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Geotechnical, physicochemical and mineralogical characterizations of soil quarries in Chad with a view to their valorization in eco-construction

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Abstract: Earth is one of the first basic building materials used by humans, available and low in energy consumption. Even today, about 50% of the inhabitants of low-income countries live in earthen houses. However, the majority of earthen constructions do not meet today's requirements in terms of mechanical and thermal constraints due to poor soil selection. In order to meet these requirements, a preliminary work at the scientific level on the identification of good soils is to be accomplished in this field. The objective of this study is to determine the properties of soils in order to evaluate their potential for use. In this work, soil samples were taken from four reference locations in Chad and subjected to geotechnical, physico-chemical and mineralogical characterizations for their use in construction. The results of the analyses carried out on these soils compared to the standards showed that the Béré soil quarry is sandy-silty, the Yeï soil is silty-clayey-sandy and the Laï and Toukra soil quarries are clayey-silty. The Béré and Yeï soils only respect the granular spindle limit of soils suitable for the manufacture of compressed earth blocks. Furthermore, the geochemical results show that these soils are predominantly siliceous (53.71%-86.75%) with a significant amount of aluminum oxide (6.79%-21.63%) and iron oxide (1.71%-9.49%). Mineralogical analysis combined with chemical analysis identified and quantified minerals including 40.41%-77.89% quartz, 12.41%-24.13% kaolinite, 2.94%-23.12% illite, 2.01%-15.82% k-feldspar and other minor minerals. These different analyses indicate that the Béré and Yeï soils are suitable for promoting compressed earth blocks.

1. Introduction

Access to decent housing is recognized as a fundamental human right (UN-habitat, 2009). However, the acquisition of viable and affordable housing is becoming increasingly difficult for the majority of the population, particularly in sub-Saharan Africa. High population and urban growth, the high cost of land and building materials, among others, are the main causes of the housing shortage (UN-habitat, 2008). In Chad, as in other countries in the sub-region, housing is often built using local materials because of their ease of use and low cost. These house constructions rarely comply with technical regulations concerning the quality of the materials used, which generally results in a short lifespan and frequent rehabilitation work (Sharma *et al*., 2015). In view of these recurrent problems, the population opts for the construction of houses with durable materials such as cement, which has significant disadvantages in production (high energy costs and environmental pollution) and use (thermal discomfort in buildings). Today, the need to preserve natural resources and to fight against climate change has given new interest to local materials (Delgado *et al*., 2006). However, in-depth studies on the properties of these materials for their better use in construction are still at the experimental stage in many countries and especially in African countries. In the present context, the use of soils for the manufacture of compressed earth bricks (CEB) constitutes one of the credible and interesting solutions being experimented in many low-income countries (Millogo *et al*., 2008), (Emeruwa *et al*., 2008), (Ndinga *et al*.,2021). The criteria for the selection of the soil include the plasticity, compactness and types of minerals prescribed by the standards in force (Kagonbé *et al*., 2021). The purpose of this work is to evaluate the geotechnical, physico-chemical and mineralogical properties of four quarries (Béré, Laï, Toukra and Yeï) of soils used in construction in Chad in the light of the analytical standards in force (Delgado *et al*., 2007), (Houben and Guillaud, 1994). The results of the methodological analyses allow us to identify the appropriate soil types for use in the manufacture of compressed earth bricks.

2. Materials and methods

The soils studied were taken from four quarries in three regions of Chad known for the quality of their mud bricks. In the four quarries where samples were taken, there are several different soil quarries with different textures and colors. The Béré and Laï sites are located in the Tandjilé region, the Toukra site in the Chary-Baguirmy region and the Yeï site in the Logone Oriental region. The geographic coordinates of the sampling sites are respectively: Béré (9.339796N and 16.151725E); Laï (9.395651N and 16.283702E); Toukra (12.00834N and 15.15101E) and Yeï (8.785433N and 17.015239E). **Figure 1** shows the location map of the sampling sites.

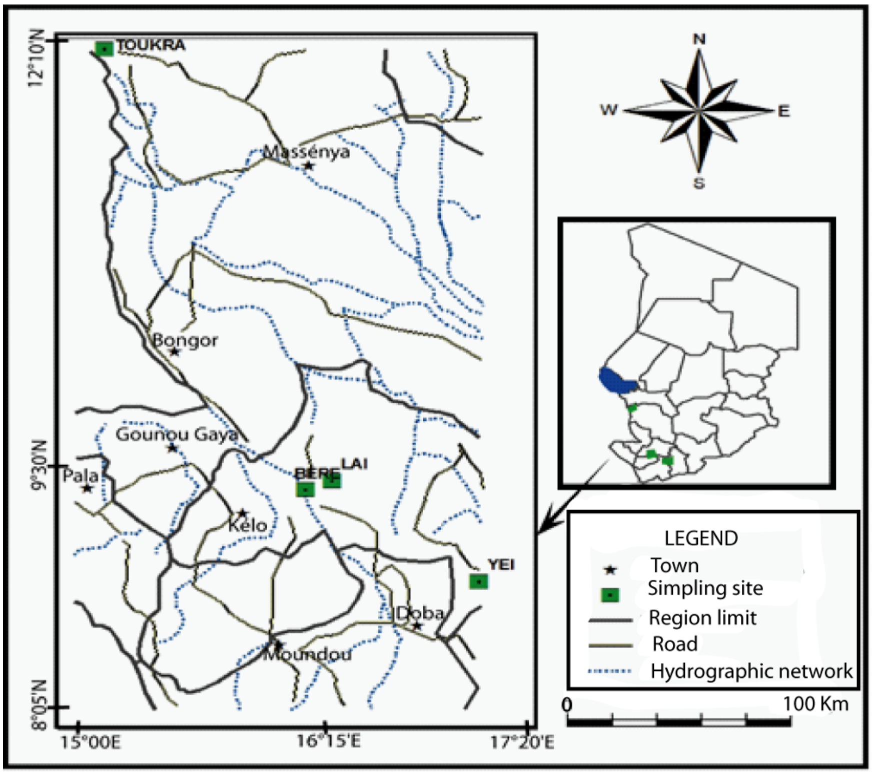

Figure 1: Location of sampling sites in Chad.

The four soils are presented in **Figure 2**. Their macromorphological description was made using the international color chart for soil identification (David Hammonds, 2013). This visual analysis focuses on the determination of the nature, the structural texture and the presence of roots or traces of biological activities.

Figure 2: Photocopy of the soil samples studied

The particle size distribution of each soil was determined by the granulometric method (dry sieving for grains larger than 0.08mm and sedimentometry for grains smaller than 0.08mm) according to standards (NF P 94-056, 1996), (NF P 94-057, 1992). This determination of the granulometry is a very important factor for the stability of soils. The plasticity of the soils was obtained by the Atterberg limits according to the standard (NF P 94-051, 1993). It allows to quantify the degree of plasticity of the soil. The determination of specific and apparent densities of solid grains is carried out using a pycnometer and a mold according to the French standard (NF P 94-054, 1991). The values of methylene blue, which allow the determination of the clay content of the sample, were obtained according to the standard (NF P 94-068, 1993). The dry density indicating the strength of the bricks and the optimal water content for the manufacture of the bricks were determined using the normal Proctor test in accordance with standard (NF P 94-093, 1999). All these geotechnical analyses were carried out in the laboratory of the Ecole Nationale des Travaux Publics du Tchad. The chemical compositions of the samples were determined by X-ray fluorescence spectrometric analysis (XRF). The XRF analyses were performed at the Spectrum Facility at the University of Johannesburg, South Africa. Samples were dried at 105°C to measure loss on ignition (LOI) and to determine chemical elements. All relevant major and minor element data as well as the determination of silica/alumina ratio and chemical alteration index (CIA) are reported in Table 4. These different values identify the proportions of the major elements and the degree of weathering of the soils. The chemical weathering indices are easily calculated from the percentage of oxides masses by applying this formula:

$$CIA = 100 \times [Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O)]$$

The calculation of CIA is generally based on the assumption that alumina represents a more immobile chemical element than other alkali elements (Wayne Nesbitt *et al*., 1982) [18]. X-ray diffraction patterns were obtained with a Philips PW1710 diffractometer at Johannesburg University in South Africa using CuKα radiation ($\lambda K\alpha$ = 0.154186 nm). Analyses were performed on the powder by applying Cu irradiation with generator settings at 40kV/40mA, use of a monochromator, and scan length from 5° to 80° of angle 2θ. OriginPro 8 software was used to produce the diagrams of various minerals. Semi-quantitative mineralogical analyses of the samples were performed for the determination of the wavelengths of each peak to identify the corresponding mineral elements (Cook *et al*., 1975), (A.N. Mefire *et al.,* 2015). In addition, by combining the results of the X-ray diffraction analysis and those of the chemical analysis by X-ray fluorescence, the contents of the crystallized mineral phases present in the samples were evaluated using a calculation technique described by (Babechuk *et al*., 2013), (Yvon *et al*., 1982). To do these operations, chemical assignments were made respectively: (1) K_2O was attributed to illite or feldspars, (2) Fe_2O_3 to goethite, (3) CaO to plagioclase, (4) Al_2O_3 was used to calculate the contribution of kaolinite after subtracting the contribution of illite or feldspars, (5) SiO_2 was used to calculate the contribution of quartz after subtracting the contribution of kaolinite, illite and feldspars.

3. Results and discussion

3.1 Macromorphological description

The soil sample from Béré is a hydromorphic soil of yellowish-gray color 7.5GY9/4, silty-sandy containing the presence of millimeter roots with centimeter porosities. The Laï sample is a ferrallitic soil of yellow-reddish color 5YR6/6, clayey-sandy, polyhedral medium compact with the presence of yellow and red spots of centimetric sizes. The Toukra soil is also ferrallitic, yellow in color, 2.5Y8/4, polyhedral sandy clay with the presence of red spots indicating hydromorphy, and millimeter-sized porosities. The Yeï soil sample is a hydromorphic soil of reddish-yellow color 10YR7/6, compact polyhedral sandy-clay in the wet state with the presence of fine millimetric to decimetric roots with decimetric porosities. These results will be confirmed in the laboratory by geotechnical analysis.

3.2 Geotechnical analysis

Figure 3 and **Table 1** represent, respectively, the particle size distribution of the different soils and the normative spindles for CEB according to standard (NF XP P13-901, 2001) and the particle size fractions of clays, silts, sands and gravels of the four soils studied. On the x-axis correspond the sieve diameters in millimeters. The different values allow us to determine the proportions of the basic elements for each soil. The ordinate axis corresponds to the percentages of the sieves, allowing the quantification of the soils.

The different proportions of particles contained in soils are determined according to standards and technical manuals (clay < 2 µm, silt 2- 63 µm, sand 63 µm- 2 mm, gravel > 2 mm) (Moevus *et al*., 2012). The knowledge of the weight of each element allows to determine the nature of the soil by the method of the Casagrande diagram. **Table 1** shows the particle size compositions of the four soils studied in comparison with the values of reference materials well suited for the manufacture of compacted earth bricks. By comparing the four soil samples with the reference soils, the soils of Béré and Yeï can be eligible for the manufacture of CEB. The proportions of clay, silt and sand listed in Table 1 allowed the determination of the nature of the samples studied by the Casagrande diagram in the **Figure 4** (Casagrande, 1948).

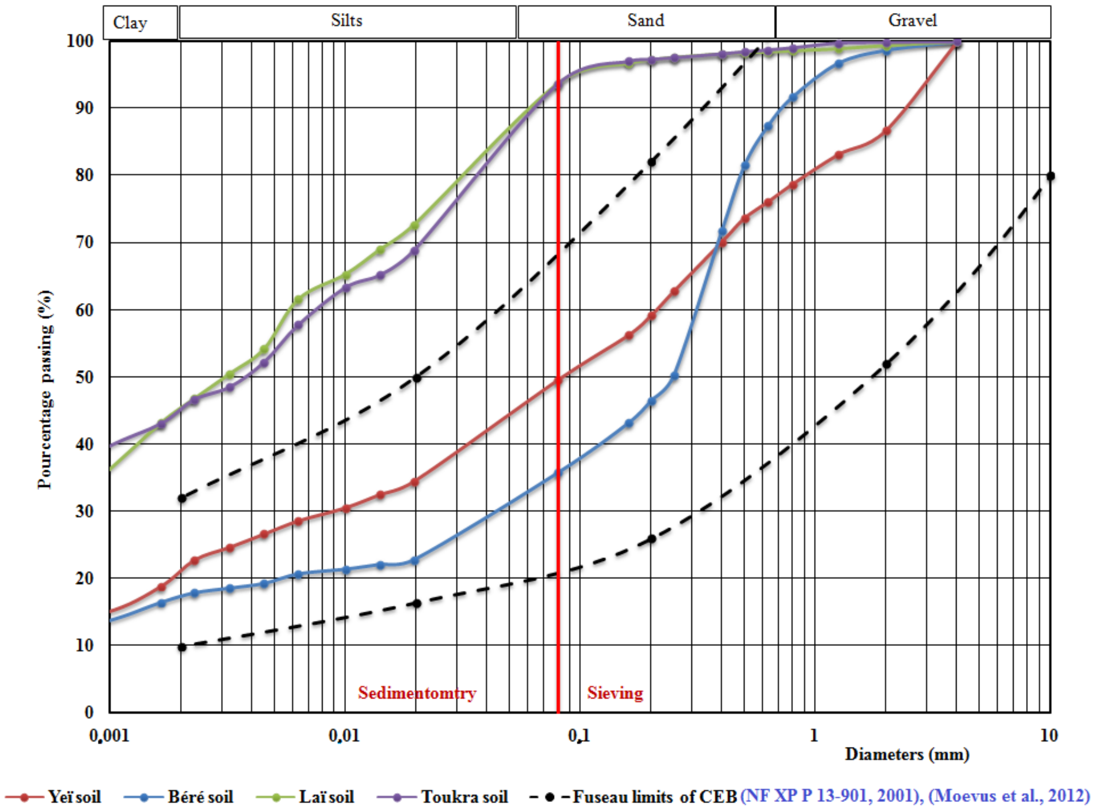

Figure 3: Soil particle size curves with the CEB zone standard.

Table 1: Size fraction of the constituents of the samples and reference soils.

Samples	Béré	Laï	Toukra	Yeï	References		
					(Vincent R., 1995)	(Wetshondo O., 2012)	(Philbert N., 2014)
Clay %	18	43	44	21	8-30	15-35	10-25
Silts %	14	42	42	23	10-25	-	30-60
Sands %	66	15	13	42	25-80	50-60	15-45
Gravels %	2	0	0	14	0-40	15-25	0-20

From the analysis of this diagram (**Figure 4**), it appears that the Béré soil is a silty-sandy sample and that of Yeï is a silty-clay-sandy sample, whereas the soils of Laï and Toukra are clay-silt samples. **Table 2** reports the Atterberg limit values of the different soils and some normative references placing the liquid limits and plasticity indices in the intervals defined by (Daot *et al*., 1991), (Morel *et al*., 2007). The results of the analyses on the four soil quarries compared to the last reference show that the soil samples of Béré and Yeï remain adaptable for the manufacture of compacted bricks. The value of the plasticity index of the Béré soil indicates that this soil is moderately plastic, while the other three soils are plastic. **Figure 5** shows the plasticity indexes of the soils that can be used to make compressed earth bricks.

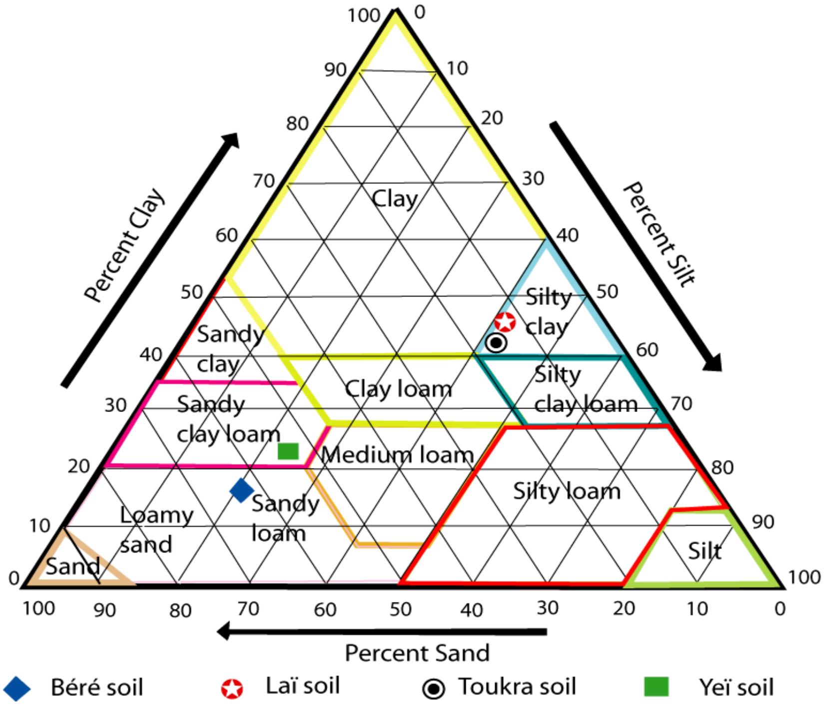

Figure 4*:* Classification of soils according to the Casagrande diagram

Table 2: Atterberg limit results of the studied samples.

Samples	Béré	Laï	Toukra	Yeï	References		
					(Daot *et al.*, 1991)	(Morel *et al.*, 2007)	
Water content (%)	2.29	4.76	3.38	5.05			
Liquid limits WL (%)	36.95	48,43	50.31	33.58	25-50	25-50	30-35
Plasticity limits WP (%)	21.86	26,38	25.29	14.89	-	10-25	12-22
Plasticity index PI (%)	15.09	22,05	25.03	18.69	2-30	7-29	7-18

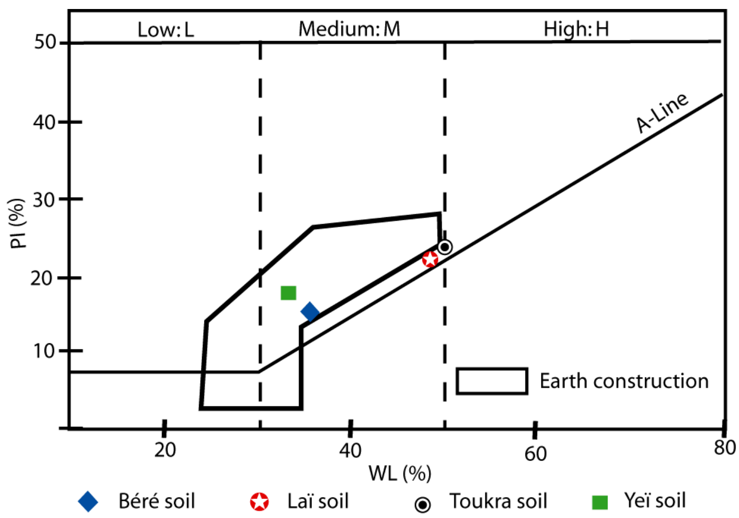

Figure 5*:* Range of soil plasticity indices usable for CEB [25].

The plasticity index of a material allows to have the knowledge of its free swelling potential described by (Seed *et al*.,1962) in (Aoun Mounira, 2016). The quarries of Béré and Yeï soils with plasticity indexes between 10% and 20% can have a medium swelling potential compared to those of Laï and Toukra whose indexes between 20% and 35% would have a high swelling potential. **Figure 6** shows the results of the normal Proctor test of the samples. **Table 3** summarizes the density, methylene blue, dry density and moisture content values from the water pycnometer, methylene blue and normal Proctor tests.

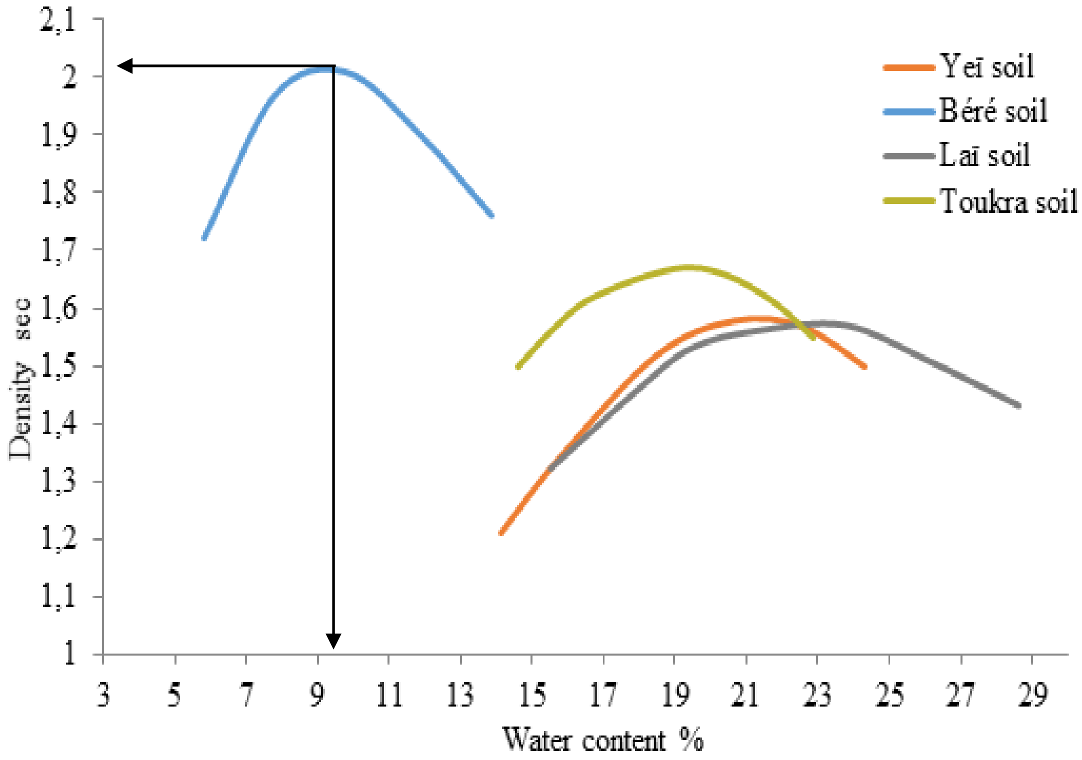

Figure 6*:* Normal Proctor test of four soils

Table 3*:* Density and Methylene Blue values of the samples.

Samples	Béré	Laï	Toukra	Yeï
Specific density (g/cm^3)	2,506	2,456	2,504	2,385
Apparent density (g/cm^3)	1,363	1,033	1,160	1,155
Bleu methylene values	1,35	2,72	3,88	1,55
Dry density (g/cm^3)	2,04	1,57	1,68	1,58
Water content (%)	9,20	23,41	19,40	21,00

The specific gravity values obtained in **Table 3** are well within the range of 2.2-3.0 g/cm^3 recommended for brick making (McKenzie *et al*., 2002). The different values of methylene blue of the studied soils were also used to determine their nature respectively. According to this classification of (NF P11-300, 1992), the soil of Béré is sandy-loam, the soils of Laï and Toukra are clayey-loamy with medium plasticity and that of Yeï is sandy-loamy-clayey with low plasticity. These results are in good agreement with the estimate of the fraction of fine elements determined by the granulometric analysis. The result of the Proctor test shows that the Béré sample is very sensitive to water compared to the others. The density obtained values are close those obtained by Moroccan Clay (d = 1.4) (Ainane *et al*., 2021).

3.3 Chemical analysis

The chemical composition of the samples collected from the four sites consists mainly of silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and trace amounts of BaO, CaO, K_2O, MgO, MnO, Na_2O, P_2O_5 and TiO_2. **Table 4** represents the different chemical elements with their percentages, loss on ignition and SiO_2/Al_2O_3 ratio as well as the chemical weathering index of each sample.

Table 4: Chemical composition of the soil samples studied

Samples	Béré	Laï	Toukra	Yeï
Al_2O_3 %	6.79	21.63	16.10	12.53
BaO %	-	0.14	0.08	0.05
CaO %	0.18	0.66	0.57	0.45
Fe_2O_3 %	1.71	9.49	6.15	3.01
K_2O %	0.34	2.67	2.34	0.50
MgO %	0.07	0.87	0.52	0.16
MnO %	-	0.12	0.11	-
Na_2O %	-	0.58	0.63	-
SiO_2 %	86.75	53.71	65.33	75.70
TiO_2 %	0.68	1.90	1.24	1.17
LOI %	3.10	8.23	5.57	5.11
Total %	99.61	100.18	98.78	98.74
$\frac{SiO_2}{Al_2O_3}$	12.78	2.48	4.05	6.04
CIA %	92.88	84.69	81.97	92.95

The results of the analyses show that the most abundant oxides are respectively silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), potassium (K_2O) and titanium (TiO_2). Silica contents are dominant compared to the other elements (53.71% and 86.75%), alumina contents vary between 6.79% and 21.63% and iron oxide contents between 1.71% and 9.49%. The high rate of alumina in the Laï and Toukra samples and the low content of alkaline elements such as K_2O and Na_2O indicate the possibility of being used as raw materials for the manufacture of refractory products (Sagbo *et al*., 2015). The high amount of iron oxide in the Lai sample was highlighted by its reddish yellow color. The alkali and alkaline earth metal contents are significantly modest. For the four samples, the loss on ignition varies between 3 and 9%, which indicates the presence of mainly hydrated minerals (goethite and clay minerals) (A.N. Mefire *et al.,* 2015). The SiO_2/Al_2O_3 ratios of these four soils studied are higher than 2%, which indicates an excess of SiO_2 and therefore confirms the presence of minerals of type 2/1 with phylosilicates of high chemical maturity in the samples studied (Crook *et al*., 1974; A. Qlihaa *et al.,* 2016). The high amount of silica in the soils indicates the presence of minerals such as quartz. High values of alumina and iron oxide are most often correlated with the presence of clay minerals such as kaolinite and goethite as well as hematite (Qlihaa *et al*., 2016; Tsosué *et al*., 2017). The CIA value showed the presence of minerals such as illite, quartz, feldspars and pyroxenes as well as kaolinite in the materials. The CIA values showed that the soils of Béré and Yeï contain mostly clay minerals such as quartz, kaolinite and gibbsite while those of Laï and Toukra show significant traces of illite and quartz (Temga *et al*., 2018). The values of the chemical weathering indices of these samples showed that the clay soils of Béré and Yeï have undergone a remarkably variable weathering than the soils of Laï and Toukra.

3.4 Mineralogical analysis

Figure 5 presents respectively the diffractograms of four studied samples whose wavelength values in Angstrom (Å) and the corresponding mineral elements can be identified. The diffractograms show that they are composed of quartz (SiO_2), kaolinite $(SiO2)_2(Al_2O_3)(H_2O)_2$, illite $(K_2O)(SiO_2)_6(Al_2O_3)_3(H_2O)_3$, k-feldspar $(K_2O)(SiO_2)_6(Al_2O_3)$, hematite (Fe_2O_3), goethite $(Fe_2O_3)(H_2O)$ and some traces of clay minerals.

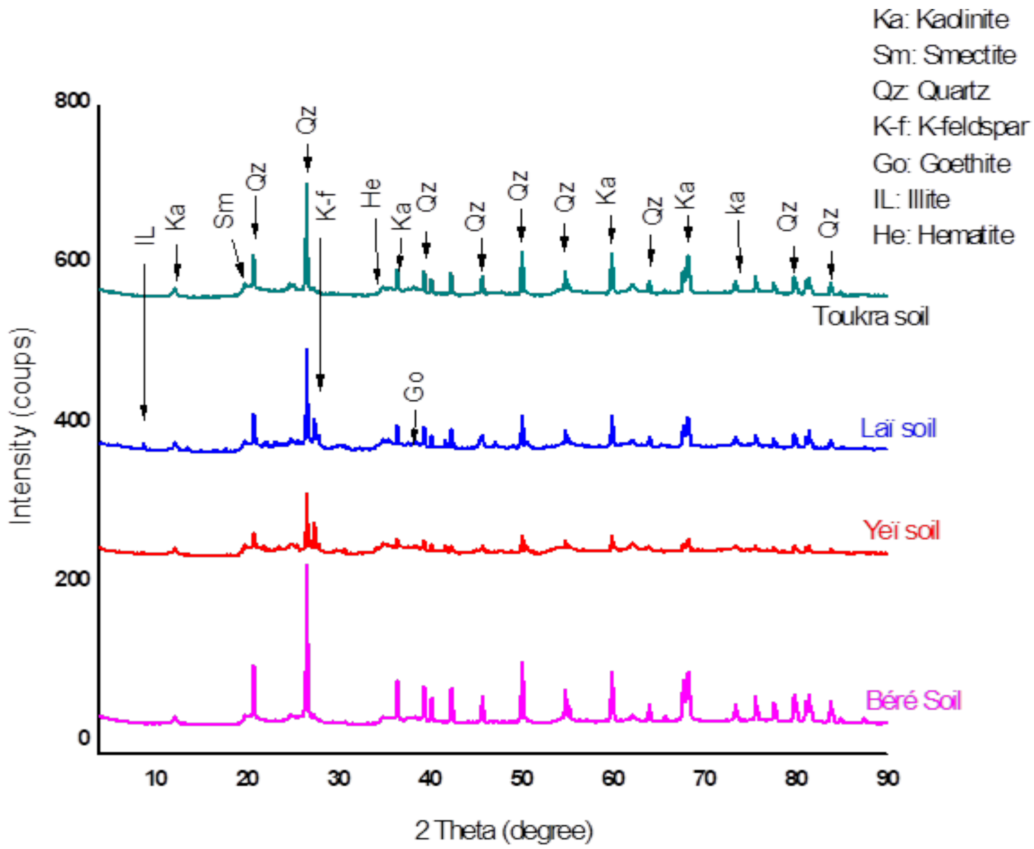

Figure 6: Diffractograms of four samples of the studied soils

The combination of the results of X-ray diffraction with those of elemental chemical analysis and the use of relations (A.N. Mefire *et al.,* 2015), (Babechuk *et al*., 2013), (Christopher *et al*., 1995), (Armel B. *et al*., 2017) made it possible to evaluate in **Table 5** the quantities of minerals contained in the four raw materials. **Figure 6** presents the mineralogical compositions of different minerals from each sample studied in the form of histograms with their respective percentages.

Table 5: Mineralogical composition of four soil samples

Samples	Illite %	K-feldspar %	Plagioclase %	Kaolinite %	Quartz %	Other minerals %
Béré	2.94	2.01	0.89	12.61	77.89	3.66
Laï	23.12	15.82	3.28	22.36	21.45	13.97
Toukra	20.26	13.87	2.83	12.41	40.41	10.22
Yeï	4.33	2.96	2.23	24.13	59.68	6.67

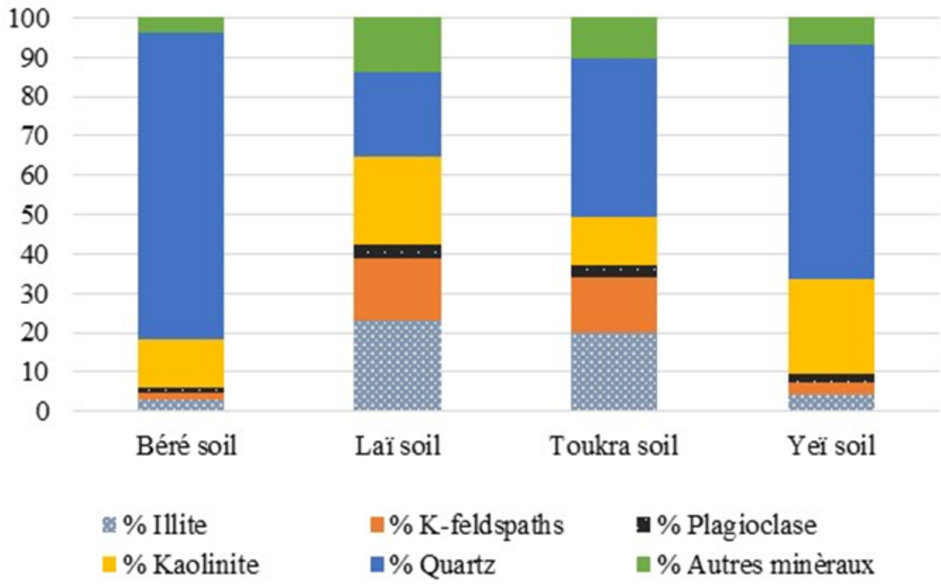

Figure 7: Histograms of minerals from the samples

Quantitative estimation of the mineral composition of the samples (**Figure 6**) confirmed the predominance of quartz with significant amounts of kaolinite, illite and feldspars and the minor presence of hematite and goethite as well as traces of plagioclase and clay minerals. These results are in agreement with the percentages of chemical elements determined. The presence of type 2/1 minerals in samples favors their use in brick formulations. The addition of stabilizers or additives such as lime, ash, fibers and waste in the samples of Laï and Toukra is recommended to avoid cracking during the manufacture of bricks. On the other hand, the Béré and Yeï samples require a stabilizer in hydraulic binder such as cement.

Conclusion

Earth is a residential construction material recognized for its many advantages. But its judicious use as a construction material requires the mastery of its geotechnical, physicochemical and mineralogical properties. It is in this context that four soil samples were taken and analyzed. The results of the geotechnical characterization indicate that the samples from Béré, Laï and Toukra as well as Yeï are respectively sandy-loam, clayey-loam and sandy-loamy-clay soils with low plasticity. The soil samples from Béré and Yeï respect the normative spindles of the BTC, but the other two soils have clay contents exceeding the recommended maximum. The high fine element content requires high water content to obtain good compaction, which may increase the risk of cracking during drying and premature degradation of buildings. Chemical analysis revealed that these samples contain almost the same chemical elements except for the Béré and Yeï soils which lack MnO and Na_2O. Silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) are the oxides containing the majority of these four soil samples. The different values of the chemical weathering index prove a long weathering of these soils. Mineralogical analysis was used to identify and quantify the minerals contained in the soil samples. The results show that quartz and kaolinite are the majority minerals in the Béré and Yeï soils, illite and kaolinite in the Laï sample and quartz and illite in the Toukra sample. Compared to the composition of the different soil samples used in the field of compressed earth bricks, the results of the different analyses show that the two soils (Béré and Yeï) are suitable for CEB, while those of Laï and Toukra require slight improvements in their compositions.

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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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