Research Article

Mineralogical, geochemical and geomechanical characterization of lateritic and alluvial clayey mixture products from Monatele - Ebebda, as building materials.

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ABSTRACT

This work focuses on the mineralogical and chemical analysis of two alluvial clays from the Sanaga River, four lateritic clays from Monatele and Ebebda regions in southern Cameroon and, on the physico-mechanical characterization of these clayey mixtures. The exploitation of XRD patterns reveals that quartz, muscovite, kaolinite corundum and rutile are the main minerals in alluvial clays, associated with goethite, hematite and ilmenite in lateritic materials. The main oxides are SiO_2, Al_2O_3 and Fe_2O_3 in lateritic clays. The low proportion of fluxing oxides ($Na_2O + K_2O + CaO + MgO < 2.50$ wt%) causes insufficient sintering during firing. Their particle size distribution is suitable for roofing tiles, lightweight blocks and solid bricks. Geotechnical characterization was carried out on five representative mixtures of lateritic and alluvial clay fired at five different temperatures, 900, 950, 1000, 1050 and 1100°C. The water absorption values are suitable for bricks (< 25%) at all the tested temperatures and for roofing tiles (< 20%) except at 900°C for the mixtures of one site at Monatele and at 1050°C for the mixture with 80 wt% of lateritic clay site at Ebebda. The flexural strength values are suitable for bricks (> 2.0 MPa) in all the sites except for two mixtures at Monatele, for tiles (> 6.5 MPa) in, one site at Ebebda and for the specimens with 80 and 60 wt% lateritic clays in one site at Monatele at 950 and 1050°C. The linear shrinkage values are high, causing deformations and microcracking on the produced bricks which require an addition of degreasers in order to reduce their plasticity before being used as building materials.

Keywords: Monatele-Ebebda (Centre Cameroon), lateritic and alluvial clays, mineralogy, géochemistry, geomechanical characterization

RÉSUMÉ

Le présent travail a pour but d'étudier la minéralogie et la chimie des argiles alluvionnaires de la Sanaga, celles des argiles latéritiques de la région de Monatele - Ebebda (Centre Cameroun) et de réaliser une caractérisation physico-mécanique des mélanges argiles latéritiques et alluviales en vue de leur utilisation dans l'industrie du bâtiment. La minéralogie des échantillons a été obtenue par DRX et la chimie, par fluorescence X et par titrimétrie (FeO) aux Laboratoires de Géosciences (GeoLabs) à Sudbury (Canada). Les essais et analyses physico-mécaniques et ceux de cuisson ont été effectués dans les laboratoires de la Mission de Promotion des Matériaux Locaux du Cameroun (MIPROMALO). Les résultats obtenus montrent que les matériaux alluvionnaires se composent de quartz, muscovite, kaolinite, corindon et rutile, auxquels s'associent goethite, hématite et ilménite dans les matériaux latéritiques. SiO_2, Al_2O_3 et Fe_2O_3 sont les oxydes dont les teneurs sont les plus élevées dans les argiles latéritiques. La faible proportion des fondants ($Na_2O + K_2O + CaO + MgO < 2.50\%$) provoque un frittage insuffisant pendant la cuisson. La caractérisation géotechnique réalisée sur cinq mélanges représentatifs d'argiles latéritiques et d'argiles alluviales, à cinq différentes températures, 900, 950, 1000, 1050 et 1100°C montre que sur le plan granulométrique, les matériaux de la région d'Monatéle - Ebebda sont aptes pour la fabrication des tuiles, blocs légers et briques pleines. Les valeurs d'absorption d'eau WA sont appropriées pour la confection des briques (< 25%) et des tuiles (< 20%), excepté à 900°C pour les mélanges d'un site à Monatélé et à 1050°C pour un mélange à 80 % d'argile latéritique d'Ebebda. Les valeurs de résistance à la flexion FS sont bonnes pour les briques (>2 MPa) dans tous les sites, excepté pour les mélanges à 100 et 80% d'argile latéritique d'un site de Monatelé. Pour les tuiles, tous les mélanges d'un site d'Ebebda sont adéquats de même que ceux à 80 et 60% d'argile latéritique d'un site de Monatélé à 950 et 1050°C. Les valeurs de retrait linéaire sont élevées, ce qui provoque des déformations et microfissuration sur les briques produites. Il est donc nécessaire d'ajouter des dégraissants qui induisent une réduction de la plasticité, avant toute utilisation de ces matériaux en construction.

Mots-clés : Monatélé-Ebebda (Centre Cameroun), argiles latéritiques, argiles alluviales, minéralogie, géochimie, géomécanique

INTRODUCTION

Nowadays, more attention is paid to clay materials due to their use in processing in many scientific and technological domains like industries, agriculture, engineering and building, environmental remediation and geologic applications (Murray, 2007). They have been widely used in the production of diversified ceramic products such as brick and tiles due to their specific properties before and after firing (Ngun et al., 2011). These materials have many advantages such as good thermal insulation, low environmental impact, less drain on natural resources, reduction of the ecological footprint construction, and reduced greenhouse gas emissions. In sub-Saharan Africa and Cameroon in particular, the import of construction materials such as lime and cement costs on average between 700 billion and 900 billion euros per year. However, the use of local materials may reduce currency losses caused by imports and increase GDP, thus facilitating access to housing. Their applications are related to the mineralogical and chemical compositions of the raw materials as well as the mechanical characteristics of the fired products (Hajjaji, 2014). Many studies have been carried out recently on clayey materials in Africa (Hajjaji, 2014; Baccour et al., 2008; Hajjaji et al., 2002; Hajjaji et al., 2010), particularly on lateritic clays in tropical countries (Andji et al., 2008; Moutou et al., 2012) as well as in Cameroon (Mbumbia et al., 2000; Elimbi et Ndjopwouo, 2002; Njoya et al., 2006; Kamseu et al., 2007; Ngon Ngon et al., 2009; Diko et al., 2011; Ngon Ngon et al., 2012; Nzeukou et al., 2013; Fadjil-Djenabou et al., 2015; Ndjigui et al., 2016; Ntouala et al., 2016) where they occupy more than two-third of the national territory (Tardy, 1993). Due to social and economic conditions, many houses in tropical countries are built with lateritic clays although these authors show that lateritic clays often have very poor characteristics after firing. This is because of their high iron content (Andji et al., 2008; Mahmoudi et al., 2008; Ngon Ngon et al., 2012; Ntouala et al., 2016). In response, it is possible to add calcite clay mixtures (Andji et al., 2008), urban river sediments (Xu et al., 2014), lime and/or cement (Al-Mukhtar et al., 2010; Jauberthie et al., 2010) in order to improve their geomechanical properties. Ntouala et al. (2016) improved the properties of the Ayos lateritic clays by adding the Nyong alluvial clays.

The aim of this work is to carry out a mineralogical and geochemical characterization of lateritic clays from the Monatele-Ebebda region and alluvial clays from Sanaga River. This is to better understand the mechanical behavior of these clay mixtures after firing. This work is a contribution to the understanding on the improvement of lateritic clays behavior and their use in the brick industry.

GEOGRAPHIC AND GEOLOGIC SETTINGS

The study area is located in the southern Cameroon plateau (Fig. 1). The altitude ranges from 376 to 811 m. It is under a transition equatorial climate zone with an average precipitation of 1539.2 mm and mean temperature of 24.2°C (1975 – 2011). This area belongs to the Sanaga watershed which is the largest watershed in Cameroon.

The area is underlain by the Yaounde series which consist of intensely deformed metasedimentary rocks and migmatites (Nzenti et al., 2008). Geological formations include quartzites, micaschists, gneisses and migmatites; these rocks are commonly thought to have experienced the Neoproterozoic nappe tectonic event that is transpressional and responsible for thrusting the large Yaounde nappe onto the Congo Craton (Ngako et al. in Mvondo et al., 2007). The superficial lateritic formations are the result of the weathering of these formations. They consist of red lateritic soils in the uplands, hills and hydromorphic soils in the lowlands (Thibault et Le Berre, 1985).

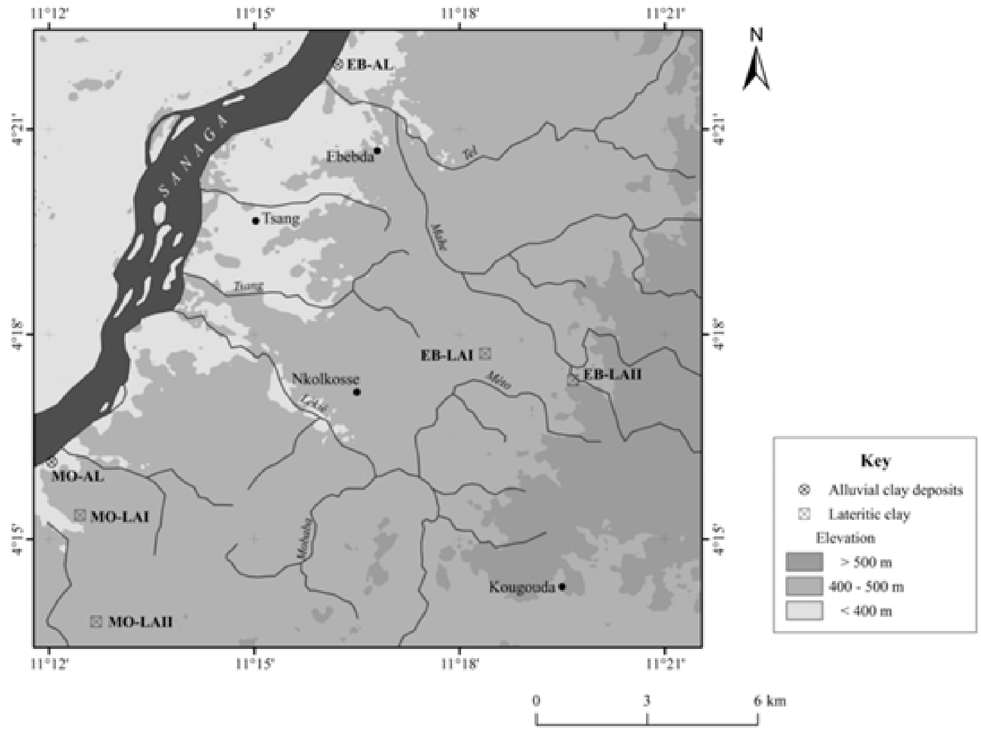

Fig. 1. Location of the study area and sampling points

MATERIALS AND METHODS

Sampling methods

Two study sites were selected for the study (Monatele and Ebebda). At each site, three samples were collected: alluvial clay on the left bank of the Sanaga swampy valley and two lateritic clays in the upper superficial unit of the soil profile. The sampling of the alluvial clays required a manual auger while the lateritic clays needed a shovel and a pickaxe. 1 kg of each sample was collected for mineralogical and chemical analyses and 50 kg of each sample for physical and mechanical tests.

Analytical procedures

The color of the dry samples and fired samples were determined using the Munsell Soil Color chart. The hue / value / chroma of the samples was determined by visual comparison with those of standard soils recorded in the Munsell Color chart. Mineralogical and chemical analyses were performed at the Canadian laboratories of Geosciences (Geo Labs). The X-ray diffraction patterns were obtained using a diffractometer (Bruker Advance 8) equipped with Ni filtered CuKα radiation, with an automatic slit and on-line computer control. The samples were scanned from 2° to 45° 2θ. Measurements were performed on randomly oriented powder preparation from bulk samples and special treatments (oriented samples, samples heated at 500°C for 4 hours, ethylene-glycol saturated samples for 22 hours) were carried out to characterize the clay fraction. Mineral identification from the diffractograms and a semi-quantitative mineralogical composition were carried out using EVA software. The relative abundance of minerals was estimated from the heights of the main peaks.

The chemical composition of the materials was determined by X-ray fluorescence after sample ignition. Sample powders were ignited and then melted with lithium tetraborate flux before analysis using Rigaku RIX-3000 wavelengthdispersive X-ray fluorescence spectrometer. International standards BIR-1-0949, SDU-1-0295 and SDU-1-0296 as well as in-house standards were run with the unknowns; comparisons of measured and reference values are available upon request. Samples were crushed using a jaw crusher with steel plates and pulverized in a planetary ball mill composed of 99.8% Al_2O_3. A two-step loss on ignition (LOI or H_2O) determination was done. Powders were first heated at 105°C under nitrogen to drive off adsorbed H_2O, before being ignited at 1000°C under oxygen to eliminate the remaining volatiles and oxidized Fe.

The liquid limit (LL) was measured by the Casagrande dish method and the plastic limit (PL) by the roller method. The measurements were realized according to ASTM D4318 - 2005 standard. Plasticity index was calculated by arithmetic difference between LL and PL.

The particle size analyses were carried with sieves and an electric shaker for particles greater than 80 µm and by sedimentometry for particles less than 80 µm. The sedimentometry was based on the principle of Stoke's law of sedimentation of individual spherical particles falling freely at steady velocity under the influence of gravity.

To evaluate the effect of alluvial clay on physical and mechanical characteristics of lateritic clays, five compositions were made in the ratio of lateritic to alluvial clays: 100% of lateritic clay, 80 - 20%, 60 – 40%, 40 – 60% and 100% of alluvial clay respectively. The adopted nomenclature includes the initial of the locality name (MO for Monatele and EB for Ebebda), followed by the clayey nature (AL for alluvial and LA for lateritic) and a number which gives the proportion of the lateritic clay in the mixture. 360 raw brick specimens of 8 cm length and 4 cm width were obtained by hydraulic pressure of 100 g of the given clay mixture blended with 17 wt% water. Bricks were then air-dried for 7 days and then oven-dried at 105°C for 24 hours to remove moisture prior to firing. Firing was done in a muffle furnace of FP34G type, with maximum temperature of 1250°C. The tested brick specimens were subjected to five firing temperatures: 900°C, 950°C, 1000°C, 1050°C and 1100°C. The temperature was increased by 5°C per minute, with a soaking time of 2 h.

The linear shrinkage was determined as follows (ASTM C531 – 2000):

$$LS\ (\%) = [(L_0 - L_1)/L_0] \times 100 \quad (1)$$

Where L_0 = length (mm) of the brick after drying at 105°C for 24 h and L_1 = length (mm) after firing.

The water absorption (WA), expressed as a percentage of the weight relationship of water absorbed after soaking in water for 24 h to the weight of the fired specimen (ASTM C20 – 2000). WA was calculated as:

$$WA\ (\%) = [(W_2 - W_1)/W_1] \times 100 \quad (2)$$

Where: W_2 = weight of soaked specimen and W_1 = weight of fired specimen.

The flexural strength (σ) in MPa was calculated for each specimen as follows (ASTM F417 – 1996):

$$\sigma = 3PL/2lh^2 \quad (3)$$

Where P = load at fracture (N), L = distance between supporting knife edge (50 mm), l = width of specimen, and h = thickness of specimen (mm).

RESULTS

Mineralogy

The X-ray diffraction patterns of the alluvial clays of Monatele and Ebebda (Fig. 2) reveal that the main minerals are quartz, muscovite, kaolinite, corundum and rutile. Their proportions are shown in Table 1. Chlorite (4.71 wt%) is present only in Ebebda. Quartz, muscovite, kaolinite, corundum and rutile are present in the four lateritic clays (Fig. 3). Goethite is absent only in MO-LAII while hematite is not found in EB-LAI. Ilmenite peaks are also observed in Ebebda zone.

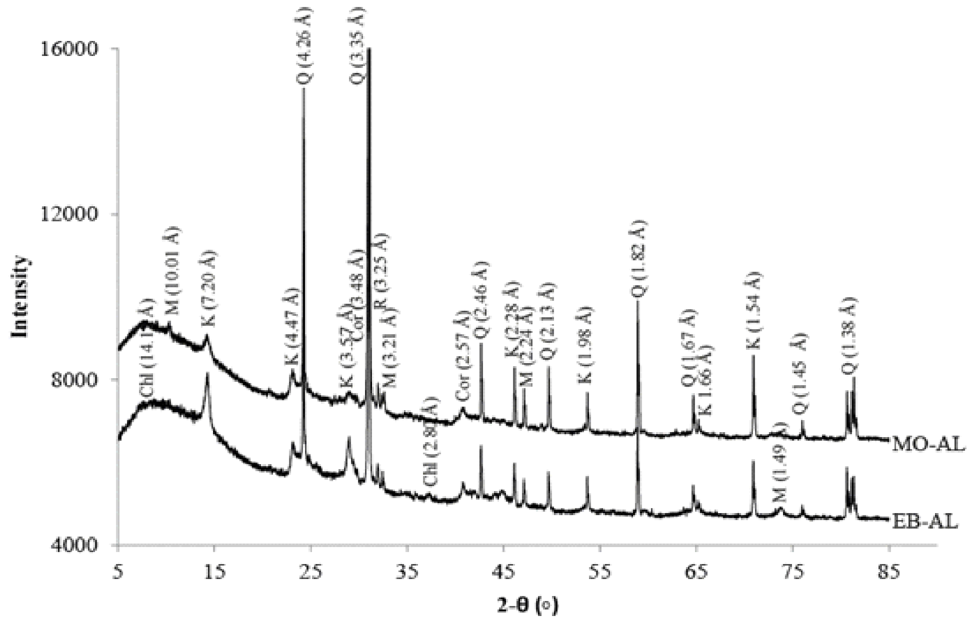

Fig. 2. X-ray diffraction pattern of the alluvial clays of Monatele and Ebebda

Table. 1. Mineralogical composition of the raw materials

Nature	Alluvial clays		Lateritic clays			
Code	MO-AL	EB-AL	MO-LAI	MO-LAII	EB-LAI	EB-LAII
Anatase	-	-	-	-	6.00	-
Chlorite	-	4.71	-	-	-	-
Corundum	6.30	5.62	4.90	6.76	4.48	4.71
Goethite	-	-	10.00	-	7.77	12.34
Hematite	-	-	3.44	3.04	-	4.68
Ilmenite	-	-	-	-	2.00	3.75
Kaolinite	11.75	22.03	32.23	7.87	22.30	25.03
Muscovite	35.00	26.74	24.71	31.46	22.17	23.17
Rutile	4.15	4.76	4.34	2.07	3.61	6.00
Quartz	42.80	36.14	20.38	48.80	31.67	20.32
Total	100	100	100	100	100	100

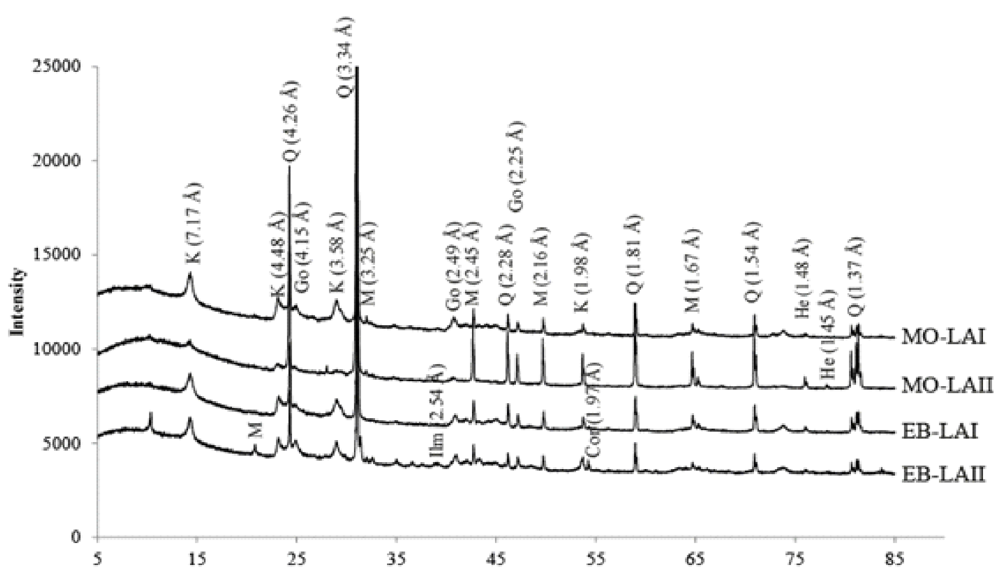

Fig. 3. X-ray diffraction pattern of the lateritics clays of Monatele and Ebebda

Chemistry

The major element concentrations in lateritic and alluvial clays from Monatele and Ebebda are shown in Table 2. SiO_2 is the most abundant oxide in these materials. It varies between 45.56 wt% (EB-LAII) and 79.99 wt% (MO-LAII). SiO_2 is followed by Al_2O_3 (8.84 wt% for MO-LAII and 24.28 wt% for EB-LAII). The Fe_2O_3 content is greater than 6.00 wt% for MO-AL (6.14 wt%), MO-LAI (6.24 wt%) and EB-LAII (12.11 wt%). Lower values of these oxides occur in MO-LAII, EB-LAI and EB-AL, 3.18 – 4.12 and 4.85 wt% respectively. K_2O contents range from 0.69 to 1.54 wt%. The contents of the other alkaline and alkali-earth elements (MgO, CaO, Na_2O) are below 0.50 wt%, except in the sample EB-LAI for CaO and Na_2O (0.53 wt% and 0.63 wt% respectively). The highest value of TiO_2 (1.70 wt%) is in EB-LAII.

Atterberg limits

The liquid limits and plasticity indices values of the alluvial clays are respectively 44 – 14% and 42 – 17% (Tab. 3) in Monatele – Ebebda region. Liquid limits values range from 42 to 44% for the mixtures with EB-LAI, 46 – 49% for those with EB-LAII, 45 – 46% for those with MO-LAI and 32 – 42% for those with MO-LAII. Plasticity index (PI) values are respectively 17 and 18% in EB-LAI and EB-LAII. The values of this parameter range between 15 – 17% for the mixtures with MO-LAI and 10 – 14 % for those with MO-LAII. The position of these samples on the Casagrande chart (Fig. 4) reveals that sample EB-AL, all the mixtures with EB-LAI and those with more than 40 wt% of MO-LAII are inorganic clays of medium plasticity. The samples MO-AL, MO-LA40 and all the mixtures with MO-LAI and EB-LAII are inorganic silts of medium compressibility or organic silts.

Table 2. Chemical composition of the raw materials

	SiO_2	Al_2O_3	LOI	MgO	MnO	CaO	Na_2O	K_2O	Fe_2O_3	FeO	TiO_2	P_2O_5	Cr_2O_3	Total
MO-AL	67.30	13.53	7.71	0.37	0.02	0.19	0.38	1.52	6.14	0.42	1.29	0.05	0.01	98.93
EB-AL	61.43	18.01	9.77	0.36	0.08	0.24	0.25	1.29	4.85	1.23	1.58	0.11	0.01	99.20
MO-LAI	54.20	23.59	11.32	0.44	0.06	0.17	0.07	1.54	6.24	0.47	1.40	0.06	0.01	99.57
MO-LAII	79.99	8.84	5.13	0.20	0.05	0.11	0.06	0.94	3.18	0.54	0.86	0.04	0.00	99.94
EB-LAI	61.65	18.55	10.22	0.37	0.13	0.53	0.63	0.69	4.12	0.34	1.37	0.06	0.07	98.73
EB-LAII	45.56	24.28	12.57	0.36	0.11	0.22	0.26	1.44	12.11	0.72	1.70	0.18	0.02	99.53

Table 3. Atterberg parameters of Monatele - Ebebda clayey mixtures

Code	MO-LAI 100*	MO-LAI 80	MO-LAI 60	MO-LAI 40	MO-AL0	MO-LAII 40	MO-LAII 60	MO-LAII 80	MO-LAII 100
LL, %	46	46	45	45	44	42	38	34	32
PI, %	17	17	16	15	14	14	13	12	10

Code	EB-LAI 100	EB-LAI 80	EB-LAI 60	EB-LAI 40	EB-AL	EB-LAII 40	EB-LAII 60	EB-LAII 80	EB-LAII 100
LL, %	44	43	43	42	42	46	48	49	49
PI, %	18	18	18	18	17	17	17	17	17

*: The number in the code indicates the proportion of the lateritic clay in the mixture

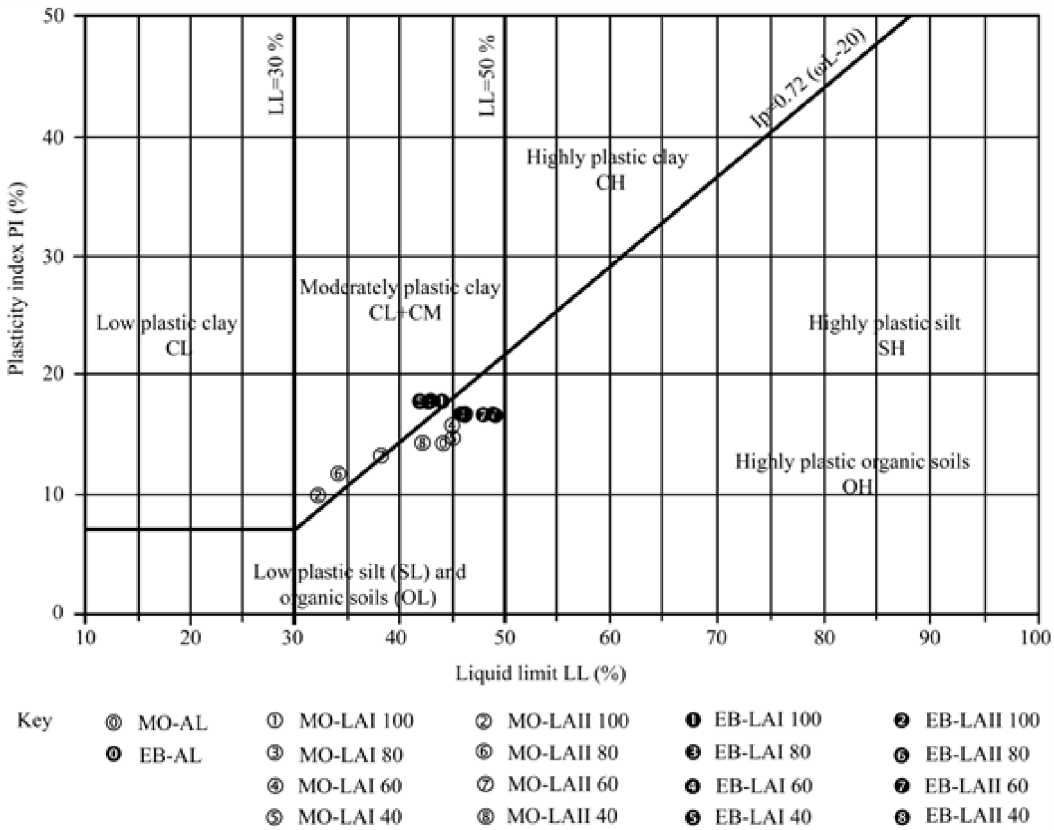

Fig. 4. Position of Monatele and Ebebda clays in the Casagrande plasticity chart

Particle size distribution

The alluvial samples MO-AL and EB-AL consist of 40.17 and 32.84 % sand, 25.98 and 17.47 % silt and, 33.85 and 46.02 % clay, respectively (Tab. 4). The lateritic samples MO-LAI, MO-LAII, EB-LAI and EB-LAII are made of 29.37, 70.00, 37.90 and 39.06 % sand, 18.53, 10.40, 24.56 and 28.65% silt and 51.80, 19.60, 37.54 and 30.62% clays, respectively. According to the Bah *et al*. (2005) Belgian classification diagram, EB-AL, MO-LAI and EB-LAI are heavy sandy clay, sandy clay (MO-AL, EB-LAII) and clayey sand (MO-LAII).

Color

The color of the bricks is related to the mixture composition and firing temperature (Tab. 5). The color of bricks obtained from the mixtures of Monatele region varies from light red (2.5YR 6/8) at 900°C to red (2.5YR 4/8) at 1100°C. EB-LAI color ranges from reddish yellow (7.5YR 7/6) at 900°C to yellowish red (5YR 5/6) at 1100°C. For EB-LAII, the color is red (2.5YR 5/6) at 900°C and at 1100°C (2.5YR 4/6).

Linear shrinkage (LS)

The linear shrinkage increased from 1000°C to 1100°C for the mixtures with the alluvial clay of Monatele (Fig. 5). Globally, at Monatele, the linear shrinkage values decreased with the alluvial clay content for the mixtures with MO-LAI. With MO-LAII, the lowest values are observed for MO-LAII100. These values of linear shrinkage are less than 2.00% for all the MO-LAII mixtures. LS values are less than 2.00 % only at 900°C for all the mixtures with MO-LAI and only at 950°C for MO-LAI40. Globally, LS values for the mixtures with Ebebda's alluvial clays increased from 950°C or 1000°C and got their maximum values at 1100°C. At this temperature, these values vary between 4.71 – 6.05% for EB-LAI and 6.70 – 9.23% for EB-LAII.

Table 4. Particle size distribution of Monatele - Ebebda clayey materials

	Gravel (%) Φ>2 mm	Sand (%) 2>Φ>0.02 mm	Silt (%) 0.02>Φ>0.002 mm	Clay (%) Φ<0.002 mm	Total
MO-AL	0.00	40.17	25.98	33.85	100
EB-AL	3.67	32.84	17.47	46.02	100
MO-LAI	0.30	29.37	18.53	51.80	100
MO-LAII	0.00	70.00	10.40	19.60	100
EB-LAI	0.00	37.90	24.56	37.54	100
EB-LAII	1.67	39.06	28.65	30.62	100

Table 5a. Physical and mechanical data of tested bricks (Monatele region)

	Code	MO-LAI 100*	MO-LAI 80	MO-LAI 60	MO-LAI 40	MO-AL0	MO-LAII 40	MO-LAII 60	MO-LAII 80	MO-LAII 100
900 °C	Color	2.5YR 6/8	5YR 6/8	2.5YR 6/8	5YR 6/8	5YR 7/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8
	LS (%)	1.11	1.04	0.72	0.79	0.40	0.19	0.25	0.19	0.09
	WA (%)	22.42	22.93	21.84	20.88	19.38	16.37	14.01	15.55	14.77
	σ (MPa)	4.09	3.48	3.04	3.52	3.02	2.61	2.66	1.81	1.39
950 °C	Color	2.5YR 6/8	5YR 6/8	5YR 6/8	5YR 6/8	7YR 7/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8
	LS (%)	5.74	6.54	4.85	1.71	1.05	0.34	0.34	0.78	0.36
	WA (%)	8.04	8.39	11.02	18.18	17.17	16.57	16.14	15.57	16.67
	σ (MPa)	-	7.92	7.11	4.93	4.78	3.15	2.33	1.88	1.53
1000 °C	Color	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8
	LS (%)	6.86	5.87	3.82	3.48	1.33	1.07	0.97	1.00	0.47
	WA (%)	8.84	12.40	12.70	17.60	16.62	14.87	15.28	14.79	14.24
	σ (MPa)	-	6.14	5.79	6.98	5.18	3.51	2.30	1.93	1.35
1050 °C	Color	2.5YR 5/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8	2.5YR 6/8
	LS (%)	8.40	7.31	5.15	3.86	3.16	1.09	1.25	1.19	0.75
	WA (%)	9.55	9.22	10.80	12.94	11.81	14.54	13.64	13.96	14.99
	σ (MPa)	7.29	11.88	10.40	6.27	5.41	3.10	2.28	1.33	1.35
1100 °C	Color	2.5YR 4/8	2.5YR 5/8	2.5YR 5/8	2.5YR 5/8	2.5YR 4/8	2.5YR 4/8	2.5YR 4/8	2.5YR 4/8	2.5YR 4/8
	LS (%)	9.96	9.28	6.56	6.20	4.43	1.81	1.47	1.31	1.18
	WA (%)	6.44	9.13	8.41	9.73	10.57	12.31	12.98	13.34	13.61
	σ (MPa)	-	-	7.02	5.95	6.07	3.00	2.04	1.51	1.20

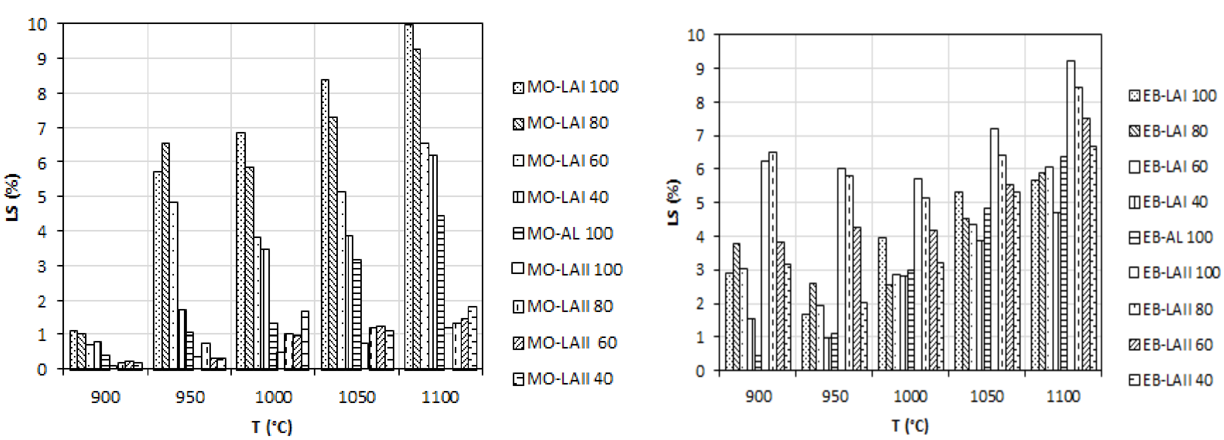

Fig. 5. Linear shrinkage variation with firing temperature of Monatele and Ebebda tested bricks

Water absorption (WA)

Water absorption results are shown in Table 5 and are presented in Fig. 6. The mixtures with MO-AL and MO-LAI, have their maximum WA values at 900°C and the minimum at 1100°C, except for MO-LAI80 with the lowest value observed at 950°C (8.39%). This parameter is greater than 20% only at 900°C for the mixtures with more than 40% of MO-LAI, 22.42, 22.93, 21.84 and 20.88% for MO-LAI100, MO-LAI80, MO-LAI60 and MO-LAI40 respectively. In the MO-AL-MO-LAII mixtures, WA values are higher than those with MO-LAI, except at 900°C where they are respectively 14.77, 15.55, 14.01 and 16.37% for

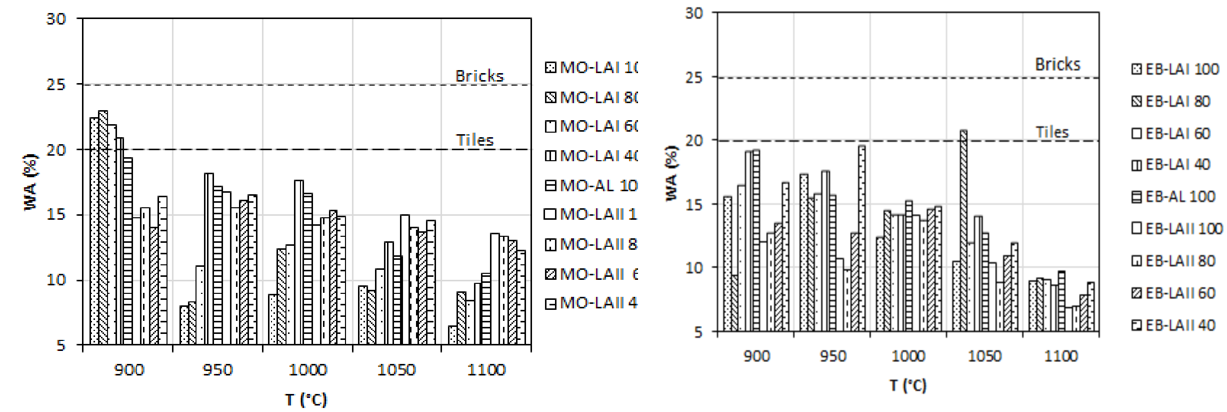

Fig. 6. Water absorption variation with firing temperature of Monatele and Ebebda tested bricks

MO-LAII100, MO-LAII80, MO-LAII60 and MO-LAII40. Like in the previous case (MO-LAI), the lowest values were obtained at 1100°C, respectively 13.61, 13.34, 12.98 and 12.31 for the same mixtures. At Ebebda, WA values decrease from 900°C to 1100°C only for EB-AL, EB-LAI40 and EB-LAI60. These values are 19.25 – 19.20 and 16.51% for the two mixtures at 900°C and 9.85 – 8.71 and 9.15% at 1100°C respectively. The highest WA values were obtained at 1000°C for the mixtures EB-LAI100, EB-LAII100, EB-LAII80 and EB-LAII60, 12.50 – 14.07 – 13.78 and 14.69% respectively. The mixtures EB-LAI80 and EB-LAII40 show their maximum WA values respectively at 1050°C (20.82%) and 950°C (19.63%). All the studied mixtures at Ebebda have their minimum WA values at 1100°C.

Flexural strength (FS)

The flexural strength of the studied mixtures are shown in Table 5. Their evolution is illustrated in Fig 7. The FS values are lower than 2.00 MPa at all firing temperatures for the MO-LAII100 and MO-LAII80 mixtures. The values of this parameter are greater than 2.00 MPa for all the other mixtures. Globally, at Monatele, the FS values of MO-LAI mixtures are greater than those of the alluvial sample MO-AL while MO-LAII mixtures FS values are lower. At Ebebda, the same trend can be observed from 950°C except for EB-LAII40 at this temperature. The FS values of EB-LAII mixtures are greater than those of the alluvial sample EB-AL while EB-LAI mixtures FS values are lower than those of EB-AL.

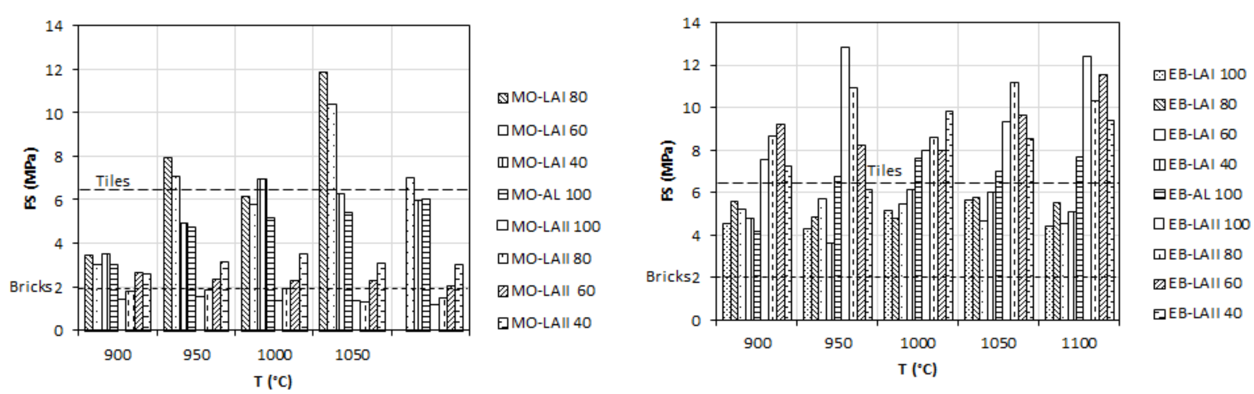

Fig. 7. Flexural strength variation with firing temperature of Monatele and Ebebda tested bricks

Table 5b. Physical and mechanical data of tested bricks (Ebebda region)

	Code	EB-LAI 100*	EB-LAI 80	EB-LAI 60	EB-LAI 40	EB-AL 0	EB-LAII 40	EB-LAII 60	EB-LAII 80	EB-LAII 100
900 °C	Color	7.5YR 7/6	7.8YR 7/6	5YR 6/8	5YR 7/6	5YR 6/6	2.5YR 6/8	5YR 5/6	7.5YR 5/6	2.5YR 5/6
	LS (%)	2.89	3.77	3.06	1.55	0.45	3.19	3.81	6.51	6.22
	WA (%)	15.62	9.47	16.51	19.20	19.25	16.75	13.55	12.81	12.02
	σ (MPa)	4.58	5.61	5.22	4.82	4.19	7.29	9.23	8.69	7.53
950 °C	Color	5YR 7/6	5YR 7/6	5YR 7/6	2.5YR 6/6	5YR 7/6	2.5YR 6/6	2.5YR 6/8	2.5YR 5/8	5YR 5/8
	LS (%)	1.66	2.61	1.95	0.98	1.12	2.02	4.28	5.82	6.00
	WA (%)	17.43	15.51	15.93	17.69	15.73	19.63	12.76	9.95	10.67
	σ (MPa)	4.29	4.88	5.7	3.66	6.77	6.17	8.22	10.93	12.84
1000 °C	Color	5YR 7/6	5YR 6/6	5YR 6/6	5YR 7/6	5YR 7/6	5YR 7/6	2.5YR 6/8	5YR 5/8	2.5YR 4/8
	LS (%)	3.98	2.55	2.87	2.81	3.00	3.20	4.18	5.13	5.71
	WA (%)	12.5	14.56	14.21	14.26	15.36	14.91	14.69	13.78	14.07
	σ (MPa)	5.17	4.81	5.49	6.15	7.64	9.85	8.00	8.60	8.01
1050 °C	Color	5YR 7/8	5YR 6/8	5YR 6/6	5YR 7/6	5YR 7/6	2.5YR 5/8	2.5YR 4/8	2.5YR 4/6	2.5YR 4/6
	LS (%)	5.33	4.52	4.35	3.86	4.85	5.34	5.53	6.40	7.22
	WA (%)	10.61	20.82	12.01	14.14	12.83	12.05	11.00	8.94	10.32
	σ (MPa)	5.67	5.79	4.68	6.01	7.03	8.56	9.66	11.18	9.32
1100 °C	Color	5YR 5/6	5YR 5/6	5YR 5/4	5YR 6/6	5YR 6/6	2.5YR 4/6	2.5YR 4/6	2.5YR 4/6	2.5YR 4/6
	LS (%)	5.67	5.89	6.05	4.71	6.36	6.70	7.50	8.44	9.23
	WA (%)	9.12	9.27	9.15	8.71	9.85	8.97	8.02	7.05	6.81
	σ (MPa)	4.45	5.55	4.55	5.12	7.68	9.44	11.56	10.36	12.45

*: The number in the code indicates the proportion of the lateritic clay in the mixture

DISCUSSION

The main mineral in Monatele - Ebebda clayey materials is quartz, in accordance with the chemical analyses which reveal the predominance of SiO_2. The high proportion of muscovite in the alluvial materials differs from the results already obtained by Nzeukou et al. (2013) in the same region and by Ngon Ngon et al. (2009) in Yaounde. According to Nzeukou et al. (2013), quartz and kaolinite are the main minerals, with low proportions of feldspar, smectite and illite. According to Ngon Ngon et al. (2009), the mineralogical composition of lateritic clays from Yaounde consists of quartz, goethite, hematite, kaolinite, rutile, anatase and halloysite. Alluvial clays of this region are characterized by the same mineralogical assemblage with the exception of hematite, and the presence of gibbsite and feldspars. The presence of muscovite in the studied materials matches with the observation made on the mixed bricks. SiO_2 is followed by Al_2O_3 and Fe_2O_3 as the main major elements. It is compatible with the results obtained by Ntouala et al. (2016) at Ayos (Eastern Cameroon). The contents of these three elements vary between 81.95 wt% (EB-LAII) and 92.01 wt% (MO-LAII). The proportion of fluxing oxides (Na_2O, K_2O, CaO and MgO) is low and ranges between 1.31 (MO-LAII) and 2.46 wt% (MO-AL). These low proportions, due to their rapid leaching during weathering have also been reported (Ngon Ngon et al., 2009, 2012; Nzeukou et al., 2013; Fadjil-Djenabou et al., 2015; Ndjigui et al., 2016, Ntouala et al., 216), and may cause insufficient sintering during firing. The high content of alkaline elements in primary raw clayey materials could have decreased the suitable firing temperature during the formation of bricks (Kamseu et al., 2007; Xu et al., 2014; Dondi et al., 2001; Baccour et al., 2008; Pardo et al., 2011). The grain size of raw clayey materials must be well-graded (Reeves et al., 2006), as it is the case in this study to increase the densification of the bricks. According to Winkler's diagram (Fig. 8) in Hajjaji et al. (2002), the grain size distribution of MO-LAII is suitable for solid bricks while for all the others materials, it is suitable for roofing tiles and light weight blocks. The yellow colors are due to the presence of anatase (Souza et al., 2002).

Taking into account the proportion of Fe_2O_3, TiO_2 and MnO (> 1.5 wt%), these mixtures after firing could not be white (Souza et al., 2002; Andreola et al., 2009). The red colors are due to the high iron contents of the studied materials. The linear shrinkage values obtained for MO-LAI, EB-LAI and EB -LAII bricks are higher than those obtained

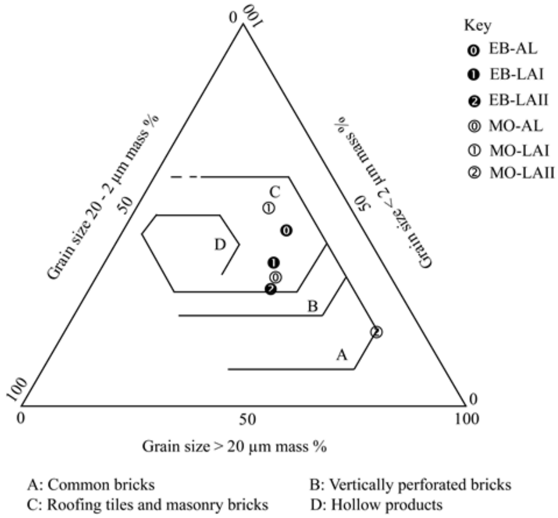

Fig. 8. Winkler's diagram

in the Sanaga (Nzeukou et al., 2013), on sedimentary clays of Nanjing-Chine (Xu et al., 2014), at Ayos (Ntouala et al., 2016), but lower than those documented at Limbe (Diko et al., 2011). Only the linear shrinkage values of MO-LAII remain low. They are lower than those obtained at Ayos (Ntouala, 2016). The evolution of linear shrinkage with the mixed compositions is linked to the iron content of the raw materials (Andji et al., 2008; Mahmoudi et al., 2008; Ngon Ngon et al., 2012; Ntouala et al., 2016). This parameter increases with the iron content of the tested brick. Indeed, in the case of mixtures with MO-LAII (Fe_2O_3 = 3.18 wt%), the linear shrinkage values are lower than that of MO-AL (Fe_2O_3 = 6.14 wt%), which is not the case for mixtures with MO-LAI (Fe_2O_3 = 6.24 wt%). At Ebebda, the linear shrinkage values differ little between the EB-LAI mixtures (Fe_2O_3 = 4.12 wt%) and EB-AL (Fe_2O_3 = 4.85%). The mixtures using EB-LAII (Fe_2O_3 = 12.11 wt%) have linear shrinkage values which increase with the lateritic clay content. During firing, the variation of shrinkage depends mainly on the degree of sintering and the initial porosity of raw clay (Milheiro et al., 2006). The quartz-rich clays have low firing shrinkage, densification and adequate mechanical behavior for the finished products (Michailidis et al., 2010). According to He et al. (2012), the amount of contraction is determined by the amount of liquid phases generated during firing. They require the addition of degreasers to avoid high shrinkage and cracks (Nzeukou et al., 2013). In general, for the ceramic products, the water absorption values must decrease with increasing firing temperature due to the gradual disappearance of porosity during sintering (Milheiro et al., 2006). This fact was verified at Monatele, except between 950 and 1000°C for MO-LAI60 - 100 and MO-LAII100 between 1000 and 1050°C. At Ebebda, the water absorption values oscillate but remain below 20%, except for EB-LAI60 at 1050°C. The oscillations of the water absorption rate observed at Ebebda and the increases at Monatele were due to microcracks appearing in these briquettes at tested firing temperatures. The water absorption is closely related to the densification of the clay matrix, and helps to have an idea about the vitrification of clays (Reeves et al., 2006; Melo et al., 2003). The proportional decrease of water absorption rate in excess at 1000°C is related to the considerable formation of the liquid phase which has penetrated isolated pores (Manoharam et al., 2011). These results are still lower than those obtained by Mbumbia et al. (2000) and Diko et al. (2011). The specified values for WA of Brazilian clay-base products (Souza et al., 2002) are WA < 25% wt% for dense bricks and ceramic blocks and WA < 20% wt% for roofing tiles. Comparing the WA results of this study with the above standards, all the mixtures could be used for dense bricks and ceramic blocks. Except for MO-LAI mixtures at 900°C and EB-LAI80 at 1050°C, these mixtures are adequate for roofing tiles. Microcracking observed on laboratory bricks contributes to their embrittlement and therefore to a decrease in mechanical strength. Due to the spatial variation of cracking, the flexural strength values are neither dependent on the firing temperature nor mixtures composition. According to Andreola et al. (2009) and Arsenovic et al. (2013), if illite is present in the prepared mixtures, it should normally improve the plasticity, promote the appearance of glassy phases which increases the densification and the flexural strength. There should be an increase in the flexural resistance value due to the formation of mullite at the expense of the kaolinite present in the raw material from 1050°C (Kornman, 2009). This fact was not observed in the case of this study. Particular interest was focused on the high content of Fe_2O_3 which acted as a flux and thus increaseed the compacity of the material and therefore the mechanical strength. The flexural strength values specified by (Souza et al., 2002) are $\sigma \geq$ 2 MPa for dense bricks, $\sigma \geq$ 5.5 MPa for ceramic blocks and for $\sigma \geq$ 6.5 MPa roofing tiles. By comparison with the results obtained, except for mixtures with 80 or 100 wt% of MO-LAII, all the experimental bricks could be used for the manufacture of dense bricks. For ceramic blocks, all mixtures between EB-LAII and EB-AL are suitable. Only EB-LAI100 mixtures at 1050°C, EB-LAI80 at 1050 and 1100°C, EB-LAI60 at 950°C, EB-LAI40 at 1000 and 1050°C and EB-AL100 at all temperatures except 900°C are suitable for the manufacture of ceramic blocks. The manufacture of tiles can be made from all mixtures with EB-LAII except EB-LAII40 at 950°C while no mixture made from EB-LAI is compliant. EB-AL100 is suitable for tiles between 950 and 1100°C.

CONCLUSION

The following conclusions can be drawn from the study.

1. The main minerals present are quartz, muscovite, kaolinite, corundum and rutile in alluvial clays. These minerals are associated with goethite, hematite and illmenite in lateritic clays. The main oxides are SiO_2, Al_2O_3 and Fe_2O_3 in lateritic clays. The low proportion of fluxing oxides caused insufficient sintering during firing.
2. The particle size distribution of the studied materials is suitable for roofing tiles and light weight blocks (MO-AL, MO-LAI, EB-AL, EB LAI and EB-LAII) and for solid bricks (MO-LAII) according to Winkler's diagram.
3. The water absorption values are suitable for bricks and roofing tiles. The flexural strength values are suitable for bricks in all the sites except for the samples with 80 wt% or more of MO-LAII. EB-LAII mixtures were suitable for manufacture of tiles. Except for a few specimens, the others mixtures required supplementary treatment for tile production. The linear shrinkage values are high, causing deformations and microcracking on the produced bricks. So they require an addition of degreasers in order to reduce their plasticity before use as building materials.

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