg limit.

According to Casagrande's plasticity diagram, only the soils (CBOKS, CNGON, CYENG, CLOUT, CMPOU, CNGOC, COLLO, CNTOM, MBOKO, MYENG) have good molding properties. They could even be used in pottery.

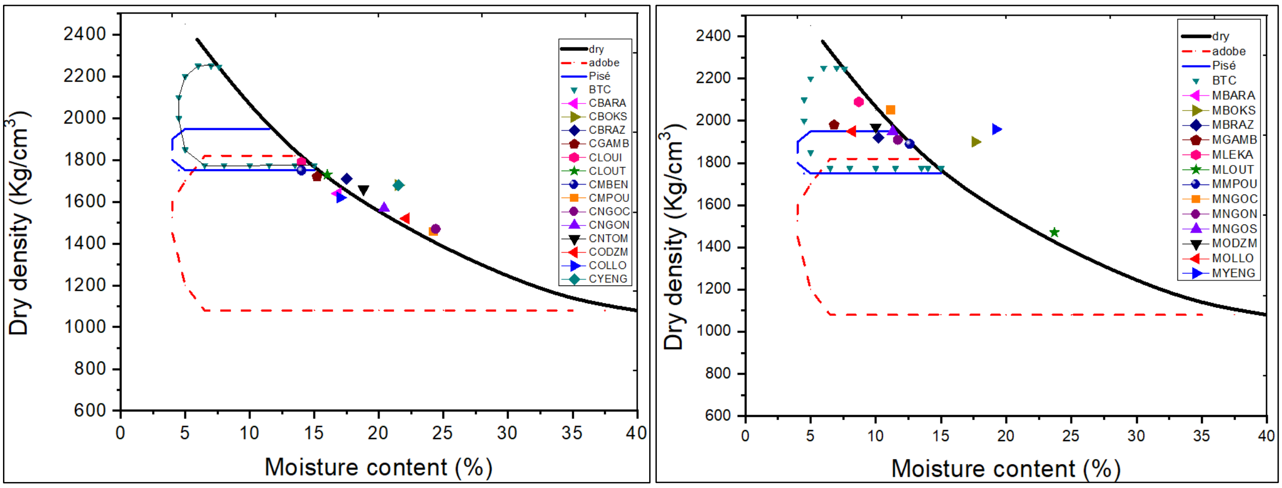

Fig. 9: Maximum dry density as a function of optimum moisture content for the production of CEB, Adobe and Rammed earth according to Houben and Guillaud 1994 [21].

Experience shows that when a soil is compacted according to a well-defined standard process at different water contents, the dry density of the material changes. The Proctor test allows to determine the optimum moisture content (OMC) for which compaction leads to a maximum dry density (MDD) and that the maximum dry density is not a direct indication of the mechanical strength of the bricks. However, for a material that has fewer pores, the more interactions there are between the grains, which gives the soil a good cohesion. Houben and Guillaud (1994) [21] used moisture content and dry density to establish soil selection criteria for earth construction. These criteria and the results of the Proctor test for the different soils are reported in Figure 8 for the *cubitermes sp* and *macrotermes sp* termite mound soils. It can be seen that the maximum dry densities are obtained for moisture contents at least equal to the saturation moisture content. This result is in agreement with the high clayey contents 33-48% of the soils (CBOKS, CLOUT, CNGON, CNTOM, COLLO, CYENG, MNGON, MNGOS) revealed by the granulometric analysis. Indeed, the more clayey the soil, the more water is needed to make it plastic. On the other hand, with these high moisture contents, there is a risk of significant shrinkage during drying, which leads to cracking of the material. However, using less mixing water will reduce the friction between grains less and, with the same compaction energy, will reduce the pores in the bricks less, and therefore should lead to lower mechanical strengths. The *cubitermes sp* termite mound soils (CLOUI, CMBEN, CGAMB, CBARA, COLLO, CLOUT) located at the limit of the saturation curve are suitable for the manufacture of adobes. The soils (CMBEN, CLOUI) suitable for the manufacture of Rammed earth and the CLOUI soil can be used in the manufacture of CEB.

The *macrotermes sp* termite mound soils (MLEKA, MGAMB, MOLLO, MODZM, MNGOS, MBRAZ, MNGON, MMPOU) are suitable for the manufacture of CEB and those of (MBRAZ, MNGON, MMPOU, MOLLO, MNGOS) in adobe.

3. DISCUSSION

From Figure 3, the variability in grain size is important for soils used in the manufacture of compressed earth bricks CEB and adobes. The frequency of the curves indicates that there are more fine particles in *cubitermes sp* termite mound soils than in *macrotermes sp* termite mound soils.

According to Table 2, the standards recommend an average clay content of 10-30% and a sand content of at least 30% for the manufacture of compressed earth bricks (C.E.B.) and adobe. Only Australian standard HB 195 (2002) [17] sets the maximum clay content at 40%. Soils from *cubitermes sp* and *macrotermes sp* termite mound soils (CLOUT, COLLO, CNTOM, MBOKS, MNGON, MNGOS, MYENG) have clay contents of less than 40% [17]. The *cubitermes sp* termite mound soils (CBOKS, CNGON, CYENG) are disqualified due to their clay content of over 40% (HB 195 2002). The *cubitermes sp* and *macrotermes sp* termite mound soils (CGAMB, CNGON, MBARA, MBRAZ, MGAMB, MLEKA, MMPOU, MNGOC, MNGON, MNGOS, MODZM, MOLLO) have a sand content below the recommended minimum of 30%. However, high clay and sand contents are likely to generate cracks during drying (strong shrinkage). Poorly graded soils have low mechanical strength. To correct this imbalance without increasing the cost of bricks, soils with more than 40% clay could, for example, be improved. The addition of hydraulic or dune sand, local plant fibers from industrial waste, palm nuts or sugar cane, finely chopped straw, plastic waste, finely sieved ash or lime at 2-6% can improve soils by reducing the clay content [26]. Cement stabilization would be less effective than lime stabilization on the mechanical properties of soils with a clay content of over 30%. In addition, Van Damme and Houben (2017) [27] have shown that the ecological cost/mechanical performance ratio of lime treatment is very high. Regarding stabilization with plant fibers, several studies show that plant fiber contents of less than 2% reduce shrinkage while increasing mechanical strength. Above this level, as is often the case with artisanal cob, shrinkage continues to fall but mechanical strength also decreases. One of the challenges for engineers would be to add enough fiber to reduce shrinkage while maintaining mechanical strengths above the minimum required. For use in Adobe, recommended clay contents range from 8-20%, which disqualifies the *macrotermes sp* termite mound soils (MYENG, MODZM, MLOUT, MBOKS) [22].

From Table 3, soils suitable for the manufacture of Adobes bricks have a liquidity limit LL (31-50%) and a plasticity index PI (16-33%) [21]. The *cubitermes sp* and *macrotermes sp* termite mound soils (CBOKS, CLOUT, CMPOU, CNGOC, CNGON, CNTOM, COLLO, CYENG, MBOKS) have the same properties as those reported by Houben and Guillaud 1994 [21].

On the other hand, for the manufacture of compressed earth bricks (CEB), all the normative documents set the liquidity limit LL (25-50%) and the plasticity index PI (2-30%). The *cubitermes sp* and *macrotermes Sp* termite mound soils (CGAMB, MBARA, MBRAZ, MGAMB, MLEKA, MMPOU, MNGOC, MNGON, MNGOS) should be discarded. According to figure 4, the disparity in specific surface areas results from the particle size distribution and the mineralogical composition of the soil. For example, the soils (MBOKS, MYENG), although having the same clay fraction of 31%, have different specific surface areas, respectively 15.28 m^2/g and 10.26 m^2/g, i.e., a difference of 32.85% [24]. This result is in agreement with Amy Cerato *et al.*, 2005 [24] who consider that, despite the fact that clays represent the largest part of the surface of all the constituents of the soil minerals, they have different specific surface areas.

According to figure 4, the presence of kaolinite in the soil is important for the manufacture of solid bricks. The clay acts as a mortar with its crystallizing properties [28], playing a role in improving the mechanical strength of the soil.

According to figures 4-5, illite is an important mineral in the composition of clay soils for the manufacture of bricks, tiles and pottery. Fired clay favors sintering at a relatively low temperature [29]. When illite is present in very high concentrations in a soil, it is the basic material for the manufacture of ceramic products.

According to figure 5, the soils (MNGON, MNGOS) with similar clay contents (37-38%) have low swelling and are composed of kaolinite and illite. The results obtained suggest that swelling does not depend on clay content. The mineralogy of the soils may be responsible for the dispersion of the swelling potential.

According to Figure 7, the plasticity of soil (CNGON) is unsuitable for the manufacture of adobe, CEB and Rammed earth bricks. Thirteen soils (CBARA, CBOKO, CBRAZ, CGAMB, CLOUI, CLOUT, CMBEN, CMPOU, CNGOC, CNTOM, CODZI, COLLO, CYENG) have a plasticity suitable for making CEB bricks. Six soils (CLOUT, CMPOU, CNGOC, CNTOM, COLLO, CYENG) are suitable for making adobe and ten soils (CBARA, CBRAZ, CGAMB, CLOUI, CMBEN, CMPOU, CNGOC, CNTOM, CODZI, COLLO) are suitable for making Rammed earth bricks. The *macrotermes sp* termite mound soils (MLEKA, MBARA, MBRAZ, MODZM, MGAMB, MLOUT) have a plasticity inappropriate for the manufacture of adobes, CEB and Rammed earth. On the other hand, the soils (MYENG, MBOKS) have a plasticity suitable for the manufacture of adobes and CEB, while the soils (MNGON, MOLLO, MNGOC, MNGOS, MMPOU) are suitable exclusively for the manufacture of CEB.

4. CONCLUSION

The geotechnical properties of the *cubitermes sp* and *macrotermes sp* termite mound soils used for the artisanal manufacture of bricks were determined and compared with current standards. The results obtained show that only 7/14 samples of *cubitermes sp* termite mound soils fully comply with the norms for Adobes bricks and CEB compressed earth bricks. For the *macrotermes sp* termite mound soils, only 4/13 samples fully incorporate the normative spindles of Adobes bricks and CEB compressed earth bricks. The *cubitermes sp* termite mound soils are composed of kaolinite and illite. The *macrotermes sp* termite mound soils are composed of kaolinite, illite and montmorillonite. The clay content of soils (CBARA, CLOUT, CNGON, CNTOM, COLLO, CYENG) varies from 33-48% and that of soils (MNGON, MNGOS) from 37-38%, whereas the maximum recommended by most standards is 30%. However, the *cubitermes sp* termite mound soils (7/14) and those from *macrotermes sp* termite mound (11/13) have sand contents higher than the minimum recommended content of at least 30%. For clay contents above 30%, mixing water contents close to saturation are necessary to obtain good compaction; this increases the risk of cracking during drying, leading to premature deterioration of the houses. With the exception of the CNGON soil, the plasticity of the *cubitermes sp* termite mound soils are suitable for the manufacture of mud bricks. For the *macrotermes sp* termite mound soils, only 6/13 have a plasticity suitable for the manufacture of mud bricks. According to the Casagrande plasticity diagram, 8/14 soils from cubitermes sp termite mound and 2/13 soils from macrotermes sp termite mound have good molding properties. The soils (CMPOU, MBRAZ, MLEKA, MNGOC, MMPOU, MGAMB) have a high swelling potential and the CNGON soil has a high plasticity. To correct the excess clay content of the soils, plant fibres, hydraulic sand or lime can be incorporated.

DECLARATIONS

CONFLICT OF INTEREST: The authors declare no competing interests

5. REFERENCES

1. United Nations. Economic Commission for Africa. (2008). *The state of African cities 2008: a framework for addressing urban challenges in Africa*. UN-HABITAT.
2. UN-Habitat. (2008). The state of african cities: a framework for addressing urban challenges in Africa. United Nations Human Settlements Programme (UN-HABITAT).
3. Houben, H., Guillard, H. (1989) . Treatise on earthen construction CRATerre. In: *The Encyclopaedia of Earth Construction*, vol. 1. Paris: Parenthèses, p. 300.
4. Guillaud, H. (2008). Characterization of earthen materials. In: Avrami E, Guillaud H, Hardy M, editors. Terra literature review – an overview of research in earthen architecture conservation. Los Angeles: *The Getty Conservation Institute*, p. 21–31.
5. Houben, H., Guillaud, H. (1994). Earth construction: a comprehensive guide. London; *Intermediate technology publications*.
6. Delgado, M. C. J., & Guerrero, I. C. (2007). The selection of soils for unstabilised earth building: A normative review. *Construction and building materials*, *21*(2), 237-251.
7. Van Damme, H., & Houben, H. (2018). Earth concrete. Stabilization revisited. *Cement and Concrete Research*, *114*, 90-102. http://dx.doi.org/10.1016/j.cemconres.2017.02.035.
8. Mujinya, B. B., Mees, F., Erens, H., Dumon, M., Baert, G., Boeckx, P., ... & Van Ranst, E. (2013). Clay composition and properties in termite mounds of the Lubumbashi area, DR Congo. *Geoderma*, *192*, 304-315.
9. NF, P. (1996). 94-056: Soil: Investigation and Testing–Granulometric Analysis–Dry Sieving Method After Washing. *AFNOR, Paris, France*.
10. NF, P. (1998). 94–068. Soils: Investigation and testing–measuring of the methylene blue adsorption capacity of a rock soil–determination of the methylene blue of a soil by means of the stain test. *Association Française de Normalisation*.
11. NF, P. (1993). 94-051. Soils: Reconnaissance and testing. Determination of Atterberg limits; Limit of liquidity at coupelle – *Limit of plasticity at Rouleau*, Marth.
12. AFNOR, N. F P. (1999). 94-093. Soils: Reconnaissance and testing. Determination of the compaction references of a material.
13. AFNOR XP P13-901 (2001). Granularity and plasticity nomograms. Classification by nature for the soil evaluation (Compressed earth blocks).
14. NTE E80 (2000), Peru. Little recommendations and these are for granularity (Adobe).
15. ARSO (1996), Regional Africa. Granularity and plasticity nomograms. Classification by nature. Enumerate and classify the soil test, not procedure explained (Compressed earth blocks).
16. SAZS 724 (2001), Zimbabwe. Recommendations for granularity, salts, organic content and ribbon test (rammed earth).
17. HB 195 (2002), Australia. Enumeration of field and laboratory test, with procedures given for some. Granularity recommendations for each technique (Adobe, Compressed earth blocks, rammed earth).
18. MOPT (1992), Spain. Suitability through field test with a decision chart. Laboratory tests advisable, with recommendations for granularity (Adobe, Compressed earth blocks, rammed earth).
19. IETcc (1971), Spain. Some provisions for general soil conditions (Adobe, rammed earth).

20. Rigassi V. (1995). Essential granularity, plasticity and compactibility. Field and laboratory identification soil tests are explained (Compressed earth blocks).
21. Houben, Hugo and Guillaud, Hubert. Earth construction: a comprehensive guide. Intermediate Technology Publications (1994).
22. Delgado, M. C. J., & Guerrero, I. C. (2007). The selection of soils for unstabilised earth building: A normative review. *Construction and building materials*, *21*(2), 237-251.
23. Mitchell, J.K. (1976). Fundamentals of Soil Behavior. John Wiley and Sons, New York.
24. Cerato, A. B., & Lutenegger, A. J. (2005, September). Activity, relative activity and specific surface area of fine-grained soils. In *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering* (Vol. 16, No. 2, p. 325). AA Balkema Publishers.
25. Skemptom, A. W. (1953) . The colloidal "Activity" of clays. Proceedings of the 3rd International Conference of soil *Mechanics and foundation Engineering. (1)* 57-60.
26. Elenga, R. G., Mabiala, B., Ahouet, L., Goma-Maniongui, J., & Dirras, G. F. (2011). Clayey soils from Congo and physical properties of their compressed earth blocks reinforced with post-consumer plastic wastes.
27. Van Damme, H., & Houben, H. (2018). Earth concrete. Stabilization revisited. *Cement and Concrete Research*, *114,* 90-102. https://doi.org/10.1016/j.cemconres.2017.02.035.
28. Millogo, Y., Hajjaji, M., & Morel, J. C. (2011). Microstructure, physical and mechanical properties of clayey material from termite mound: a stabilized material for adobe building. *Applied Clay Science*, *51*, 160-164.
29. Sié Kam, Lamine Zerbo, Seynou Mohamed et al. (2009). Clay ceramics from Burkina Faso used in building construction. *J. soc. Ouest-Afr. Chim*.027; 55 – 62.