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Characterization of lithomorphic Vertisols from Kaélé (Northern Cameroon) and their valorization in bricks production

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Abstract

This work is a contribution to the knowledge of Kaele's lithomorphic Vertisols (Northern Cameroon) and their valorization in bricks production. Physical, chemical, mineralogical, geotechnical and mechanical characterizations indicate that these soils are grey to dark grey, compact, and have drying slits that go down to a depth of one meter. They are sandy-clayey to clayey, weakly acidic to basic (6.8 - 9.5 pH), have a medium to coarse polyhedral structure and are rich in organic matter ($2.55 \leq MO \leq 7.08\%$) and relatively well decomposed. Their CEC is between 12.80 and 36.80 meq/100g and the sum of exchangeable bases is medium to high (7.65 to 55.77 meq/100g), dominated mainly by Ca and Mg. These soils are moderately to highly saturate (55.4 to 267.4). They have high silica content (70.93 % SiO_2), average alumina content (18.15 %Al_2O_3) and iron content (8.65 %Fe_2O_3). Bases are dominated by CaO, MgO, Na2O, k_2O, TiO_2, P_2O_5, while Cr^{2-}, Mn^{2+}, and BaO^{2-} are negligible. Their MIA varies between 13.49 and 42.58% showing a low to moderate alteration. The Si/Al + Fe ratio varies between 1.9 and 5.5 implying the presence of 2/1 type clays. From a mineralogical standpoint, these soils are mostly composed of smectite associated to kaolinite and quartz. In addition, oxides are represented by goethite and sometimes hematite. In order to use them well for a sustainable management, earth brick formulations were carried out. Thus, a lime stabilization of the horizons of these soils at the following concentrations: 4%, 6% and 8% showed that the different horizons of these Vertisols have a favorable water absorption (18.25% - 51.52% water absorption), an average linear shrinkage (0.1 – 1.16 cm), an average bulk density (1.08 – 1.51) and a mechanical strength (0.821 – 2.46 N/mm²) which is higher than that of clay in the field (1.05 – 2.05 N/mm²). The characteristics of Kaele's lithomorphic Vertisols can be judiciously exploited in view to promote competitive crude earth bricks.

1. Introduction

Vertisols are clayey dark soils typical of tropical area which enjoy contrasting climate alternating wet and dry seasons [1]. They cover more than 320 million hectares or 2.4% of the global land surface [2] described them as soils with dark color that have a crumbly structure of the surface layer or gilgaï (micro-relief). They are generally located at the top or on the slopes of interfluves, formed from the rock (lithomorphic Vertisols) ([3]; [4]). They can also form on alluvium that occupy variable topographic positions (topomorphic Vertisols), under widely varying climatic conditions ([3]; [5]; [6]). They are particularly excellent supports for growing rice, off-season sorghum (mouskouari), pottery materials and brick production ([7]; [8]; [9]). Their industrial and technological uses or valorization requiring in priority characterization which depending on their physico-chemical, geochemical and mineralogical properties [4]. However, these Vertisols have limits; they are difficult to handle because of their complex physical characteristics (swelling, shrinkage). Therefore, in Kaélé, lithomorphic Vertisols which recover 2/3 of the soil are the most available resource in agriculture, pottery and construction ([10];[11]). Then, mud bricks made from these materials have low mechanical strength due to their physical complexity. They split in dry season but they are bulky and very sticky in rainy season. They easily degrade in contact with water, causing major damage to soil structures and reducing construction durability [9]. In addition, the constructions made by this material are permanently attacked by termites. The constructions are thereby the subject of regular maintenance ([12]; [13]). To solve their housing problem, the people have to resort to block burning which requires a high consumption of energy. the blocs burning most often supplied by forest species, which are becoming increasingly scarce and promoting desertification in this part of the country with a fragile ecology [14]. The present study is focused (1) on the on the physical, chemical, mineralogical, and mechanical characterization of lithomorphic Vertisols from Kaele in view to evaluate their suitability to brick production and (2) the stabilization of lime brick at different concentrations in view to evaluate their mechanical properties and then identify the best formulation for sustainable management.

2. Materials and methods

2.1 Geological setting

Kaélé is located in the Sudano-Sahelian zone of Cameroon especially in Mayo Kani division in the Far North region, between latitude 10°13' and 10°20'N and longitude 14°23' and 14°28'E [15]. Its area is around 200 km^2 (**Figure 1**). This studied zone experiences a Sudano-Sahelian climate characterized by mean annual rainfall of 997.3 mm and a mean air temperature of 31°C [16]. Minimum temperatures are observed in August when precipitations are abundant, while maximum temperatures are reached in April ([17]; [11]). The natural vegetation is a dry savannah with rare tree species where grassland dominated. The tree species observed are mainly Balanites aegyptiaca, Ziziphus mauritiana, Faidherbia albida, Combretum sp and Bombax costatum. The landscape is characterized by plains with altitude around 640 m above the sea level and a few gentle dune slopes. An important part of this plain called yaere is sometimes flooded during the wet season. The main type of soils encountered in the area is lithomorphic Vertisols, poorly tropical ferruginous soils, and hydromorphic soils (flooded soils in lowlands) ([18]; [10]). Preliminary explorations and geological prospecting have made it possible to identify the locations of the wells. This study was carried out in the southwest (SW) part of Kaélé.

2.2 Sampling technics

Two profiles were realized in the studied area at Dardo Tipili (DT) and at Tipili Yewey (TY). The samples were taken from the various horizons identified from the surface to the depth of the profiles until the source rocks (DTR and TYR). The depths of the pits vary from 2.20 (TY) to 2.85 (DT) meters. The DT profile is coordinated to 10°05'N and 14°20'E at 635 m of altitude while the TY profile is coordinated 10°05'N and 14°22'E at 637m altitude (**Figure 2**). After a detailed description, four samples were collected in DT profile, and three in TY profiles. They were air-dried and sieved to 2mm. The fine earth thus obtained was used to carry out the various laboratory analyses.

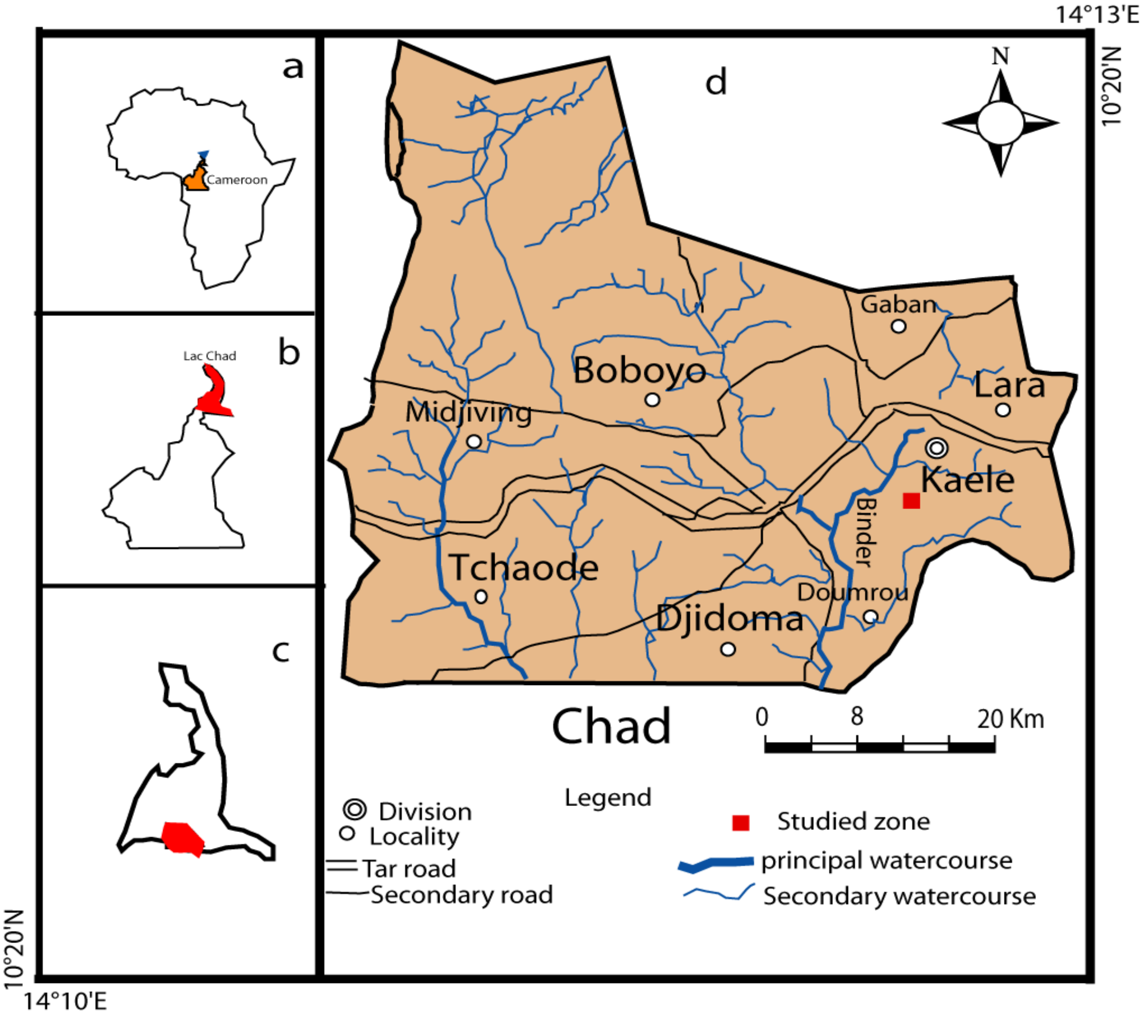

Figure 1. Location map of Kaélé. a: continent of Africa, b: Cameroon; c: Far North Cameroon and d: studied zone

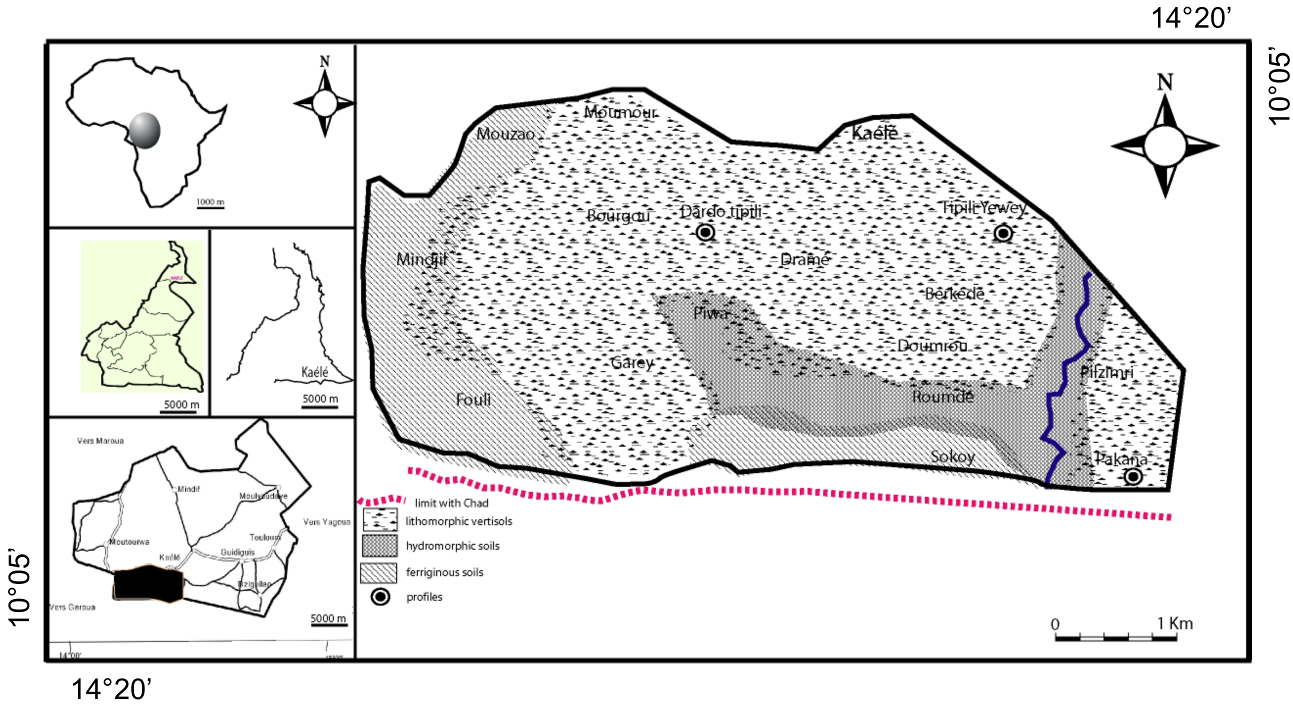

Figure 2. Sampling map in the studied zone.

2.3 Analytical methods

The physico-chemical analysis, the formulation of the specimens and the mechanical tests were carried out in Cameroun at the FASA laboratory at Dschang University, at MIPROMALO (Mission for the Promotion of Local Materials) and at LABOGENIE. Mineralogical analysis was performed by X-ray diffraction and chemical analysis by X-ray fluorescence spectrometry on the total fraction in the GEOLABS laboratory in Canada.

For the physico-chemical analyzes, the following tests were carried out: particle size analysis, organic matter (OM), content of exchangeable bases, CEC and pH. Particle size analysis of soils consists of evaluating the size of the particles. It was carried out by the Robinson pipette method. The technique used to determine the total organic carbon content of the samples was that of Walkley and Black (1934). The OM is deduced by multiplying the OC (organic carbon) rate by 2 (Sprengel factor). The pH was measured in water and KCl with pH meter in 1/2.5 water and KCl suspensions. The exchangeable bases were determined in the soil according to the Metson method. The cation exchange capacity was determined by saturation of the adsorbent complex with the NH^{4+} ion, extraction of exchangeable bases.

Mineralogical analysis was carried out by X-ray diffraction on total powder of the fine fraction. Minerals were identified upon diffraction spectra using High Score X'Pert Plus software (Version 3.0). Each Mineral proportion is obtained by the ratio between the surface areas of specific XRD peaks of each mineral to the total surface of the sample XRD pattern. Major elements were determined by the XRF-MO1 method. The Inductive Plasma Coupled Mass Spectrometry (ICP-MS) method was used for the analysis of minor and trace elements. The CIA (chemical index of alteration) and the MIA (index of mineralogical alteration) were computed in view to determine the degree of alteration of materials. MIA was inferred from the major element data ([18]; [19]; [20]):

$$MIA = 2\ ([Al_20_3 / (Al_20_3 + Ca0 + Na_20 + K_20)] \times 100) -50).$$

The geotechnical characterization combined with the mechanical parameters consisted in determining on the one hand the parameters on the sample’s horizons, and on the other hand on the specimens of stabilized bricks. On samples collected from different horizons, the following tests were carried out: the natural water content of the soil, the particle size distribution, the Atterberg limits (liquidity limit, plasticity limit, plasticity index) and the swelling coefficient.

The water content is the parameter of the fundamental state of soil behavior. It is determined by the stoving method according to standard NFP94-050. The water content is therefore determined by the relation:

$$W= (Mo- M1 \div M1) \times 100.$$

With W: percentage of the water content; Mo: mass of the wet sample; M1: mass of the dry sample.

The Atterberg limit is determined from the Casagrange apparatus on the fraction less than 400µm. The liquidity limit (Wl) is the water content that corresponds to the closure of the groove 10 to 12 cm long by one centimeter in length after 25 shocks in the Casagrande device. The plasticity index defines the extent of the plasticity domain. It is the difference between the plastic limit and the liquidity limit and is written by the following formula:

$$Ip = Wl \text{ x } Wp.$$

The coefficient or rate of swelling was measured by a method derived from that of Robert and Tessier (1974) using a glass graduated in volume. A volume V0 of the sample dried at 105°C in an oven and ground to 2 mm is introduced into this tube. It's obtained by the following relation:

$$Cs = \left(\frac{V0 \quad V1}{V0}\right)X100$$

With Cs: coefficient of swelling; Vo: volume of the dry sample, V1: volume of the wet sample.

The method of distribution of the sizes of the particles or granulometry of the material was carried out in two stages: By wet sieving for soil particles greater than 80µm. According to the NFP 946056 standard, wet sieving provides access to the sieve at 80µm. To have the data sharpness, the measurements were taken 3 times. To obtain the percentages of the fraction of each given particle size, the following procedure was carried out:

$$\%\ \text{fraction} = \left(\frac{fraction \leq 80mm}{T}\right)X100$$

On stabilized bricks, linear shrinkage, bulk density water absorption and compression test were performed. Only the samples from the horizons of the TY profile have been subjected to geotechnical and mechanical tests.

For the stabilization of these soils, the aerial lime (or slake) was used. The samples were stabilized at four different contents (0%, 4%, 6% and 8% lime each added to 100g of material). The specimens were made from a cylindrical iron mold and lime-stabilized clay material, 6 cm high and 4 cm in diameter. The manufacture of the specimens consisted of grinding and mixing the material with the stabilizer, molding and drying of the stabilized bricks. Grinding consisted of crushing the material, passing it completely through a sieve with a mesh size of less than 1 mm. To make the results clear, readable and understandable, a nomenclature of specimens at different levels has been adapted.

3. Results and Discussion

3.1 Morphological and physico-chemical characterization of lithomorphic Vertisols of Kaélé

Two main profiles are described below. They are DT (Dardo Tipili) and TY (Tipili Yewey) profiles. The morphological characterization of the soils consisted in describing the horizons from the top to bottom. The DT profile is located 3 Km in the South of Kaele and more than 200 cm thick and formed on granite (**Figure 3**). Micro reliefs (gilgaï) and desiccations cracks are observed at the surface.

0-45 cm: Horizon DTHA, dark gray (2.5Y-4/1), clayey, lumpy, grains of pebbles and the boundary with the next horizon is almost sharp.

45-65 cm: Horizon DTHB$_{th1,}$ very dark gray (10YR-3/1), clayey silt, massive, large pores, nodules, worms, non-progressive boundary.

65-85 cm: Horizon DTHB$_{th2,}$ greyish dark brown (10YR-4/2), clayey sandy, massive to blocky, porous, unaltered minerals of quartz and feldspar.

85-185 cm: Horizon DTHB$_{Ca,}$ greyish brown (2.5Y- 5/2), sandy silt, blocky, porous, limestone nodules, pebbles and unaltered minerals of quartz and feldspar.

185-285 cm: Horizon DTHC: alloterite, light gray (2.5YR-7/1), sandy and particular.

From 285 cm: DTR/Rock (granite), light gray (2.5YR-7/1), massive or blocky, alterated.

The Profile TY is situated 2 km in the SW of Kaélé city, at latitude 10°05'N, longitude 14°21'E and altitude at 637m. It is 180 m thick and shows three horizons formed on granite (**Figure 4**), one can observe:

0 - 40 cm: Horizon TYHA, greyish-brown (10YR-5/2), sandy clay, blocky or massive, porous, plant roots, non-progressive limit with the following horizon.

40 - 60 cm: Horizon TYHB_{Ca}, greyish-brown (10YR-5/2), sandy clay, particular, some pebbles, gravels and consolidated limestone nodules, progressive limit with the underlying horizon.

60 -160 cm: Horizon TYHB_h, gray (10YR-5/2), sandy clay, blocky to particular, compact, few roots, progressive limit.

160 -220 cm: Horizon TYHC: whitish alloterites, grains of quartz and form a deposit of sand.

From 220 cm: TYR/ granite, massive.

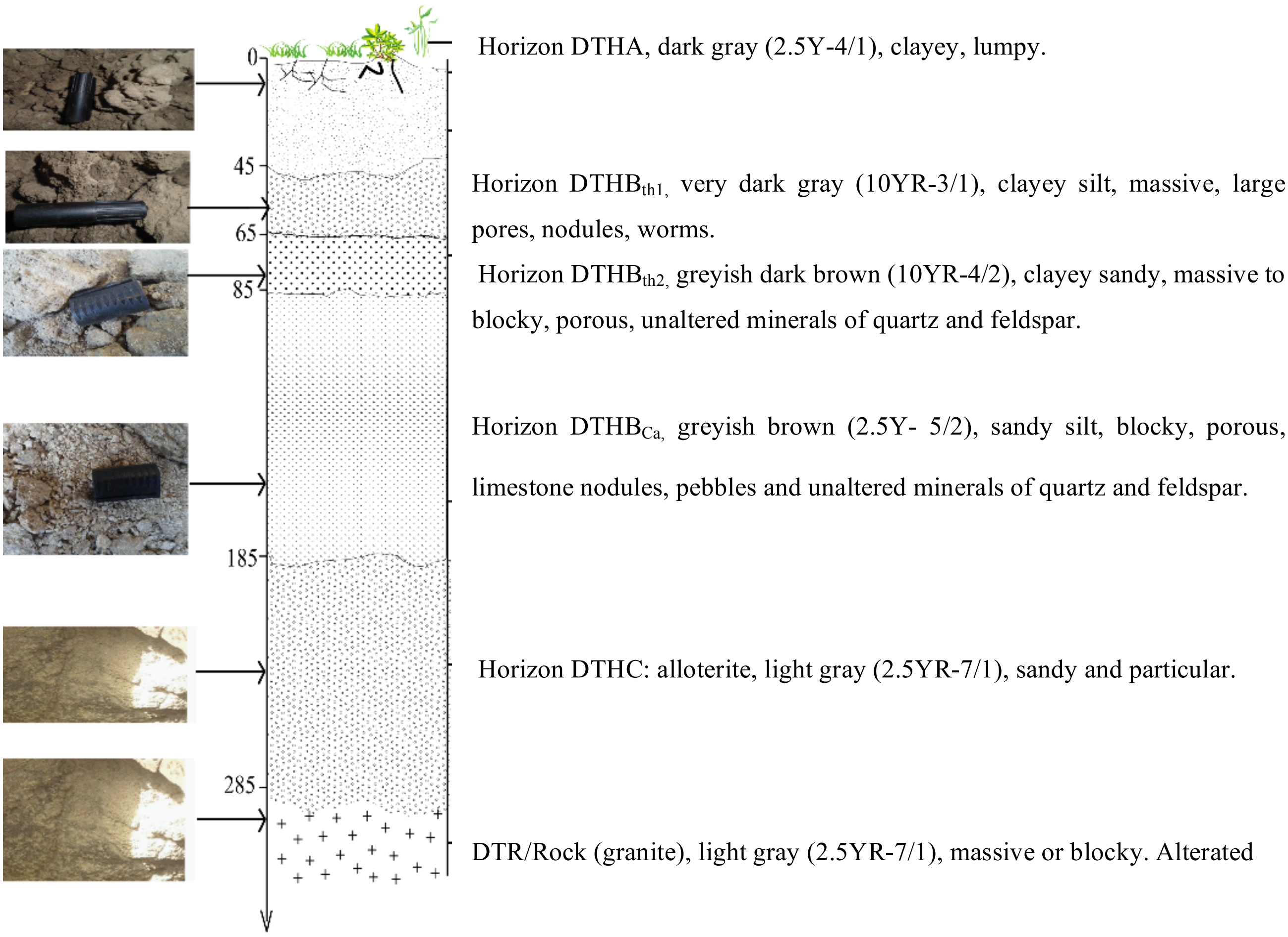

Figure 3. Lithomorphic Vertisols profile of Dardo Tipili

In Kaele, lithomorphic Vertisols are wides preadest. They are mostly gray and naturaly presenting cracks and sliding surfaces (gilgaï). Their structure is massive with prismative macrostructure on the surface ([4]; [9]; [10]; [21]; [22]). They are clayey, compact, porous and have shrinkage or desiccation slots up to one meter depth. These characters are be related to a high proportion of fine fraction. Weakness of biological activity is generally observed in these types of soils ([23]; [24]; [25]; [26]). The color of Vertisols due to granite alteration is globaly gray to dark gray. That dark gray color is due to the high silica content in the clay fraction of the soils allowing a very low amount of organic matter on the entire horizons of profiles ([23]; [24]; [25]). Then, The dark color of Vertisols results from the formation of a complex between mineralogical clay and organic matter ([1]; [27]; [4]). The lithomorphic Vertisols present a thickness which is more than 3.5 m in depth ([27]; [10]).

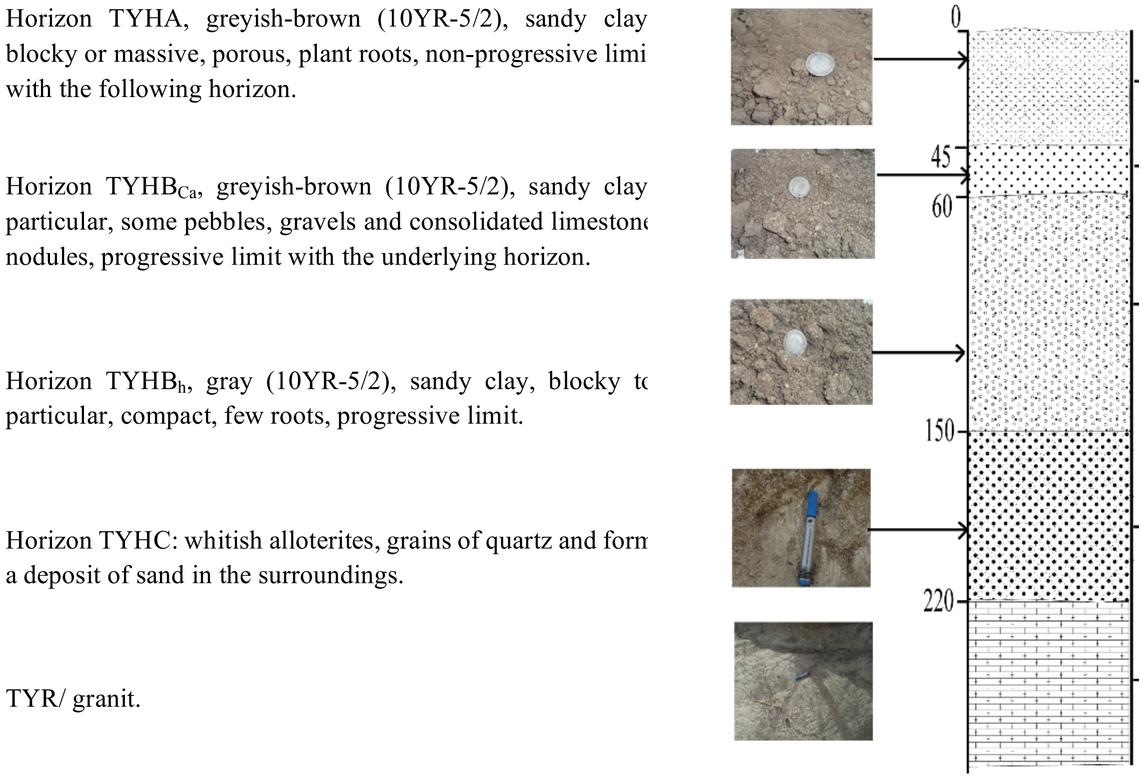

Figure 4. Lithomorphic Vertisols profile of Tipili Yewey

As Vertisols reveal the predominance of fine fraction with 60 to 70% (28), those of Kaélé varies between 50 to 70%. There is the phenomenon of swelling, which is linked to this fine fraction ([27]; [28]; [25]; [24]). The physicochemical analyses of the lithomorphic Vertisols of Kaele (DT and TY) display 14.44% to 86.02% of clay, 7.62 to 57.31% of sand and 6.35 to 36.24 of silt (**Table 1**). Those Vertisols are generally sandy-clayey to clayey. Contrary to sand content, it is observed that, clay content increases from the bottom to the top.

Table 1. Physico-chemical parameters of lithomorphic vertisols of Kaele

Samples	Clay	Sand	silt	Texture	pH_2O	pKCl	OM	OC	TN	C/N	Ca^{2+}	Mg^{2+}	Mg/Ca	S	CEC	S/T
DTHA	86.02	7.62	6.35	CL	6.84	6.11	3.78	1.89	0.42	4.500	0.2	7.4	37.00	7.65	12.8	55.4
$DTHB_{th1}$	24.95	44.8	30.25	CL	6.8	5.9	7.08	3.52	0.4	8.800	0.22	24.82	112.82	25.23	23.2	10.8
$DTHB_{th2}$	25.72	48.3	25.98	SL	6.75	5.63	2.55	1.27	0.35	3.629	0.32	19.68	61.50	20.08	24.4	82.2
$TYHB_{Ca}$	48.00	18.00	34.00	SL	9.5	7.6	1.69	0.98	0.13	7.538	11.88	1.52	0.13	13.60	20.64	65.89
TYHA	30.36	35.87	33.76	SC	7.6	6.54	4.59	2.29	0.31	7.387	0.34	29.26	86.06	29.65	36.8	80.5
$TYHB_{Ca}$	16.14	57.31	26.55	SC	8.19	6.69	4.59	2.29	0.31	7.387	0.22	24.34	110.64	24.73	24	10.3
$TYHB_{h}$	14.44	49.32	36.24	SC	8.34	6.51	4.8	2.4	0.29	8.276	3.15	54.45	17.29	57.77	21.6	267.4

The pH_{KCl} varies from 8.34 to 5.63 while the pH_{H2O} varies from 6.7 to 9.5, decreasing from the bottom to the top. These Vertisols are neutral to basic. Their organic matter content (1.69 to 4.8%) is medium to very high, and also decrease from surface to depth as clay content and acidity. The nitrogen (N) content varies from 0.13 to 0.42% and the C/N ratio, from 3.62 to 8.82, indicating that the OM is well decomposed. The exchangeable bases are dominated by magnesium (Mg^{2+}) (7.4 - 19, 68 meq/100g for DT and 1.52 -54.45 meq/100g for TY in Mg) followed by calcium (Ca^{2+}) (0.2 - 11.88 meq/100g for DT and 0.34 - 3.15 meq/100g in Ca). The Mg/Ca ratio showing an overall high degradation rate in organic matter in these soils (0.13 - 112.82). They display low to medium cation exchange capacity (12.8 - 24.4 meq/100g) (**Table 1**). The S/T ratio shows that these soils are saturated to very saturated (55.4 - 108).

The different physicochemical characteristics of lithomorphic Vertisols overall have a granulometry which includes clay content varying from 16.14% to 86.02%. Then, silt varies from 7.00 to 36.24% and sand from 7.62 to 75.00%. This hight content of clayey fraction makes part of Vertisols ([1]; [23]; [29]; [30];[5];[31];[10], [3] ; [32]; [24]; [26]). According to Ghislain's guide for interpretation of soil analyses (2005), these soils are classified as heavy soils. Their obtained pH (6.8 to 9.5), indicates a weakly acidity to moderate alkaline character according to the agronomist's memento (1993) ([4]; [9]). The organic matter (1.69 to 1.8%) observed in these soils are related to the vegetation and water regime ([3]; [9]). The C/N (3.62 to 8.82) show that OM on these Vertisols are well decomposed [32]. The content of exchangeable bases is mainly dominated by Mg^{2+} followed by Ca^{2+} and the absorbant complex is saturated by those ions. The cation exchange capacity (16.00 - 39.84 meq/100g) is high and its increases with the rate of clay fraction [10]. These CEC values indicate that the soils are composed of mixture of smectite and kaolinite ([10]; [33]). The lithomorphic Vertisols of Kaele are saturated to very saturated, with very high S/T ratio ([33]; [34]).

3.2 Mineralogical and geochemical characteristics of the studied soils

The XRD patterns of the studied samples are presented in **Figure 5.** It appears that the main clay mineral of different horizons is smectite (**Table 2**), identified by its broad basal spacing d00 at 14.97Ǻ. It is associated to minor amount of kaolinite identified by its basal spacing at 7.2Ǻ. Quartz, feldspar and iron oxides (hematite and goethite) are also present along the profile (**Figure 6**). The content of smectite slightly increases from the bottom to the top. The presence of smectite associated to kaolinite suggests that the main crystallochemical process involved is bissialitisation and monosiallitisation ([4]; [8]; [9]). These phenomenons are due to hydrolysis of rock mineral, which result in a partial loss of silica and alkali cations. This inducts the neoformation of 2/1 types clay mineral ([27]; [4]).

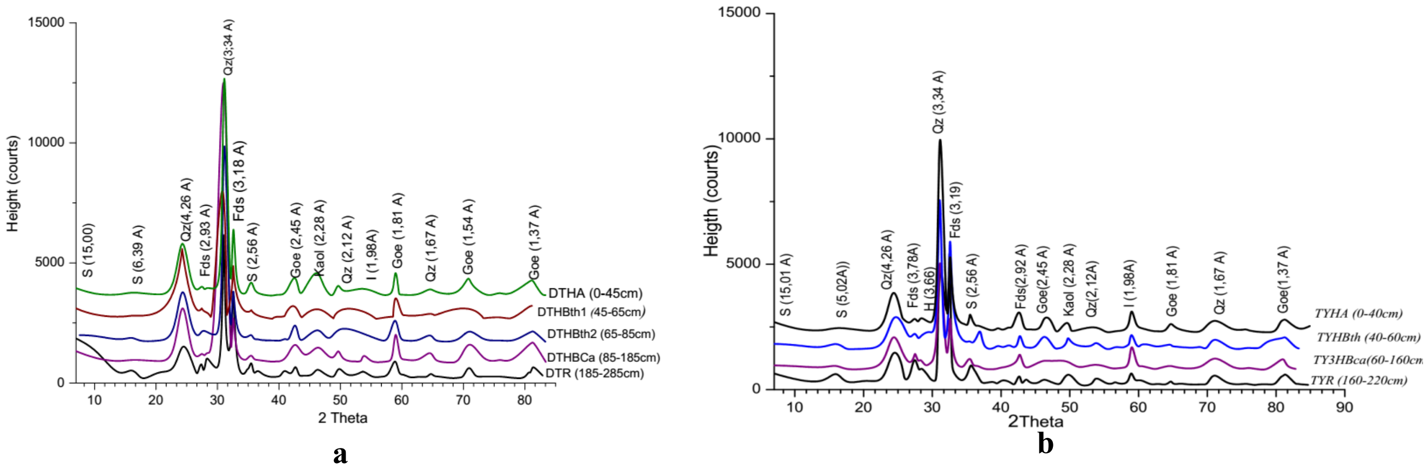

Figure 5. X-Ray Diffraction (XRD) of DT and TY profiles.

The major, trace and rare earth elements content of the rocks and bulk soil samples are presented in **Table 3, 4, 5**, respectively. In DT profile, the amount of Mg and Ti content decrease while each of profile TY increases. Globally, amounts of Si, Fe, K, Nitrogen and LOI (loss on ignition) increase while Ca, Na are decreasing from the bottom to top of both two profiles (**Figure 7**).

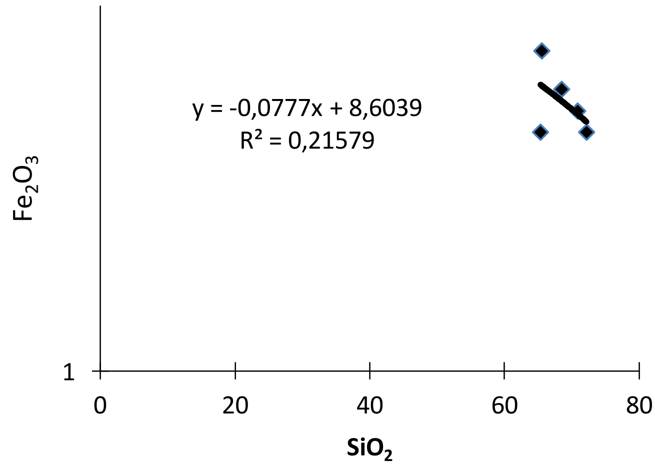

Figure 6. Variation of iron and alumina in function of silica on the Kaele's lithomorphic Vertisols

Table 2. Relative mineralogicaly composition of lithomorphic vertisols of Kaele.

Echantillon	Smectite	Illite	Kaolinite	Quartz	Feldspath	Hématite	Goethite
DTHA	++	+	+	++++	+++	+	+++
$DTHB_{th1}$	++	+	+	++++	++	/	+++
$DTHB_{th2}$	++	+	+	++++	+++	/	+++
$TYHB_{Ca}$	++	+	+	++++	++	/	+++
DTR	+++	+++	+	++++	++++	/	++
TYHA	++	++	+	++++	+++	+	+++
$TYHB_{Ca}$	++	++	+	++++	++++	+	+++
$TYHB_h$	++	++	+	++++	+++	+	+++
TYR	++	++	+	++++	++++	+	+++

Table 3. Major elements for lithomorphic vertisols of Kaele.

Samples/ majors elements	DTHA	$DTHB_{th1}$	$DTHB_{th2}$	$TYHB_{Ca}$	DTR	TYHA	$TYHB_{Ca}$	$TYHB_h$	TYR
SiO_2	68.42	65.54	72.16	70.87	65.32	67.58	66.72	63.61	62.28
Al_2O_3	13.56	14.15	12.77	12.74	15.97	15.08	16.26	16.2	16.76
Fe_2O_3	3.46	4.09	2.86	3.14	2.86	3.22	3.44	3.76	4.02
TiO_2	0.66	0.73	0.52	0.58	0.36	0.56	0.51	0.6	0.56
K_2O	0.98	0.99	0.94	0.86	1.75	1.26	1.28	1.12	0.83
MgO	0.6	0.68	0.43	0.52	0.79	0.67	0.43	0.48	0.32
CaO	2.521	2.332	2.722	2.824	3.19	0.106	0.073	0.052	0.165
Na_2O	2.52	2.21	3.01	2.66	4.61	3.025	3.232	3.04	6.84
P_2O_5	0.072	0.069	0.057	0.065	0.13	3.46	3.99	3.2	4.8
BaO	0.058	0.06	0.058	0.054	0.08	0.06	0.056	0.056	0.035
MnO	0.08	0.094	0.069	0.074	0.02	0.003	0.003	0.003	0.002
Cr_2O_3	0.006	0.008	0.004	0.004	0.002	0.069	0.056	0.056	0.054
LOI	6.96	8.43	4.35	5.15	4.58	5	4.5	6.64	2.94
Nitrogen	2.75	3.76	1.82	2.23	1.54	2.06	1.95	3.06	0.74
CIA	69.25	73.67	65.68	63.43	61.83	66.06	65.66	68.76	57.33
MIA	38.5	47.34	31.37	26.86	23.66	32.13	31.32	37.52	14.66
Si/ Al	8.69	8.38	10	9.75	7.2	8	7.4	7	6.62

LOI: Loss on ignition.

The studied soils are mainly constituted by SiO_2 (62.28 - 72.16%), Al_2O_3 (12, 63 - 16.76%) and Fe_2O_3 (2.86 - 4.09%). Those results are in agreement with many studies ([10]; [26]; [27]; [34]; [31]). The silica is predominant and its content is relatively high to very high. That is similar to topomorphic

Vertisols ([26]). The Si/Al ratio, which varies between 6.62 and 10, reveals the presence of 2/1 type clay, with an alumina-silicate character on the horizons (**Table 3**). Then, there is a bissialitization environment ([35]; [36]; [10]; [9]).

Table 4. Trace elements for lithomorphic vertisols of Kaele

Trace elements/ granit	DTHA	$DTHB_{th1}$	$DTHB_{th2}$	$DTHB_{Ca}$	DTR	TYHA	$TYHB_{Ca}$	$TYHB_h$	TYR
V	42.54	49.06	30.83	34.97	17.17	34.29	32.72	38.78	12.71
Cr	19.13	22.02	11.94	14.58	7.82	11.14	10.06	13.42	4.78
Co	12.097	14.25	8.923	9.385	5.039	8.127	7.095	6.995	2.129
Ni	12.9	14.6	8.5	10	6.4	9.3	8.1	9.9	4.3
Cu	15.7	19.3	10.5	12	3.3	6.2	5.3	5.8	4.2
Zn	33.5	36.3	21.9	25.4	64.4	44	22.7	26.2	22.5
Rb	12.161	14.07	8.205	9.169	2.16	13.559	9.305	11.506	1.831
Ga	5.499	6.494	3.486	4.265	2.296	5.163	4.092	5.878	2.785
Sr	63.42	66.15	42.42	51.01	109.8	53.12	47.84	60.7	187.55
Y	9.654	11.76	6.123	7.134	5.347	34.29	32.72	38.78	12.71
Zr	2.923	3.776	2.361	2.415	2.995	2.585	2.26	2.986	2.844
Nb	0.219	0.204	0.155	0.166	0.237	0.153	0.153	0.145	0.244
Ba	173.16	210.5	118.9	131.98	78.51	161.1.	130.33	147.71	33.57
Pb	5.87	6.98	4.64	4.91	5.75	3.86	3.9	4.41	2.45
Th	0.062	4.946	2.308	2.571	0.952	2.922	1.873	2.394	1.173
U	0.6122	0.673	0.443	0.4899	0.2549	0.3768	0.4291	0.5469	0.3171
La	17.91	21.37	11.66	13.44	11.15	15.22	15.12	17.45	15.48
Ce	47.99	56.38	33.7	39.86	29.13	0.6232	0.6185	0.7895	0.6513
Nd	21.923	21.72	11.38	13.126	12.624	14.511	14.388	16.553	14.826
Cd	0.029	0.028	0.029	0.033	0.08	0.016	0.021	0.019	0.05
Hg	0.014	0.015	0.09	0.01	0.006	0.009	0.006	0.006	0.006

Table 5. REE of lithomorphic Vertisols of Kaele.

REE/ Chondrite	DTHA	$DTHB_{th1}$	$DTHB_{th2}$	$TYHB_{Ca}$	DTR	TYHA	$TYHB_{Ca}$	$TYHB_h$	TYR
La	17.9	21.37	11.7	13.4	11.2	15.2	15	17.5	15.5
Ce	48	56.38	33.7	39.9	29.1	36.6	41	47.8	21.2
Pr	4.55	5.517	2.92	3.39	3.19	3.78	3.7	4.29	3.93
Nd	21.9	21.72	11.4	13.1	12.6	14.5	14	13.6	14.8
Sm	3.34	4.061	2.2	2.4	2.09	2.5	2.4	2.97	2.47
Eu	0.72	0.865	0.46	0.54	0.5	0.55	0.6	0.7	0.51
Gd	2.65	3.117	1.66	1.96	1.42	1.78	1.7	2.1	1.73
Td	0.36	0.431	0.23	0.26	0.18	0.23	0.2	0.28	0.23
Dy	1.97	2.395	1.29	1.43	0.99	1.28	1.3	1.57	1.32
Ho	0.37	0.448	0.24	0.26	0.19	0.24	0.2	0.3	0.25
Er	0.98	1.202	0.62	0.73	0.51	0.62	0.6	0.79	0.65
Tm	0.14	0.163	0.09	0.1	0.07	0.09	0.1	0.11	0.09
Yb	0.82	0.962	0.53	0.59	0.42	0.5	0.5	0.67	0.53
Lu	0.11	0.136	0.07	0.08	0.06	0.07	0.1	0.09	0.07
ΣREE	96.4	109.9	62.3	72.8	58.7	73.2	77	86.8	58.4

The MIA of Kaele's Vertisols which presents values between 9.22 and 47.34, proves that these soils are weakly to moderately altered. These values also indicate the abundance of smectite in Vertisols ([37]; [38];[26];[9]). The content of ferromagnesian minerals is 2 to 16 % of Fe_2O_3, 1.68 to 8.23% of CaO and 0.77 to 2.38 % of MgO. Those values have implied that they are lithomorphic Vertisols [27]. This suggests that the ferromagnesium contents on lithomorphic Vertisols vary from one medium to another. The continuity observed in the horizons and the identical characteristics two profiles will indicate that these soils are formed from the same granite basement [10].

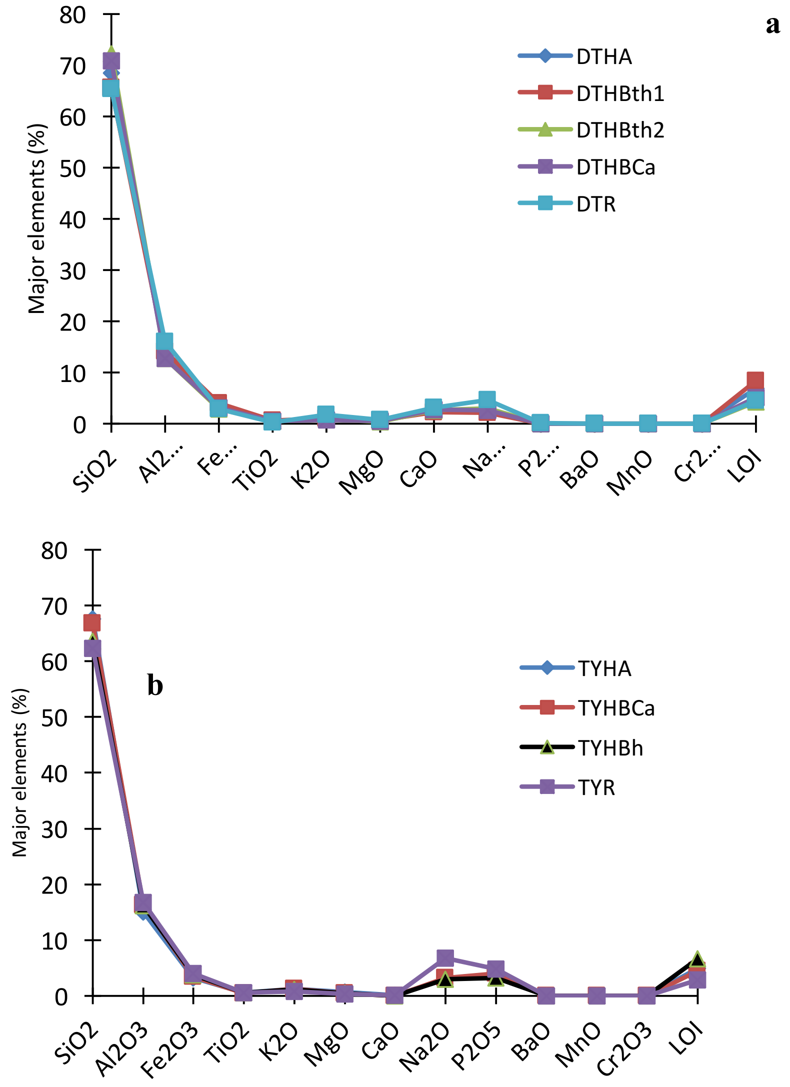

Figure 7. Major elements rate of (a) DT and (b) TY profiles.

The rock-normalized trace element spectra (McDonough and Sun, 1995) presented in **Figure 8**, occur in regular ways. These soils present depletion or leaching in Cr, Zn, Sr, Ba, Ce and La. They also present enrichment or predominance in Ga, Sr, Nb, Th, Cu, U, Rb, Y, from the surface to the depth of the profiles. Horizons are poor in alkaline elements (Li (1.046 - 6.69ppm) and Rb (1.83 - 14.73 ppm) from top to bottom of profiles (DT and TY), until the granite. They are, otherwise, rich in alkaline earth metals such as Sr (32.72 - 187.57ppm) and Ba (33.57 - 210.5ppm) (Table 4). Alkalis and alkaline earth indicate existence of bisialitizing medium ([33]; [13]). The spectra normalized to chondrites [39] reveal negative anomalies in Eu (δEu = 0.03 - 0.91), some positive anomalies in Ce (δCe = 0.66 - 1.07). The weathering processes preferentially eliminated Eu. It's also suggests that they have a common source material, such as granitic bedrock. Additionally, the granite-normalized REE distribution of the soil horizons display similar behaviour with a slight negative Ce anomaly and a significant negative Eu anomaly, which could be attributed to chemical fractionation of the plagioclase during weathering processes. The REEs are remobilized in the weathering materials and their content increases from the bottom to the top of the profiles (**Figure 9**).

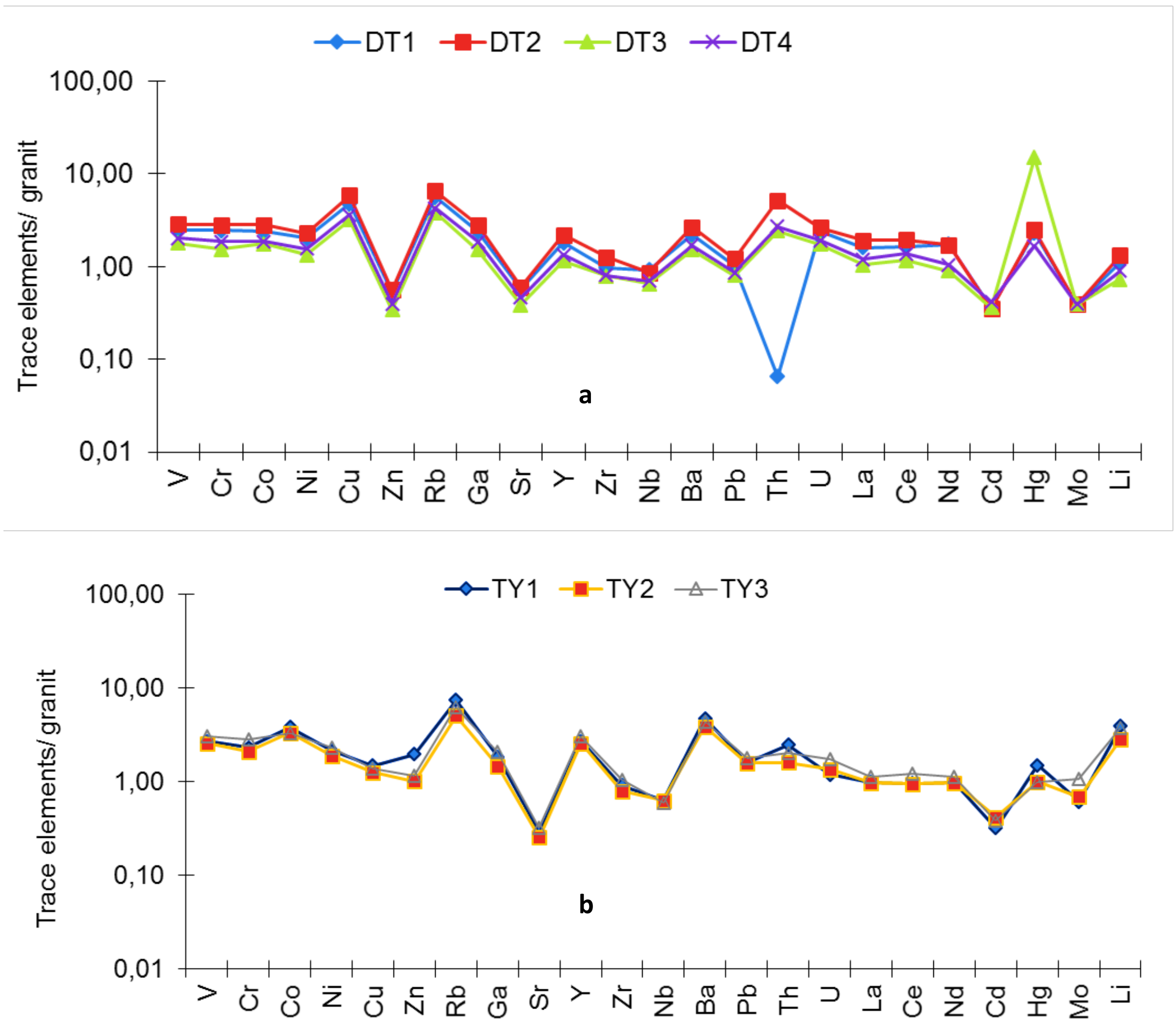

Figure 8. Trace elements of (a) DT and (b) TY profiles normalized by Granite.

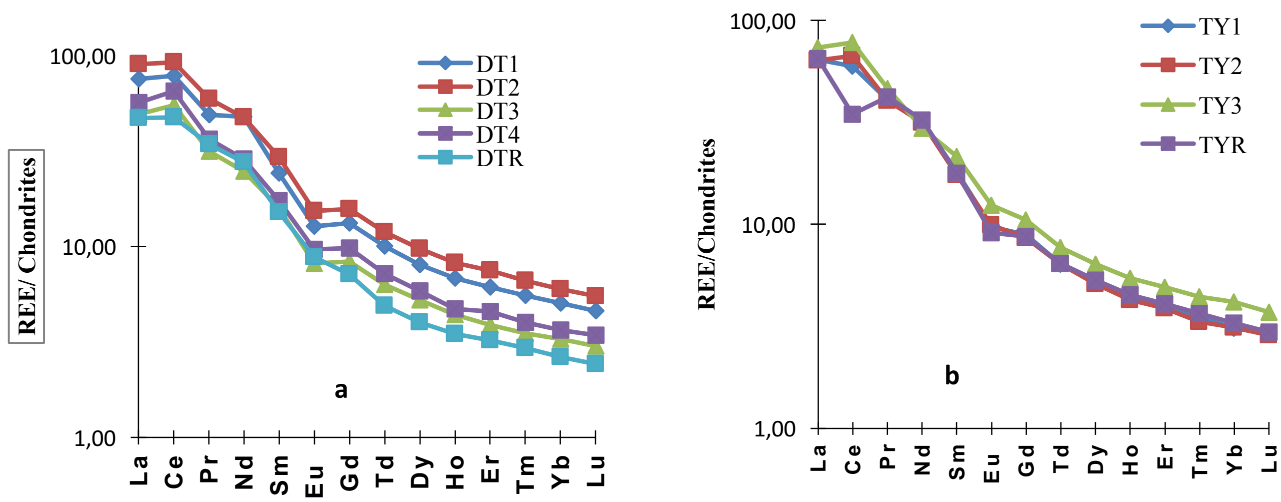

Figure 9. REE of (a) DT and (b) TY profiles normalized by chondrites.

3.3 Geotechnical characteristics and mechanical parameters of Kaélé Vertisols

The geotechnical and mechanical studies were carried out only on the samples of the horizons of TY profile, a representative site of large-scale exploitation in brick production at the studies zone (Kaele).

The plasticity determination of crude clay materials of TY soils consisted of evaluating the liquidity limit, the plasticity limit and the plasticity index of the samples taken from the first two horizons (TYHA and TYHBCa) (**Figure 10**). The results indicated that the TYHBh (depth horizon) is less plastic than the overlying horizons (TYHA and TYHBCa). The liquidity limit is 28 at TYHBh, but is found at 39.90 and 51.1 at TYHA and TYHBCa respectively. The plasticity index of TYHBCa (17.1%) is higher than that of TYHA (14.1%). This plasticity increases from top to bottom of the profile and is very low in TYHBh (5.73%), which is sandy (**Table 6**).

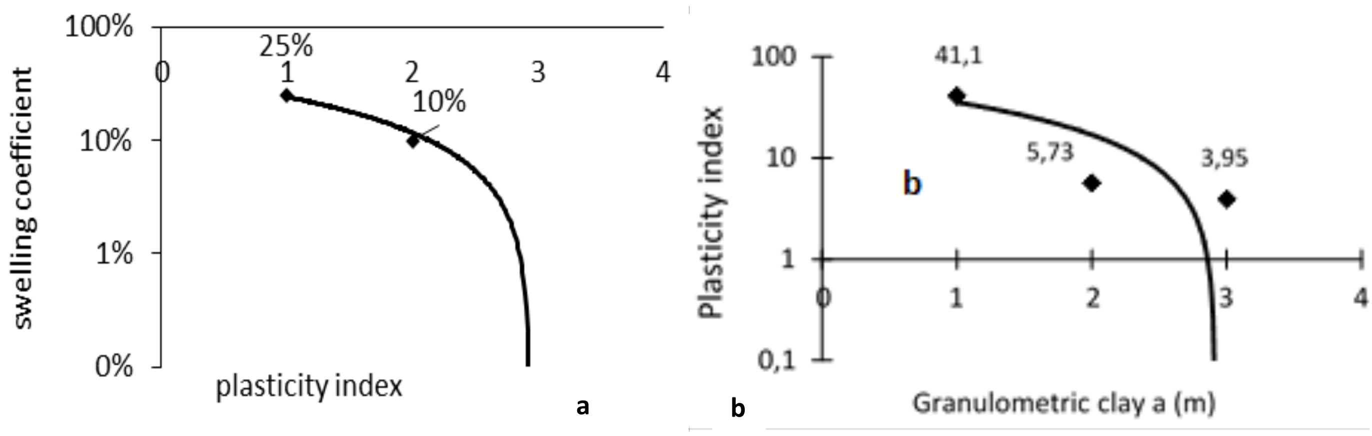

Figure 10. Swelling coefficient (a) and plasticity index (b) of Vertisols samples from the Tipili Yewey profile.

After 24 hours of immersion, the TYHBCa sample had a slight swelling of either 1ml which equal to a coefficient of 10%. However, those of TYHA and TYHBh samples effectively swelled, with a swelling coefficient of 25% and 23.07%, respectively. Therefore, the subsurface horizon (TYHBCa) experiences a slight swelling compared to the other two horizons (TYHA and TYHBh). It decreases considerably from the surface towards the median (25 to 10%), then increases at the bottom (10 to 23.07%) (**Table 6**). There is a positive correlation between the swelling and the plasticity of the material, from the surface to the depth (**Figure 10**). This shows that the horizons of lithomorphic Vertisols of Kaélé can be homogenized for good exploitation. The liquidity limit (Lw) and the plasticity index (Pi) are respectively between 28 to 51.10% and 5.73 to 17.10%. They systematically decrease from the surface to depth of the profile. Then, many authors, also shown that clay contained content in these soils is active ([27]; [24]; [3]; [26]). The increase and/or decrease in the liquidity limit depend on the type of soil: it decreases for the montmorillonitic clay soil. In addition, treatment with the lime on saturated calcic clays shows increases of the liquidity limit. Swelling tests (swelling coefficient) indicate that after 24 hours of imbibing the samples of material horizons, a swelling rate is observed which varies from 10 to 25%. It decreases from the surface (TYHA) to depth (TYHBh) of profile. These values explain the behaviour observed in Vertisols ([10]; [9]).
The Granulometry or grain size particles of building materials of Kaele shows that clay content gradually decreases from the surface to the depth (30.22 - 2.22 %) (**Table 7**). It can be seen that this reduction is systematic on the surface. The silt content is between 1.75 and 10.85% (**Figure 11**). It decreases considerably from the surface (10.85%) towards the median horizon (1.50%) and increases slightly at depth (1.75%). The sand content varies between 27.19 and 40.57%. It increases from the surface towards the median (27.19 to 40.57%) and decreases in depth (40.57 to 29.92%).

Table 6. Liquidity limit, plasticity index and swelling of lithomorphic vertisols

Samples	Lw	Pw	P_I	V1 ml	V0 ml	Cg (%)
TYHA	39.90	25.80	14.10	10	12.5	25%
$TYHB_h$	51.10	34.00	17.10	10	11	10%
$TY3HB_{Ca}$	28	22.45	5.73	10	13	23.07 %

Table 7. Particles size of TY profile

Horizons (diameters)	**TYHA**	**$TYHB_{Ca}$**	**$TYHB_h$**
< 2 µm	30.28	2.39	2.22
2 - 80 µm	10.85	1.50	1.75
80 - 200 µm	20.92	21.95	18.66
200 - 500 µm	9.17	2.41	3.12
500 µm -1mm	10.59	20.68	2.35
1-2 mm	7.43	17.48	27.57
2 - 3.5 mm	9.20	27.59	23.15
> 3.5 mm	1.56	6.00	21.18
Total	100	100	100

These results show that the surface horizon (TYHA) is clayey sandy while the B horizons (TYHBca and TYHBh) are sandy clayey. The particle size content of these Vertisols varies between 3.48 to 41.1%. These results are more or less related to those observed by many authors ([27]; [9]; [10]) who found 10 to 40% of clays content. However, lithomorphic Vertisols of Kaélé are more clayey on the surface (41.1%). This can be explained by the low weathering rate and the proximity to the basement [27].

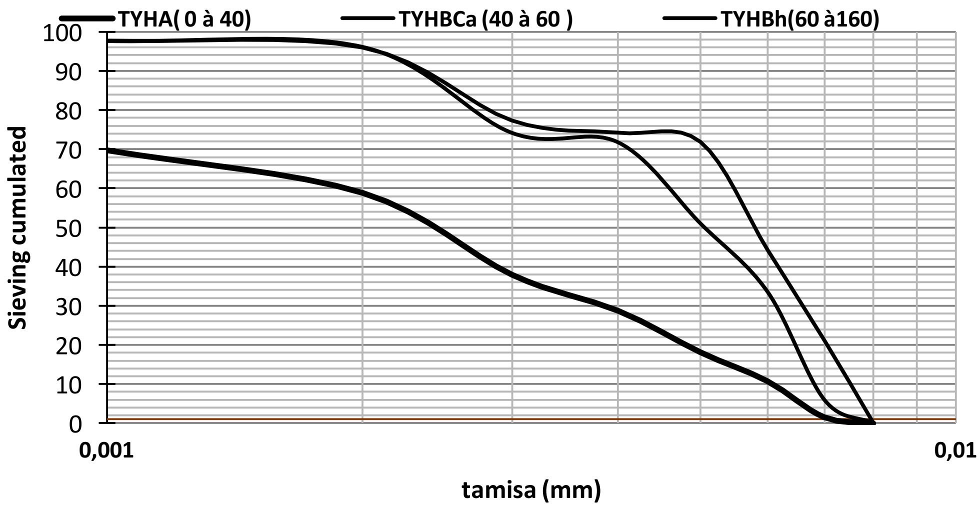

Figure 11. Distribution of particles size.

The linear shrinkage of the specimens from the three samples stabilized respectively at 0%, 4%, 6% and 8% lime varied according to the horizons (**Figure 12**). So, It was found after linear shrinkage tests that TYHBca specimens stabilized at 6% and 8% of lime gave favorable results. Indeed, when the shrinkage decreases considerably or varies very little on a specimen at the end of treatment, they have poor quality ([40]; [41]). This is the case of TYHA and TYHBca samples which stabilized at 4% of lime and TYHBh stabilized at 8% of lime. Consequently, the specimens of TYHA and TYHBca

stabilized at 4% of lime and those of TYHBh stabilized at 8% of lime shown a shrinkage that varies either very little or is widely [9]. So, these dosages would not be advised or recommended to producers in the field, because they are very poor quality specimens. The decrease in the mass of the specimens during the treatment time is due to the departure of the dosed water during the molding. It can be seen that these tests only characterize fired bricks and those stabilized with lime ([42]; [12]; [9]). The latter observed an increase in the mass of the specimens as a function of the lime dosage; and it is the same with those of the lithomorphic Vertisols of Kaélé. Some authors showed that their sensitivity to water despite the stability is due to the grain size ([42]; [9]). However, other authors ([43]; [44]) showed that it is due to the organic matter content which is above 2 %. When organic matter content is more than 2%, the material suffers from a short and / or long-term settlement problem.
The apparent density of the specimens was determined at 24 hours after molding, at 7, 30, and 75 days of cure or treatment in the open air, then finally dried in an oven at 105°C (**Figure 13**). The highest densities are those of unstabilized mud bricks from the B horizons (C0TYHBca and C0TYHBh). It varies slightly in all horizons for stabilized specimens (4, 6 and 8 % of lime) [43]. In fact, it gradually decreases with the curing time and decreases from 1.08 to 1.51 g/cm^3 for specimens stabilized at 0% of lime. It increases from 1.09 -1.49 g/cm^3 for specimens stabilized at 4% of lime, from 1.19 to 1.32 g/cm^3 for those stabilized at 6% of lime and finally from 1.21 to 1,30 g /cm^3 for specimens stabilized at 8% of lime. The incorporation of lime has a slight effect on the density of the specimens because it varies from the start to the end of the cure (75 days). It decreases slightly with 4% to 6% of lime and increases with depth, for specimens stabilized at 8% of lime. The incorporation of lime had an effect on the density of specimens because it varied very little from the beginning to the end of process (75 days) in lithomorphic Vertisols. But, in topomorphic Vertisols, this bulk density does not vary on the specimens [13]; [15].

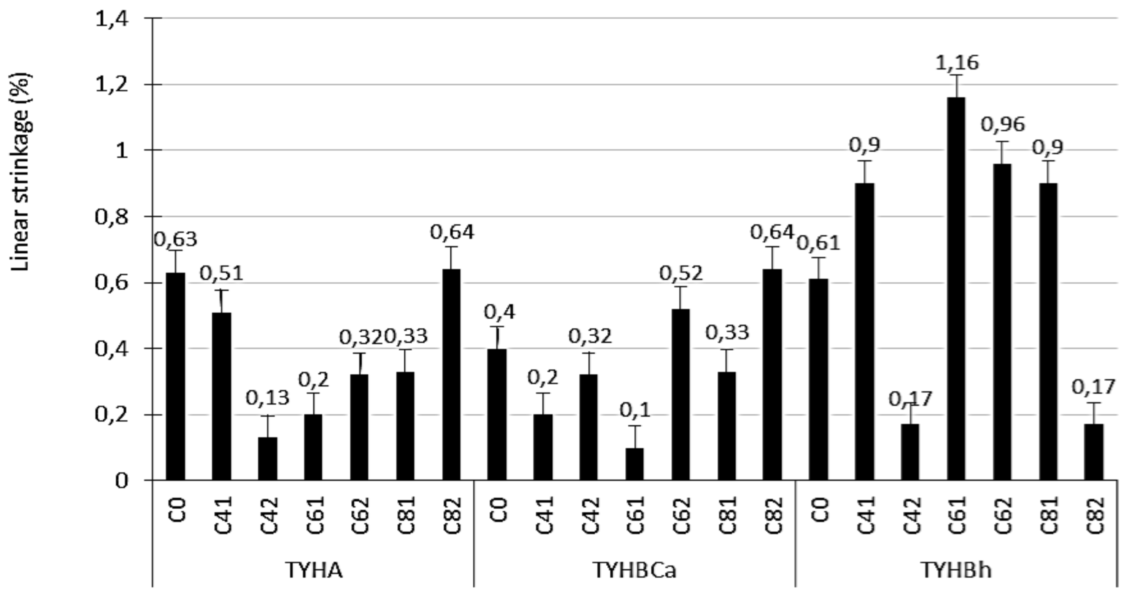

Figure 12. Linear strinkage of stabilized specimens.

The dry bulk density for specimens stabilized with lime decreases from 1.32g/m^3 to 1.08g/m3 when the lime dosage increases. This behaviour has also been observed by several authors ([12]; [9]). Moreover, the change in bulk density is due to the size of particles and the specific density of soil. This reduction is therefore the product of the reorganization of the clay particles caused by phenomenon of flocculation/aggregation [9]; [41].

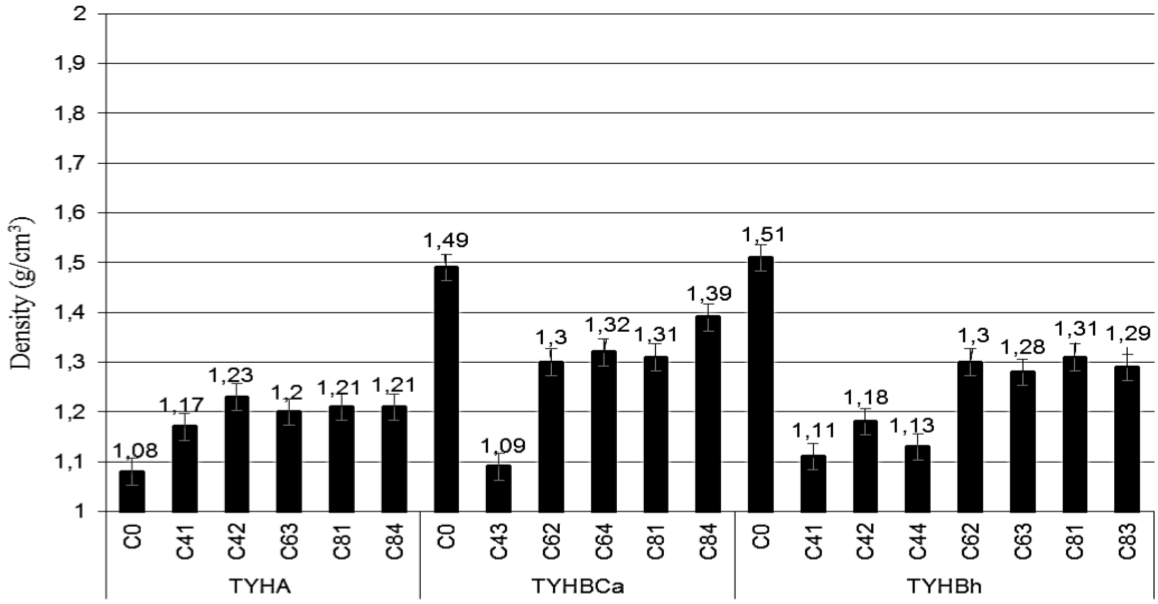

Figure 13. Density of specimens.

From the results of the water absorption tests, it appears that the more clayey horizons TYHA and TYHBca specimens are the most resistant after 24 hours (**Figure 14**). But, the TYHBh horizon stabilized at all concentrations (4%, 6% and 8%) exhibits a behavior similar to unstabilized brick (at 0% of lime).

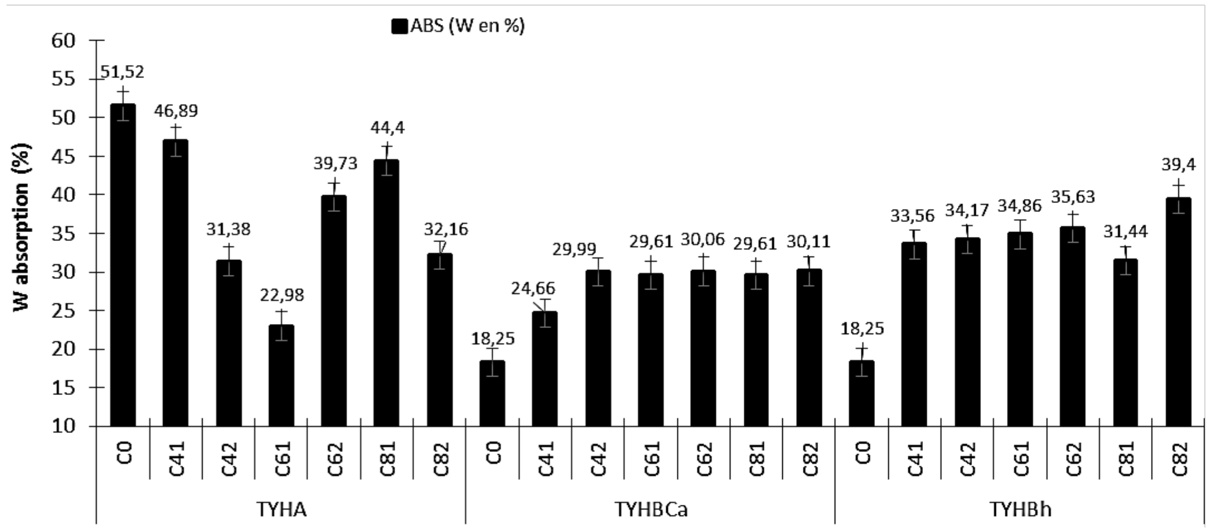

Figure 14. Water absorption of specimens.

The compressive strength of the fired brick of the ground varies between 1.8 - 2.0 N/mm², while that of stabilized specimens is between 1.85 to 2.46 N/mm² (**Figure 15**). There is noted that unstabilized specimens are dissolved in water after 24 hours of immersion. It is proving their fragility in contact with water ([9]; [26]). Specimens of the TYHBca horizon stabilized at 6% lime exhibited the highest strength 2.46 N/mm² compared to other specimens. They are the most resistant, followed by TYHBca at 8% of lime, TYHA at 0% of lime and TYHA at 8% of lime. This resistance is higher than those of bricks fired in the field. Furthermore, the TYHA and TYHBca specimens of this profile stabilized respectively at 6% and 8% of lime exhibit a resistance which is close to that of fired brick (1.64 - 2 N/mm²).

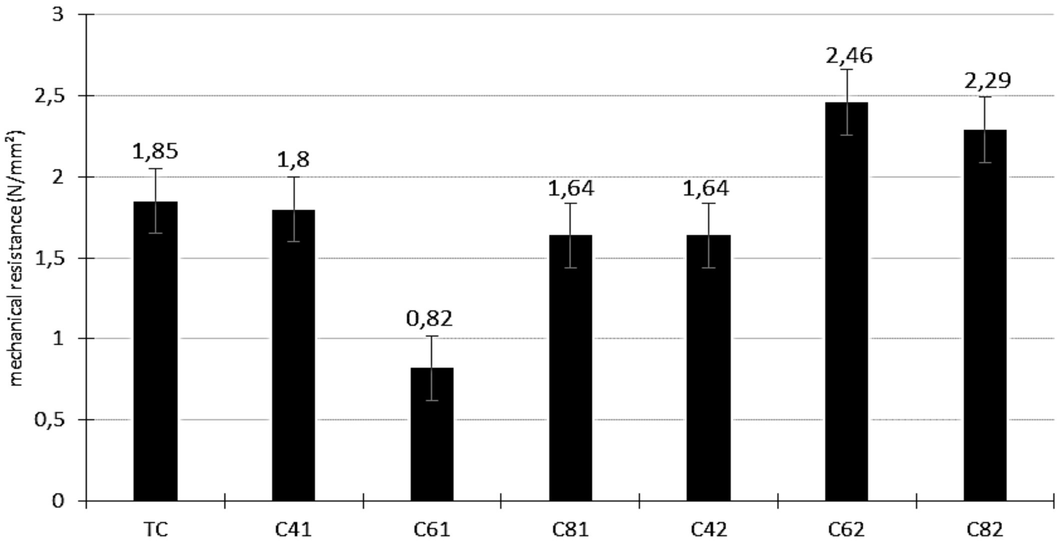

Figure 15. Mechanical resistance of specimens in function of lime concentration. TC = specimens of crude brick, C4, C6, C8 = concentration of lime (4, 6 and 8%); 1 and 2 design horizons.

The mechanical resistance test was focused only on the first two more clayey horizons (TYHA and TYHBca). The dept horizon specimens (TYHBh) were not tested, as they did not all withstand the water absorption test and given their accessibility in the field, and it is low plasticity index due to of the low clay content. This horizon will therefore not be recommended for lime stabilization. However, the combination of the first two horizons (TYHA and TY2) would be a good initiative because of their stability and resistance. The incorporation of lime has a positive effect on the mechanical resistance of Kaele's lithomorphic Vertisols. This is in relation to several results obtained by many authors ([41]; [9]; [13]). In addition, only the materials of the TYHA surface horizon and TYHBca subsurface horizon (40 to 60cm) stabilized at 6% and 8% of lime which have mechanical compressive strengths greater than those of fired brick on the ground (2.46 N/mm² (stabilized brick) against 2.04 N/mm² (fired brick). Nevertheless, The TYHA horizon stabilized at 4% of lime has a resistance similar to that of fired brick [13].

Conclusion

The purpose of this study was to characterize the Kaele's lithomorphic Vertisols from a morphological, physicochemical, geochemical, mineralogical, geotechnical and mechanical perspective. Analyses carried out show that the studied vertisols are generally gray to dark gray and clayey to clayey-sandy. The source rocks on which these soils outcrop are Granites. These soils are weakly acidic to weakly basic with pH values and display low content in organic matter which is not well mineralized. Smectite is the main phyllosilicate mineral, associated to kaolinite, illite, Quartz and feldspar. They high to very high content silica, follow those of Alumina and Iron. Overall the studies, of lithomorphic Vertisols of Kaele stabilized with 6% and 8% of lime can be suitable use as constitute an alternative to fired bricks in this locality. This formulation will allow their use for sustainable management. However, the combination of the first two horizons (TYHA and TYHBca) would be a good initiative because of their stability and resistance.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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