Mineralogical, geochemical characterization and application of an alluvial clay material

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Abstract

Field surveys were conducted in which six samples of clay were collected and characterized. The results of the mineralogical analysis, carried out by X-ray diffractometry on total powder and on the clay powder reveal the presence of kaolinite, illite and chlorite clay minerals, with the clay color predominantly reddish. The non-clay minerals identified were quartz, goethite, gibbsite, feldspar, hematite and anatase. The geochemical composition obtained by X-ray fluorescence shows that the material of the study area are richer in SiO_2 , Al_2O_3 and Fe_2O_3 . The $\text{SiO}_2/\text{Al}_2\text{O}_3$ of all the samples were greater than 1 indicative of kaolinitic clays while $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ are less than 1 indicative of the presence of iron based compounds. Also low contents of TiO_2 , MgO , CaO , MnO , NaO , P_2O_5 and K_2O were also revealed. The different results obtained show that the process of meteoric weathering is the origin of the genesis of these clays. The physical analysis consisted in obtaining the particle size distribution and the Atterberg limits. The proportions of sand vary between 14 and 20%; silts between 18 and 28% and finally clays between 52 and 65% with the clays belonging to two textural classes namely fine clays and clays. The Atterberg limits indicates that the materials are plastic with plasticity indices between 30 and 34.1%. Based upon the Winkler diagram to ascertain their ceramic uses, four samples were disqualified for solid brick manufacture while two samples were recommended for masonry tiles and bricks.

Keywords Clay materials · Mineralogical analysis · Geochemical composition · Physical analysis · Ceramic purposes

1 Introduction

Clays make up one of the most abundant industrial raw materials on the surface of the earth constituting about 90% of the earth's bulk [46]. These clay minerals are mainly detrital and are derived from physical or chemical alteration of pre-existing rocks [30]. They are rich in aluminum and silicon and therefore have been utilized in the construction industry for the production of bricks and ceramics and they also find wide application in other manufacturing industries such as pharmaceuticals and cosmetics. It is very probable that the sphere of clay utilization will continue to broaden, therefore exploring and cataloging

the clay deposits of any locality will significantly contribute to potential socio-economic development. Thus far Njoya et al. [41] have presented an exhaustive summary comprising the location, clay types and possible utilization of some Cameroon clay deposits, though more exploration is crucial as well as the creation of ventures for their utilization. More than thirty five years of research carried out by some researchers lends credence to the enormous potentials for industrial utilization and applications of argillaceous materials. For example, Njopwouo and Wandji [37, 40] valorizes hallosyte, cosmetic applications such talc is proposed by Nkoumbou et al. [38, 39]. Meanwhile for baked clay products, a host of researchers such as Diko et al. [5], Djangang

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et al. [6–10], Elimbi et al. [13, 15, 16, 17], Elimbi and Njopwouo [14], Kamseu et al. [18–20, 22], Leonelli et al. [27], Melo et al. [29], Pialy et al. [45]. The attempts at formulating geopolymers based on clays rich in kaolinites were carried out by Kamseu et al. [21], Lemougna et al. [26], Obonyo et al. [44] and Tchakoute et al. [48, 49]. Clays have also been utilized as a mineral filler in rubber reinforcement and as a catalyst in the polymerization of styrene [33–36] and, most recently, in the production of composite films utilizing cassava starch and kaolin [28]. With a rich repertoire of the potentials of clay utilization for industrial concerns so far gathered, exploration of more deposits is still necessary in order to catalogue and create an inventory of areas with some valuable quantities of clay deposits that could be harnessed for industrial applications. Consequently, the aim of this study is to broaden this repertoire by characterizing the clay of Baboutcheu—Ngaleu.

2 Description of study site

Baboutcheu-Galeu has a surface area of 18 km² and is one of six villages located in Bafang Subdivision between latitude 5°05'N and 5°08'N and longitude 10°09'E and 10°12'E of the Upper-Nkam Division of the West Region of Cameroon. Baboutcheu-Ngaleu village is bordered to the north by Baboné, to the south and east by Bakassa and to the west by Bakondji, Bakou and Fondjanti as shown in Fig. 1a. It has a tropical climate with two alternating seasons: a rainy season from March to November and a dry season from December to February. The lowest average rainfall is recorded in December with 9 mm of rainfall, while the month of September is the wettest with an average rainfall of 366 mm. The month of March is the hottest month with a temperature of 22.2 °C and the month of July the coldest with a temperature of 19.6 °C. The annual average rainfall in this zone is 2085 mm with an average temperature of 21.0 °C.

The study site falls within the highlands of western Cameroon and at an altitude of between 1320 and 1522 m. They form a vast chain of highlands (Bamoun plateau, Bambouto, Bamenda, Oku and Bana mountains) and plains (Noun and Ndop), consisting of superficial formations (alluviums, eluviums and alterites), volcanic formations (basalts, trachytes, phonolites, rhyolites tuffs, ignimbrites) and granito-gneissic basement [43]. The town of Bafang is located 14 km from the volcano-plutonic complex of Bana [23] comprising basalts (composed of plagioclase (labrador, bytownite), pyroxene, and olivine) and anatexites as shown in the geologic map in Fig. 1b. The landscape consists of steep slopes that are covered with shrubs and trees and in most cases

Fig. 1 **a** Location map of the study area scale 1/50,000. **b** Geologic map of study area. Extract of the geologic map of the Federal Republic of Cameroon. Douala-west. [12]

evidence of human tempering exists most notably due to farming and road construction activities. There are two types of soils: namely, the lowland soils (hydromorphs) which are rich in organic matter and often flooded during the rainy season and the mountain soils which are ferrallitic, silty clays with some lateritic hard pans in certain areas.

3 Materials and methods

3.1 Clay estimation and sampling

Three field outings were carried out with the first one being a reconnaissance survey which enabled the identification of the presence of potential sampling sites having the clay cones as well as the textural evaluation of the clay along road cut slopes. During the second visit, two trial pits were made at the foot of the hill of size $4\text{ m} \times 2\text{ m} \times 8\text{ m}$. On the third visit the topo sequential method was used, whereby five other similar trial pits were established on site consisting of one between the bottom of the hill and the hill crest, then one at the hill crest. Also on the descending side of the hill, one trial pit was dug at the mid distance again between the hill crest and the foot of the hill. This method enabled the proper realization of the vertical variation of the facies along the slope and along the walls of the dug trial pits. Sample collection was done on the basis of the variation of the color of the facies with this depth. Thus, a sample was taken at the top, two samples each collected from the trial pits on each side of the slope, giving a total of 19 samples collected. The morpho-structural description of the profiles focused on the main parameters that are: the limit between the facies, the thicknesses of the different facies, the depth and the various elements figured out. The macroscopic description of the samples took into account the color and the texture. In the field, the texture was determined by touch and color thanks to the Munsell [32] color code.

3.2 Clay preparation and characterization

3.2.1 XRD analysis

The X-ray diffraction was carried out at the University of Liege in Belgium using a Brucker D8-Advance type diffractometer (copper $K\alpha_1$ radiation $\lambda = 1.5418\text{ \AA}$, $V = 40\text{ kV}$, $I = 30\text{ mA}$). The measurements were carried out in the range 2θ from 2° to 45° 2θ for non-oriented powders and 2° – 30° 2θ for oriented blades following the procedures of Moore and Reynolds [31]. This enabled the mineralogical content of the clays to be obtained by the interpretation of the mineral phases using Eva software.

3.2.2 XRF analysis

The chemical composition of 19 samples were obtained by X-ray Fluorescence Spectroscopy (XRF) with an ARL™ PERFORM'X spectrometer of the University of Liège.

3.2.3 Particle size analysis

The grain size distribution was carried out by wet sieving of the fraction $> 80\text{ }\mu\text{m}$ and sedimentation analysis for fractions between 80 and $2\text{ }\mu\text{m}$ following ASTM norms D-422 [1], while the Atterberg limits were obtained by the Casagrande method following ASTM D-4318 [2].

4 Results and discussion

4.1 Morphostructural descriptions of the trial pits

The morpho-structural description of the trial pits was based on parameters such as the thickness of the different facies, the boundary between the facies, the depth and the elements encountered.

Trial pit P_1 , was dug at the bottom of the slope at a depth of 130 m (Fig. 2) with the coordinates being ($05^\circ 07' 05.1''$ of latitude, $10^\circ 09' 03.6''$ east of longitude and at an altitude of 1262 m). It has three well differentiated levels: top soil was 15 cm thick and dark in color, containing roots more than 2 cm in diameter. A yellowish-red (5YR 3/4 yellowish red) clayish facies level followed, with a thickness of 20 cm and clayish texture with multiple dark gray (5YR 3/1) and reddish-yellow (5YR 5/8) patches. The third level has a lightly red (10 R 5/4) clay-colored facies, 100 cm thick with a clayish texture and with roots up to 2 cm in

Fig. 2 Trial pits profiles at the bottom of slopes

diameter. The boundaries between the two facies are not clearly distinctive.

Trial pit P_5 , was realized at the bottom of the slope opposite trial pit P_1 at the geographical coordinates ($05^{\circ}07'02''$ of latitude, $10^{\circ}09'08''$ of longitude and at an altitude of 1246 m), and to a depth of 200 cm as shown in Fig. 2. Here, we note the presence of two levels with the first layer made up of topsoil having a small thickness (5 cm) and having roots of average diameter. The second layer is a clayish facie of clayish-silt texture, 170 cm thick and reddish-yellow color (7.5YR 6/8 reddish-yellow). Here we also note the presence of nodules with a red to yellow color, blocks with diameters up to 4 cm as well as roots of very small diameter.

Trial pit P_2 , was dug at the median of the slope between the bottom and the crest with the geographic coordinates ($05^{\circ}07'05.1''$ of latitude, $10^{\circ}09'03.6''$ E of eastern longitude and at an altitude of 1262 m). The trial pit is 550 cm deep (Fig. 3) and is made up of three horizons, consisting of topsoil, 20 cm thick containing small diameter roots. The mineral horizon is differentiated into two levels. The level with clay facies is light red (10R 6/8 light red) and is 450 cm thick with a clayey-silt texture. At this level we note the presence of nodules of about 20 cm thick with diameters of between 0.5 mm and 0.5 cm, as well as roots of diameter relatively less than 1 cm. The second level consists of an array of gray color and extends to a depth of 70 cm.

Trial pit P_4 , was dug at the mid distance between the crest and the bottom on the descending side of the hill at the geographical coordinates of latitude $05^{\circ}07'05''$ and

longitude $10^{\circ}09'01''$ E and at an altitude of 1255 m. It has a depth of 400 cm (Fig. 3) and is made up of two levels with a dark-colored topsoil, 50 cm thick containing roots up to 2 cm in size. The facies level is yellowish red (5YR 5/8 yellowish-red), 340 cm thick with a silty clay texture.

Trial pit P_3 was dug at the crest of the hill to a depth of 800 cm (Fig. 4) with the geographical coordinates ($05^{\circ}07'03.6''$ of latitudes North, $10^{\circ}09'03.2''$ of longitude East and at an altitude of 1289 m). The material consists of a silty clay texture of a light red color (10R 6/8 light red) with a thickness of 976 cm. We also notice the presence of small roots in this horizon. A summary of the profile characteristics of each of the trial pits is shown on Table 1 while Fig. 5 shows the facies of samples collected.

4.2 Particle size analysis

The results of the particle size analysis show that the clay materials studied consist of three fractions of varying proportions. Table 2 shows that the proportions of sand vary between 14 and 20%; silts between 18 and 28% and finally clays between 52 and 65%. In particular, the E6 sample is distinguished by its high value in sand content (20%), and (28%) in the silt content. Sample E2

Fig. 3 Profile of trial pits at the median of slopes

Fig. 4 Profile of trial pit P_3 located at the top of the slope

Table 1 Summary of morpho-structural and macroscopic characteristics of samples from the trial pits

Trial pits	Coordinates	Code	Thickness (cm)	Texture	Color	Observations
1	N: 05°07'04,4" E: 10°09'05,6" Altitude: 1262 m	E1	20	Clayey	Yellowish red (5YR 3/4 yellowish red)	Patches of variable color (5YR 3/1 very dark gray, and 5YR 5/8 reddish-yellow), Contains roots of up to 2 cm
		E2	100		Light red (10 R 5/4 light red)	
2	N: 05°07'05,1"E: 10°09'03,6" Altitude: 1262 m	E3	550	Clayey-silt	Light red (10R 6/8 light red)	Nodules are present with diameters ranging from (0.5 mm–0.5 cm) as well as roots < 1 cm
3	N:05°07'03,6" E: 10°09'03,2" Altitude: 1289 m	E4	796	Clayey-silt	Light red (10R 6/8 light red)	The presence of small roots is noted
4	N: 05°07'05" E: 10°09'01" Altitude: 1255 m	E5	340	Silty-clay	Yellowish red (5YR 5/8 yellowish red)	Having roots of diameter > 2 cm
5	N: 05°07'02" E: 10°09'08" Altitude: 1246 m	E6	170	Clayey-silt	Reddish yellow (7.5YR 6/8 reddish yellow)	Nodules with red to yellow color and blocks of diameter 4 cm as well as roots of very small diameter

Fig. 5 Clay facies obtained from the study site**Table 2** Particle size analysis of analyzed samples

Fractions	E1	E2	E3	E4	E5	E6
Sand (%)	16	17	18	14	19	20
Silt (%)	20	18	22	24	27	28
Clay (%)	64	65	60	62	54	52

samples are presented on Table 3 This table shows that the plasticity indices of the samples are between 30 and 34.1%. These materials have higher liquid limits in sample E1 (LL = 92.1%) and lower in sample E3 (LL = 72.1%). Sample E3 has the lowest (PL = 42.1%) while the sample E2 has the highest value (PL = 58.8%). The plasticity index is obtained as the difference between the liquid limit and the plastic limit for each sample. It should be noted that despite the slight differences between these different values, these clay samples remain almost identical.

Stacked area chart showing the proportion (%) of sand, silt, and clay in five trial pits (P1 to P5). The y-axis represents the proportion in percentage, ranging from 0 to 65. The x-axis represents the trial pits. The legend indicates: clay (green), silt (red), and sand (blue).

Trial pit	sand (%)	silt (%)	clay (%)
P1	16	17	67
P2	17	22	61
P3	13	24	63
P4	18	27	55
P5	20	28	52

[illegible]

Table 3 Atterberg limits of different samples

	E1	E2	E3	E4	E5	E6
LL (%)	92.1	91.9	72.1	75.2	83	83.7
PL (%)	58.5	58.8	42.1	42.9	48.9	49.8
PI (%)	33.6	33.1	30	32.3	34.1	33.8
Description	Plastic	Plastic	Plastic	Plastic	Plastic	Plastic

PI = LL–PL

LL—liquid limit, PL—plastic limit and PI—plasticity index

5 Mineralogy

The various diffractographs resulting from XRD analysis of the various samples carried out on the total powder, clay fraction, clay fraction subjected to ethylene glycol and clay fraction subjected to a heat treatment of 500° is shown in Fig. 8. The X-ray spectra and the results of semi-quantification carried out on total powder show that the clay materials of the study area are made of the following in descending order of importance of: 45.21–60.70% of total clay with a peak at 4.47 Å, 17.16–21.76% of goethite, with a peak of 4.14 Å, 2.27–10.22% of quartz with peaks of 4.37 Å, 4.25 Å and 3.34 Å. Then 4.35–13.37% of feldspar with peaks at 3.25 Å, 3.28 Å, 3.18 Å and 3.13 Å, 3.76–10.35% of hematite with peaks at 2.70 Å and 2.70 Å, 0.34–7.43% of gibbsite with a peak of 4.85 Å and finally 1.75–3.14% of anatase with a peak of 3.57 Å. The proportions of the different minerals present in the samples is given on Table 4.

The XRD performed on the clay fraction gives the spectra of different minerals present in the fine fraction of the studied clay materials (E1, E2, E3, E4, E5 and E6), with their various spectra shown in Fig. 9 and Table 5 gives the proportion of the various minerals in the fine fraction. The diffractographs of all the samples show a peak at 7.14 Å which persists both in normal and in ethylene glycol. This peak disappears or flattens after heating. We also note a peak at 14 Å having the same behavior as that at a peak of 7.14 Å. In sample E1, there is a peak at 10 Å which persists in normal, ethylene glycol and on the heat treated samples. The XRD associated with the semi-quantification for all the analyzed samples makes it possible to identify the following 45.83–100% of kaolinite with a peak at 7.17 Å, 0–13.77% of chlorite with a peak at 14.11 Å and 0–40.47% of illite with a peak at 10 Å. It follows from this semi-quantification that kaolinite is the most abundant mineral of the clay fraction. The reason for this is attributed to monosialitic hydrolytic alteration that would have affected pre-existing surrounding rocks [12]. This also agrees with Bitom [3] that the abundance of kaolinite could be related to the resiliification of the gibbsite following the equation

The gibbsite identified by XRD in the samples studied could be related to an allitizing hydrolytic alteration or the desilification of kaolinite. Bomeni [4] who carried out a similar work at Babouantou shows that the presence of feldspars would indicate the absence of alkali and alkaline earth metals resulting from leaching. Upon focusing on these remarks, it will be judicious to conclude that the gibbsite present in the clay materials of Baboutcheu-Ngaleu would not have resulted from a hydrolysis of allitizing type but from the de-silification of the kaolinite. Bitom [3] also proposes an equation to understand this de-silification reaction.

The goethite found in the study site is believed to be related to hydrolytic alteration of alitite type, because the average value of precipitation (2085 milliliters) shows that the study site is well watered. In addition the high altitude (1500 m) is also a parameter which cannot be ignored. The presence of feldspars at a low proportions may be justified by the fact that the area is well drained. The presence of illite in the samples indicates a hydrolytic alteration climate of the bisialitizing type that initially affects feldspar minerals such as orthoclase or a neoformed mineral such as kaolinite [4]. The reason being that the alteration of the kaolinite present in the samples is the origin of the formation of illite. The presence of illite could confirm the process of bisillitisation. Based on the range of minerals obtained (gibbsite, goethite, hematite, kaolinite, chlorite and illite), it would be logical to infer that the clay materials of the study area are as a result of an hydrolytic alteration in a supergene medium combining allitization, monosilization and bis-aluminization.

6 Geochemistry

The chemical composition of major elements expressed as percentage of oxide, as well as the loss on ignition is presented on Table 6. It follows from this table that: Silica (SiO₂) and alumina (Al₂O₃) are the most abundant oxides

Fig. 8 Diffractogram of samples E1, E2, E3, E4, E5 and E6 obtained by XRD on total powder

in all analyzed samples, with contents ranging from 46.14 to 55.39% and 25.21 and 34.88% respectively. However, the E4 sample is distinguished by its low silica content

(46.14%). In addition, the Fe_2O_3 contents are high in all the samples.

The values of K_2O , NaO , CaO , P_2O_5 , MgO , MnO are relatively low to trace. Indeed, the sample E1 shows

Fig. 8 (continued)

Table 4 Composition of various minerals obtained from total powder

Sample	Clay	Gibbsite	Goethite	Hematite	Anatase	Quartz	Feldspar
E1	54.75	7.43	19.16	5.21	3.14	2.74	7.54
E2	54.25	7.3	18.99	3.76	2.64	7.23	5.83
E3	49.03	6.21	17.16	6.8	1.79	10.22	8.79
E4	60.7	0.34	17.7	5.47	2.58	8.85	4.35
E5	56.06	3.42	19.62	4	2.29	8.81	5.17
E6	45.21	1.34	21.76	10.35	1.75	6.22	13.37

zero values in K_2O . Similarly, it should be noted that NaO appears to be the least occurring oxide in all the samples because its values are totally zero in samples E1, E2, E4 and E6. The low levels of MgO, MnO, CaO and NaO in some samples and their absence in others may be explained by their high mobilities and significant leaching during the kaolinitization process [42]. In the present study these low grades may be characteristic of refractory minerals such as kaolinite in the clay materials studied [23]. The low zero levels of P_2O_5 , MgO, and MnO may be related to the presence of accessory minerals [45]. These accessory minerals have not been identified by XRD. However, other more advanced methods may be used to determine them. Since SiO_2 (46.14–55.39%), Al_2O_3 (25.21–34.88%) and Fe_2O_3 (15.22–19.37%) are the most abundant chemicals in clay materials of Baboutcheu-Ngaleu, it suggests that the significant quantities of SiO_2 is the result of intervention of a neoformation in the study area and this is confirmed by the presence of newly formed clays such as kaolinite detected by XRDs. The ratio of SiO_2/Al_2O_3 values greater than 01 would indicate an abundance of silica rather than alumina [42]. The values around (01) are characteristic of kaolinitic clays [25], whereas Pialy et al. [45] states that values around two (02) indicate a mixture of kaolinite/mica or illite. The High silica/alumina values would indicate the presence of kaolinite identified by XRD. On the other hand, Fe_2O_3/Al_2O_3 ratio is less than 1 in all samples, indicative of the presence of iron-based compounds. [4] alludes to the fact that these low values recall the presence of iron oxide and hydroxide such as hematite, goethite and ferrihydrite. Given the high percentage of goethite present in all samples as well as the low percentage of hematite, it would be preferable to attribute this to the presence of goethite in hematite. [45] suggests that the presence of variable proportion of Titanium oxide (TiO_2) is due to the presence of anatase, while Koneshloo [24] states that the high loss on ignition values would be due to the elimination of the water of constitution and the decomposition of certain associated minerals such as carbonates as well as the combustion of organic matter.

7 Some possible areas of application of clays studied

According to Sigg [47], in order to utilize clay for ceramic purposes, it must adhere to a certain particle size specification. The particle size composition plays an important part in the drying, shaping and firing characteristics of clay materials. In order to ascertain the suitability of the clay samples for ceramic applications, the particle size proportions were plotted on the Winkler [50] triangular diagram shown in Fig. 10. Consequently, four samples E1, E2, E3 and E4 were disqualified for solid brick making, while samples E4 and E5 were recommended for masonry tiles and bricks. From the mineralogy, kaolinite is the main clay mineral in the samples studied, which is also the most important mineral in the ceramics industry because of its refractory characteristics. The addition of feldspar would enhance the flux characteristics by promoting the appearance of a viscous phase during the heat treatment which contributes to reducing the porosity and improving the mechanical properties of clay products. From a geochemistry perspective, Table 7 presents the eligibility limits of clay for ceramic applications. Alumina which is another refractory material, whose recommended proportions vary between 9 and 45, plays an important role in the plasticity of clays. Generally, the increase in alumina content improves the plasticity of the clays, which allows the ease of molding. The alumina contents obtained in the samples falls within the recommended eligibility limits. The silica contents acceptable for ceramic use (35–85%) are close to those of the analyzed samples (46.14–55.3%). Upon examination of Winkler 1954 diagram and the table of legibility limits, other suitable materials could be added to enlarge the sphere of utilization of the clay materials.

Fig. 9 Diffractogram of samples E1, E2, E3, E4, E5 and E6 obtained by XRD on clay fraction

Table 5 The proportion of different clay minerals present in the clay fraction

Minerals	E1	E2	E3	E4	E5	E6
Kln	45.83	82.3	79.82	80	100	46.1
Chl	13.69	6.19	7.89	20	0	13.77
Ill	40.47	11.15	12.28	0	0	40.11

Kln kaolinite, *Hem* hematite, *Ant* anatase, *Gbs* gibbsite, *At* total clay, *Qtz* quartz, *Chl* Chlorite, *Gt* goethite, *Fld* feldspath, *Ill* illite

Table 6 Geochemical composition of major elements in the samples in terms of percentage of oxides

Sample identification	E1	E2	E3	E4	E5	E6
SiO ₂	47.86	46.93	48.99	46.14	55.39	48.23
TiO ₂	1.97	1.65	1.54	1.66	1.67	1.47
Al ₂ O ₃	32.53	34.70	29.21	34.88	25.21	33.63
Fe ₂ O ₃	17.31	15.50	19.37	15.22	16.51	15.60
MnO	0.04	0.12	0.08	0.73	0.15	0.17
MgO	0.24	0.47	0.40	0.44	0.52	0.50
CaO	0.01	0.10	0.11	0.55	0.22	0.18
NaO	0	0	0.04	0	0.10	0
K ₂ O	0	0.47	0.23	0.27	0.19	0.19
P ₂ O ₅	0.011	0.02	0	0.07	0	0
TOTAL	100	100	100	100	100	100
LOI	11.12	11.68	11.74	10.96	12.3	10.86
SiO ₂ /Al ₂ O ₃	1.47	1.35	1.68	1.32	2.20	1.43
Fe ₂ O ₃ /Al ₂ O ₃	0.53	0.45	0.66	0.44	0.65	0.46

Fig. 10 Particle size of the samples plotted on the Winkler [50] diagram. Fields application: (I) solid bricks (II) multi-hole bricks, (III) masonry tiles and bricks, and (IV) hollow products

8 Conclusion

The main objective of the present study was to determine the physico-geochemical and mineralogical characterization of the clay materials of Baboutcheu-Ngaleu, in a bid to expand the catalogue of clay deposits for possible industrial or artisanal exploitation. To achieve this goal, we proceeded with two methods: field methods and laboratory methods. With regards to field work, it was a question of identifying the various facies present and characterizing them macroscopically. For this, different trial pits were made according to the so-called

topo sequential method and samples were taken from the profiles of the trial pits. As a result, the color and the textures were determined. The laboratory physical analysis consisted in carrying out particle size analysis and determining the Atterberg limits by the Casagrande method. Then the mineralogical analysis by X-ray diffractometry on total powder and treatment on clay fraction under different conditions (normal, ethylene glycol and heating at 500 °C) were carried out. Finally the geochemical analysis of the samples were carried out by X-ray fluorescence. The particle size analysis shows the presence of the clay fraction in large proportions (52–64%), the silty fraction in average proportions of (18–28%) and the sandy fraction in a small proportions of (14–20%). The Atterberg limits show that the clay materials studied are plastic clays, with plasticity characteristics varying between (14–45%), and a plasticity index between (30–34.1%). From the mineralogical point of view, the XRD reveals the presence of clay minerals such as kaolinite (45.83–100%), chlorite (0–13.77%) and illite (0–40.47%) but also non-clay minerals such as goethite (17.16–21.76%), gibbsite (0.34–7.43%), hematite (3.76–10.35%), feldspar (4.45–13.37%), quartz (2.74–10.22%) and anatase (1.75–3.14%).

On the geochemical level, the oxides present are SiO₂ (46.14–55.39%), Al₂O₃ (25.21–34.88%), Fe₂O₃ (15.22–19.37%), TiO₂ (1.47–1.97%), and the alkalis (K₂O and NaO), alkaline earth metals (MgO and CaO), MnO, P₂O₅, the proportions of which are very low to trace. The proportions of SiO₂ are abundant in all samples. The SiO₂/Al₂O₃ values are greater than one in all samples, while the Fe₂O₃/Al₂O₃ ratios are less than 1 in all the samples studied. The clay in the study area is principally a kaolinite clay and based upon the Winkler diagram to ascertain their ceramic uses, four samples were disqualified for solid brick manufacture

Table 7 Eligibility limits for ceramic application of clays

Nature of elements	Formulation	Tolerance limits	Effect on finished product
Silica	SiO ₂	35–85	Refractory and adds on the mass
Alumina	Al ₂ O ₃	9–45	Refractory, improves mechanical resistance, and gives a white color
Magnesite	MgO	0–5	Porosity
Lime	CaO	0–25	Porosity
Iron sesquioxide	Fe ₂ O ₃	0–10	Reddish color, melting
Titanium oxide	TiO ₂	0.3–2	Yellow color
Alkaline oxides	NaO + K ₂ O	1–5	Melting point
Carbon dioxide	CO ₂	0–10	Volume
Sulfur trioxide	SO ₃	0–4	Volume/toxicity
Combined water	H ₂ O	5–11	Volume/weight

while two samples were recommended for masonry tiles and bricks production.

However we recommend further tests to be carried out to properly understand the clay microstructure as well as mechanical trial tests such as compressive strength, tensile test, water absorption and sound transmission to further confirm its wide applicability.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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