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LETTERS

Suitability of the soils of Monatélé (Centre Cameroon) in the production of fired compressed earth bricks, statistical analysis, and modeling of the mechanical behavior

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Abstract

The present work consists of a statistical study of the properties of the soils of the locality of Monatele used for the confection of compressed and stabilized earth bricks by calcination. This study is based on sixteen (16) samples taken from four (04) sites, namely, Nkolossananga, Nkol-Medock, Avoh, and Enieg. The results of the chemical and mineralogical tests show that the soils sampled are composed of quartz, Kaolinite, Hematite, Muscovite, Calcite, Rutile, Pyroxene, Montmorillonite, and Illite, with variable proportions. The water content of these soils varies from 10.32 to 26.35%. The granulometric analysis supported by Methylene Blue reveals dominant proportions of clay ranging from 32.8 to 53.7%. The plasticity test shows that the studied soils are almost essentially medium plasticity clays and high plasticity clays depending on the case. The HBR classification identifies them as clayey and silty soils belonging to classes A-7–6 and A-5. The physical–mechanical tests carried out on the fired brick specimens show that the density decreases with the increase of the temperature, while the water absorption, the flexural strength, and the compressive strength increase under the same conditions. The statistical study of the studied properties shows good correlations between the different granular classes present in the studied soils. In particular—0.79 between the proportions of gravels and silts and—0.68 between sands and clays. The values of methylene blue and plasticity also show interesting correlations with the percentage of silt, namely, 0.52 and 0.54, respectively. The Pearson correlation matrix also reveals that mechanical strength, water absorption, density, and firing temperature show good correlations with each other. These allow for the establishment of predictive models for compressive strength with a correlation coefficient $R^2 = 0.83$.

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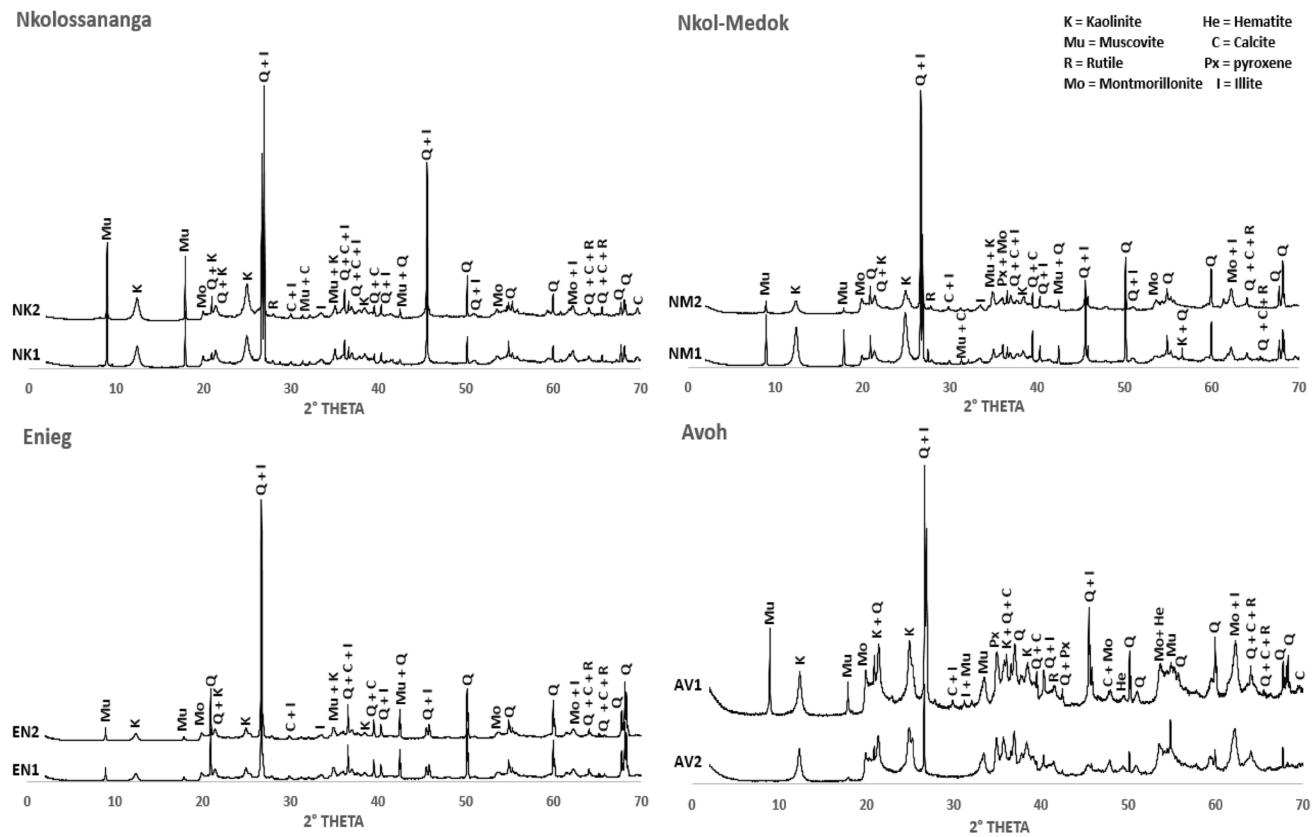
Graphical abstract



Keywords Lateritic clay · Compressed earth brick · Calcination · Characterization · Statistical analysis

1 Introduction

In developing countries, access to housing is limited by the high prices of construction materials, which are mostly imported. In Cameroon, it was estimated in 2014 that 49.8% of the population had access to housing in permanent materials; 37.5% of the population lived below the poverty line [1]. High population growth since then has continued to keep the country in a deleterious situation. For a population whose income is mostly modest, the strategy adopted by the country in recent years has been to develop local resources.

Studies on the soils of Cameroon have shown that 70% of the territory is covered by laterite, and most of it is concentrated in the equatorial part [2–5]. Laterites can be used in various fields, such as art, real estate, and civil engineering [6–9]. The geotechnical behavior of lateritic soils depends on several parameters. Authors [10, 11] have shown that particle size, plasticity, chemical, and mineralogical composition influence the geotechnical behavior of soils. Still others [12, 13] studied the influence of brick stabilization on their mechanical properties. The study of the thermal behavior of materials made from lateritic soils, in particular compressed earth bricks (CEB), has shown that they offer good thermal inertia and thus savings related to thermal expenses for air conditioning or heating [14]. The use of laterites as compressed earth bricks is, therefore, an interesting alternative in the field of construction.

Based on the above investigations, this work proposes to valorize the lateritic soils of the locality of Monatélé for the production of CEB stabilized by firing and to bring out the relevant parameters which influence the properties of the produced bricks via statistical analyses and regression modeling method. The aim is to determine the physical, geochemical, and mineralogical characteristics of the lateritic soils of Monatélé; classify these soils; make and fired the CEBs and determine their physicomechanical properties; to establish correlations between the studied parameters and develop predictive models of the behavior of the CEBs stabilized by firing.

2 Experimental methods

2.1 Location and sampling

2.1.1 Location

The study area is located in the locality of Monatélé, between latitude 04°1004°18 North and longitude 11°45–11°65 East, and is bounded to the North by the commune of Ebebda, to the North-East by the commune of Sa'a, to the South-West by the commune of Evodoula and the department of Nyong-et-Kélé and Nguibassa of the department of Nyong-et-Kele, to the East by the commune of Obala and Elig-Mfomo, and to the West by the Sanaga River. Figure 1 illustrates the geographic context of the study area.

2.1.2 Sampling

Sampling was done manually using a pick and shovel, followed by labeling. Sampling pits of 1.10–1.20 m of average depth were made at a pitch of 50 m, with a staggered mesh. The GPS coordinates of the various sampling points were recorded as seen in Table 1. Sixteen (16) samples were taken from the four (04) sampling sites studied and were named NK1, NK2, NK3, and NK4 for Nkolossananga site; AV1, AV2, AV3, and AV4 for Avoh; NM1, NM2, NM3, and NM4 for Nkol-Medock; and EN1, EN2, EN3, and EN4 for Enieg site. The location map for each site is shown in Fig. 2.

2.2 Experimentation

Mineralogical analysis was obtained by X-ray diffraction measurements that were performed using a Bruker-AXS D8 diffractometer equipped with a Lynx eye position-sensitive detector, with Cu Kα radiation ʎCu = 1.54056 Å operated at 40 kV and 40 mA, an increment of 0.013° 2θ, and a measurement time in 30 s steps. Chemical analysis was obtained by an X-ray fluorescence spectrometer (XRF), and a Niton XL3t980 hXRF analyzer (equipped with a 50 kV X-ray tube with Ag anode and a silicon drift detector with an 8 mm spot) was used. Physical and mechanical analyses were carried out in the geotechnical laboratory of MIPROMALO and Labogenie (Cameroon). The natural water content was determined according to the NF P94-050 standard [15]. The specific gravity was determined by the NF P94-054 standard [16]. The dry particle-size analysis and sedimentometry were carried out according to NF P94-056 [17] and NF P94-057 [18] standards, respectively. The methylene

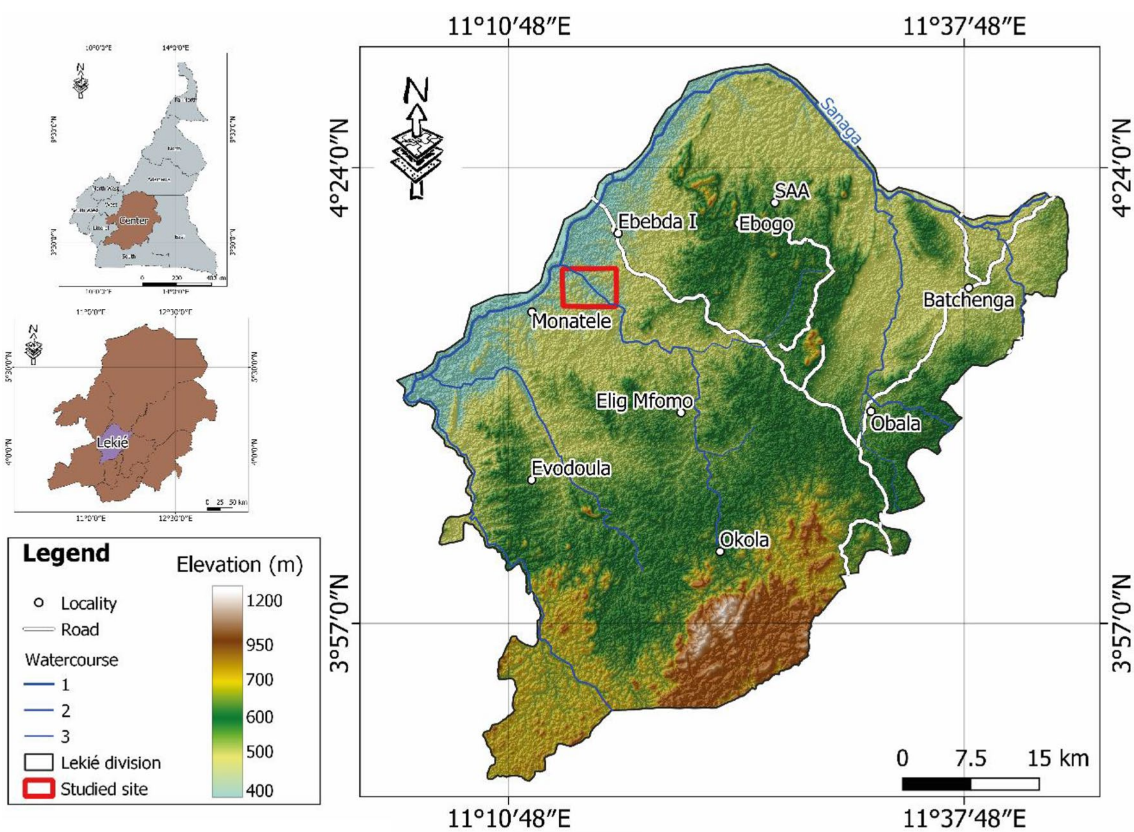


Fig. 1 Location map of the study area

Table 1 Geographical coordinates

Sites	Samples	Latitudes (*x*)	Longitudes (*y*)	Altitudes (*z*)
NKOLOSSANANGA	NK01	4.27157	11.25317	426
	NK02	4.27173	11.25354	427
	NK03	4.27206	11.25339	432
	NK04	4.27194	11.25309	433
AVOH	AV01	4.27648	11.22529	424
	AV02	4.27670	11.22500	423
	AV03	4.27701	11.22527	422
	AV04	4.27672	11.22554	425
NKOL-MEDOCK	NM01	4.26539	11.21385	404
	NM02	4.26574	11.21377	409
	NM03	4.26591	11.21400	408
	NM04	4.26561	11.21448	410
ENIEG	EN01	4.25764	11.21428	437
	EN02	4.25793	11.21415	437
	EN03	4.25778	11.21393	436
	EN04	4.25754	11.21400	436

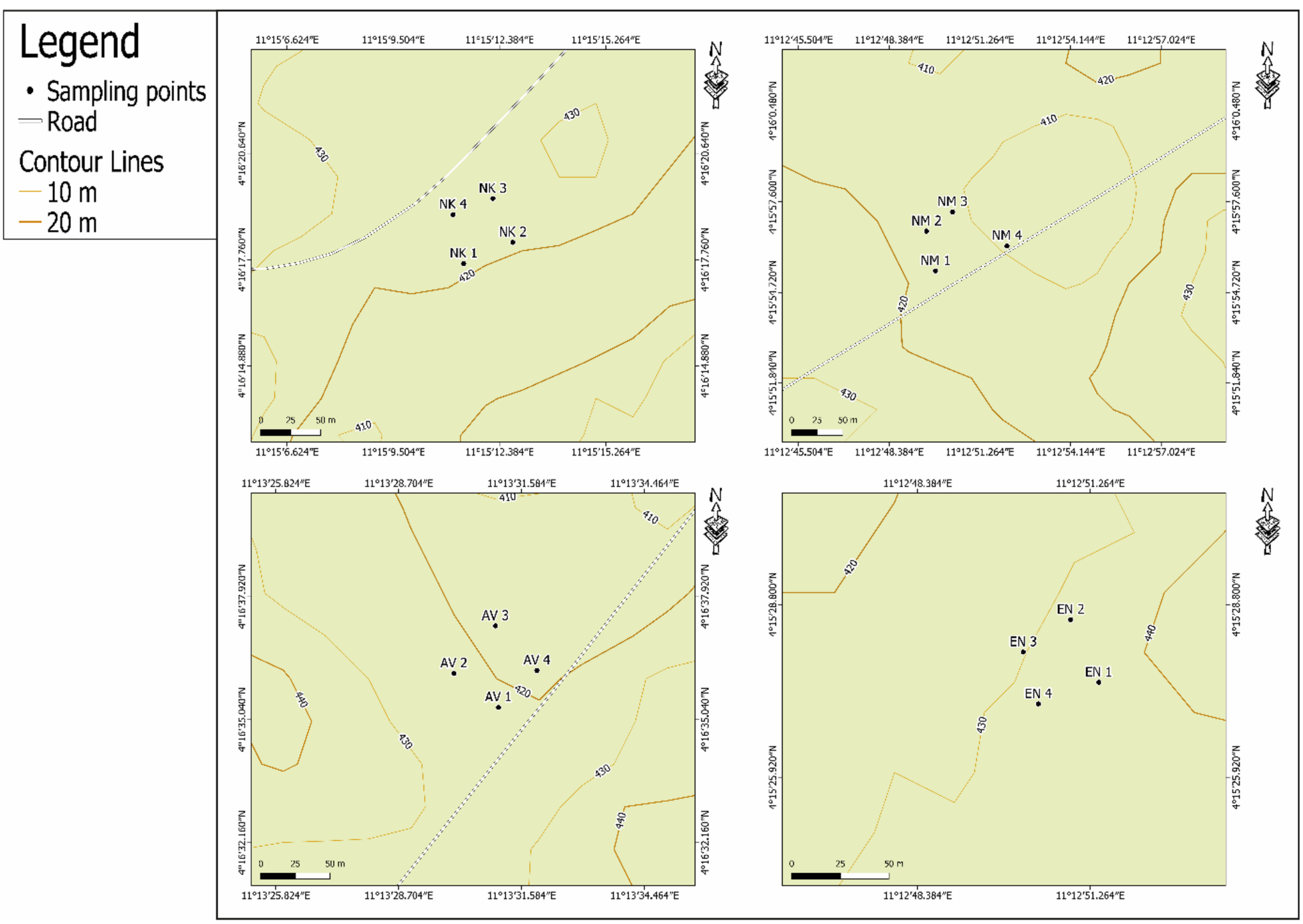


Fig. 2 Sampling map

blue test was carried out according to NF P94-068 [19] standard. The compaction and the bearing capacity were carried out, respectively, through the modified Proctor test according to NF P94-093 [20] Standard. La matière organique a été déterminée conformément à la norme XP P94- 047 [21]. The Atterberg's limits were determined according to NF P94-051 [22] standard. The liquid limit was determined by roller, while the plastic limit was determined using the Casagrande apparatus. The compressive and bending strengths were measured on prismatic soil specimens of dimensions 4×4×16 cm. The samples produced were made using a traditional artisanal method, namely: extraction of the soil, its preparation (drying, crushing, sieving, and mixing with water), compaction using a hydraulic press followed by demoulding, and finally drying in the open air. For the stabilized specimen, trois (3) températures (850 ℃, 950 ℃ et 1050 ℃) ont été utilisées pour la cuisson des briques. The compressive and bending strengths were measured, respectively, according to NF P94–420 [23] and NF P 94–422 [24] standards.

3 Results and discussion

3.1 Description of the lithological profile

Two (02) main soil profiles representative of the sampling wells carried out on the four (04) study sites were highlighted and described according to the observations made in the field. The descriptions were made along with the profiles from the surface to the depth.

- From 0 to about 0.3 m: this horizon consists of a thin layer of dark-colored topsoil in which the presence of organic matter and plant debris is still visible. This horizon has mainly a sandy-clay texture and constitutes the A horizon of the soil alteration profile of the study area.

- From about 0.3 to 1.1 m deep: this horizon constitutes the B horizon of the soil alteration profile and is made up of a layer of sandy-clay and sandy-clay textured soil whose hues can vary from reddish to yellowish. Within this soil layer, a small proportion of unconsolidated lateritic cuirass nodules can be observed.

The profiles thus described are illustrated in Fig. 3.

3.2 Mineralogy and geochemistry of raw materials

The diffractograms of the samples from the study area (Fig. 4) show that they are essentially composed of quartz, Kaolinite, Hematite, Muscovite, Calcite, Rutile, Pyroxene, Montmorillonite, and Illite. These mineral phases are regularly found in laterites [4, 7, 11]. The presence of Illite, pyroxene, calcite, and muscovite is because the area has a metamorphic basement [25]. The presence of varying quantities of clay minerals such as montmorillonite and kaolinite, resulting from the alteration of pre-existing

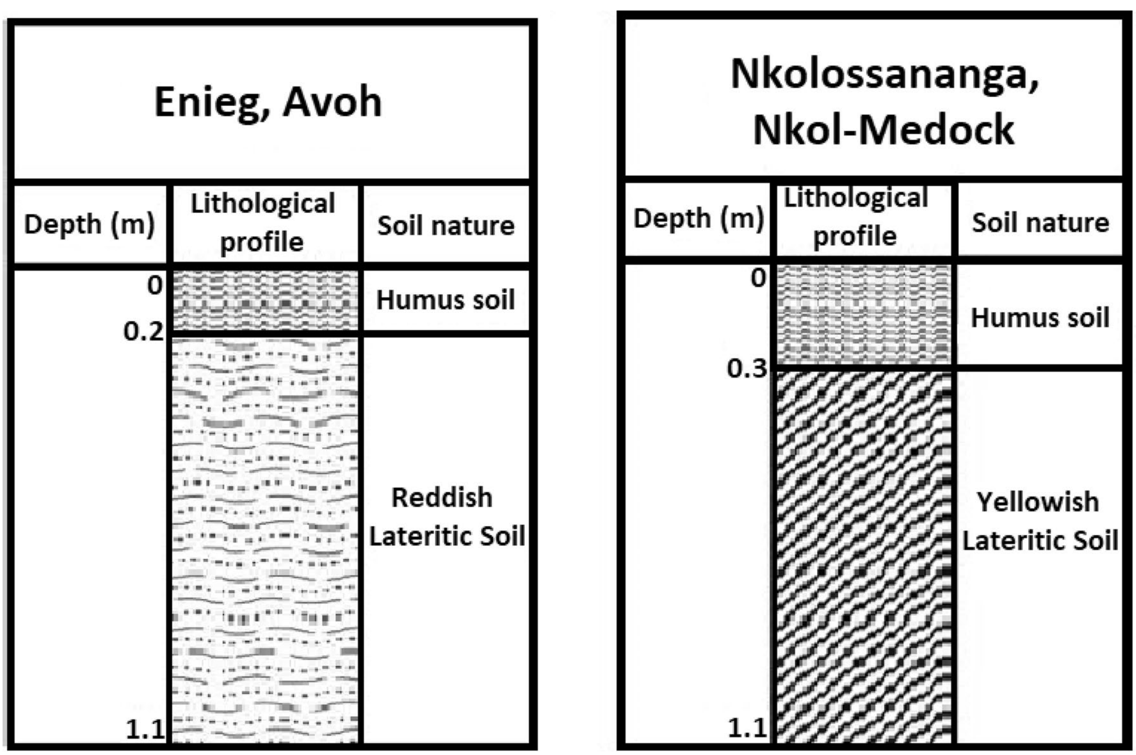


Fig. 3 Lithological profile

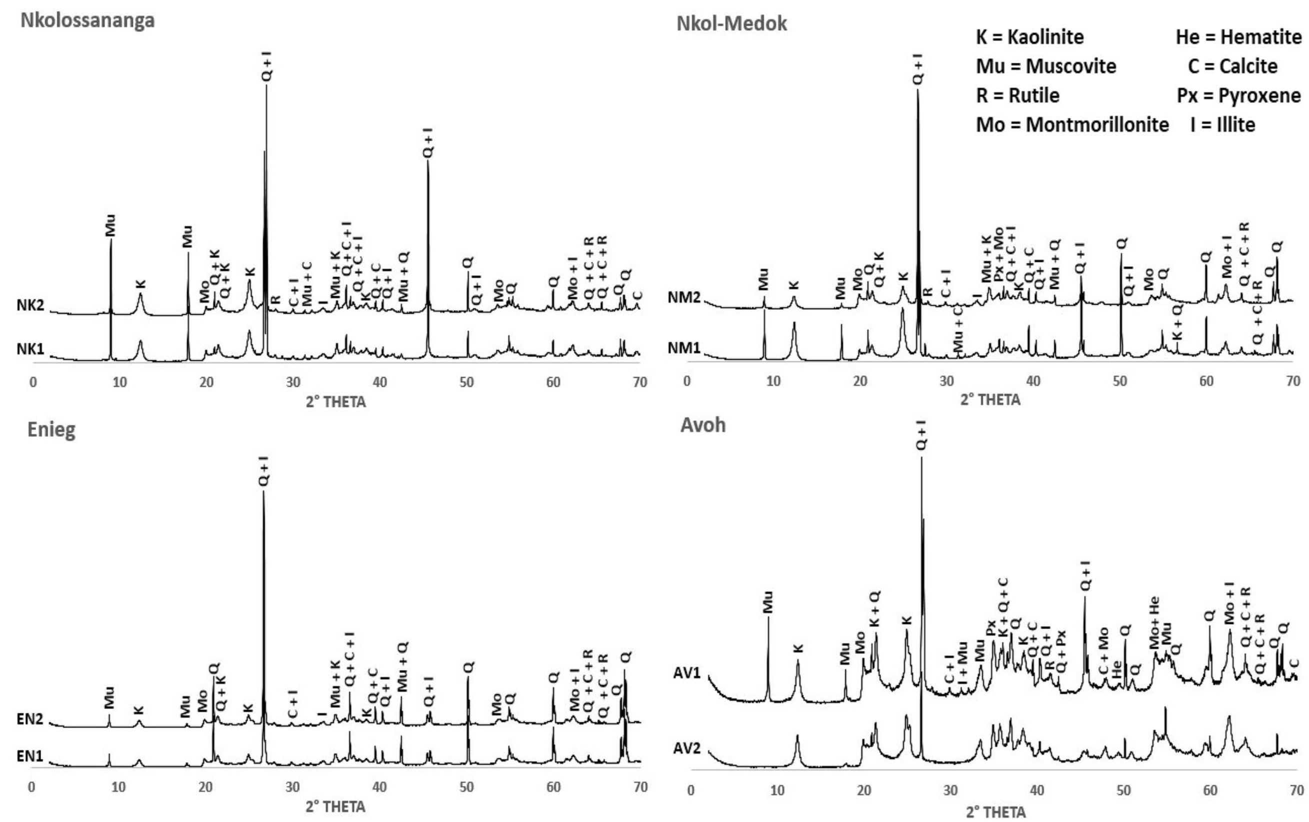


Fig. 4 XRD of raw materials

Table 2 Chemical composition of soils in the study area

Samples	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_5	LOI
NM1	50.29	13.15	9.15	0.52	0.21	0.14	2.91	2.35	0.04	11.27
NM2	45.26	21.95	13.23	0.4	0.44	0.1	1.63	0.15	0.08	11.22
NK1	40.09	22.23	14.14	0.01	0.22	0.05	1.55	0.2	0.04	13.09
NK2	46	23.56	14.22	0.11	0.76	0.08	1.68	0.22	0.07	10.82
AV1	32.84	21.43	20.29	1.58	0.25	0.13	0.43	0.12	0.08	13.32
AV2	38.71	22.21	18.14	0.37	0.25	0.07	1.1	0.13	0.07	13.65
EN1	40.43	17.42	17.51	0.44	0.35	0.15	0.18	1.35	0.07	14.28
EN2	53.14	15.15	14.86	0.1	0.31	0.05	1.49	0.02	0.1	8.53

rocks, would favor the firing of the material in addition to a good aptitude for shaping [26]. The studied soils seem to present interesting mineralogical properties in the manufacture of fired clay bricks. The results of the geochemical analyses recorded in Table 2, which present the base oxide content of the samples taken, tend to confirm the mineralogical results obtained. Indeed, the presence of hematite in the Avoh site influences the Fe_2 O_3 content (20.29%), compared to the values of the Kol-Medok (9.15%), Nkolossananga (14.14%), and Enieg (14.86%) sites, which are lower. Furthermore, the values of Al_2 0_3 and SiO_2 show the relative abundance of muscovite kaolinite and hematite in all samples [4, 7]. The relatively low contents of CaO, Na_2 O, MgO, and K_2 O indicate that calcite, montmorillonite, and Illite are present in low amounts [11]. Also, fire losses measured on the Nkolossananga and Avoh soils are higher than on the other soils. This suggests a greater presence of organic matter and carbonates in these soils [27].

3.3 Physical parameters of raw materials

The values of the geotechnical parameters measured on the studied soils are recorded in Table 3.

Table 3 Physical parameters of studied soils

Parameters	Nkolossananga				Avoh				Nkol-Medock				Enieg			
	NK1	NK2	NK3	NK4	AV1	AV2	AV3	AV4	NM1	NM2	NM3	NM4	EN1	EN2	EN3	EN4
TE (%)	17.75	23.83	15.1	26.35	14.38	13.07	13.49	20.61	17.47	13.15	10.32	15.99	15.33	13.67	12.46	10.79
Dr	2.54	2.54	2.49	2.5	2.48	2.34	2.12	2.12	2.64	2.64	2.54	2.66	2.64	2.64	2.42	2.54
G%	6.7	5.3	7.67	2.6	3.1	9.2	22.1	9.9	10	25.8	9.2	3	38	14.2	10.2	5.4
S%	34.7	35.2	18.8	24.9	23.4	40.3	27.3	17.4	35.8	12.4	27.4	29.8	21.7	30.9	25.7	36
L%	23.4	26.7	23.9	26.3	19.8	14.7	12.7	23	17.1	8	10.8	20.4	6.4	11.1	14.8	21.4
A%	35.2	32.8	49.6	46.2	53.7	35.8	37.9	49.7	37.1	52.8	52.6	46.8	33.39	43.8	49.3	37.2
VBS	3	2.9	2.8	2.9	3	2.6	2.5	2.6	2.5	2.6	2.3	1.8	1.7	1.9	1.8	1.8
Wl	44.52	50.39	46	55.92	50.64	62.48	43.22	50.21	36.9	52	38.52	42.23	47.42	45.17	43.62	38.42
Wp	22.39	26.18	29.28	23.61	33.09	34.73	20.9	26.23	22	27.73	22.64	21.35	24.2	19.7	19.04	22.95
Ip	22.12	24.2	16.72	32.31	17.55	27.75	22.31	23.97	19.54	24	15.84	20.88	23.21	25.46	24.58	15.46
MO%	3.79	4.18	5.07	6.98	3.21	3.47	4.5	1.8	3.12	4.13	4.5	4.98	3.3	4.5	4.98	4.5
Wopm (%)	20.2				22				23.2				24.4			
γdmax(t/m3)	1.41				1.38				1.41				1.55			

3.3.1 The natural water content

Overall, the water content (TE%) varied from 10.32% to 26.35%, as shown in Table 2. The samples were taken in March, a period corresponding to the beginning of the rainy season, which could explain the water content values obtained. The abundant presence of certain clay minerals such as kaolinite and montmorillonite in the soils results in high-water content, which is explained by the fact that these clays tend to absorb a lot of water. Thus, the high-water content observed in the soils of the study sites would suggest the presence of these clay minerals within these materials in some proportion more or less important.

3.3.2 The specific gravity

The average values of real density are, respectively, 2.51, 2.26, 2.62, and 2.56 for the soils of Nkolossananga, Avoh, Nkol-Medock, and Enieg (Confer Table 3). The specific gravity values of the lateritic soils in the equatorial zone are generally ranging between 2.5 and 3.6 g/cm^3 [28]. There is a significant relationship between chemical content and densities. Lower density values on studied soils would characterize a high alumina content, while the higher values would be due to a high iron content [29]. Thus, the Avoh soils would be the richest in alumina with an average of 2.26, while those of Nkol-Medock would tend to contain more iron in their chemical composition. The higher specific gravity values could indicate that the soils studied are very heavy

Table 4 Correlation matrix for mean values of physical parameters of soil an compressive strength (Pearson)

Variables	TE (%)	Dr	*G%*	*S%*	*L%*	*A%*	VBS	Wl	Wp	Ip	MO	Wopm	γsmax	C1050
TE (%)	1.00													
Dr	−0.10	1.00												
G%	−0.94	0.17	1.00											
S%	0.32	0.08	0.01	1.00										
L%	0.99	−0.21	−0.92	0.37	1.00									
A%	−0.38	0.05	0.06	−0.99	−0.44	1.00								
VBS	0.85	−0.46	−0.95	−0.13	0.85	0.03	1.00							
Wl	0.57	−0.88	−0.58	0.14	0.66	−0.27	0.76	1.00						
Wp	0.39	−0.88	−0.55	−0.31	0.46	0.17	0.78	0.90	1.00					
Ip	0.69	−0.52	−0.50	0.70	0.77	−0.79	0.53	0.79	0.45	1.00				
MO	0.55	0.72	−0.37	0.54	0.48	−0.48	0.07	−0.31	−0.55	0.20	1.00			
Wopm	−0.96	0.33	0.98	−0.11	−0.96	0.20	−0.96	−0.72	−0.63	−0.65	−0.30	1.00		
γsmax	−0.48	0.46	0.74	0.62	−0.47	−0.53	−0.86	−0.57	−0.82	−0.08	0.28	0.70	1.00	
C1050	0.60	−0.80	−0.72	−0.19	0.65	0.06	0.90	0.93	0.97	0.56	−0.34	−0.80	−0.84	1.00

Table 5 Descriptive statistics of CEB parameters

Variable	Observations	Minimum	Maximum	Moyenne	Ecart-type
Firing temperature en ℃	12	850.0000	1050.0000	950.0000	85.2803
σc (Mpa)	12	6.7000	11.4800	8.5267	1.3787
σf (Mpa)	12	1.5000	3.4100	2.1767	0.6808
Bulk density	12	2.0600	2.3000	2.2200	0.0669
Water absorption	12	7.8900	20.2500	14.1550	3.9953

with coarse textured fragments. According to the Pearson correlation matrix values presented in Tables 4 and 5, high specific gravity values would tend to cause a decrease in the compressive strength of fired specimens, implicitly indicating that the presence of abundant coarse fragments in the material harms the mechanical properties of bricks obtained after firing. The materials used are relatively less dense than those in the literature (Fig. 5).

3.3.3 Granularity

The particle-size analysis performed on the collected samples resulted in the particle-size curves shown in Fig. 6. This shows the particle-size classes recorded in Table 3. In general, the particle-size analysis reveals that the particle-size distribution varies slightly from one site to another. The predominant granular fractions in the soils of the study area are mainly clay and sand fractions. In more detail, the gravelly fraction ($\phi > 2$ mm) is present in these materials in proportions ranging from 2.6 to 38%. This fraction represents the least predominant fraction in these materials with isolated maximum values recorded for samples AV3 (22.1%), NM2 (25.8%), and EN1 (38%). The silty fraction in these soils is present in small proportions. But overall, these values are higher than those observed on the gravelly fraction. The sandy fraction is moderately represented in the materials studied with values varying between 12.4 and 40.3%. This fraction is one of the most strongly represented in the soils of this area. The clay fraction is the predominant fraction in the majority of the soil samples collected in the study area. This fraction has values that vary between 32.8% and 53.7%. The projection of the values from the particle-size analysis in the ternary diagram (Fig. 7) from the Belgian classification [39] allows the classification of these soils as heavy clayey sands. Carmen et al. [40] in their investigations show that sandy-clay soils are the most recommended for use in compressed earth bricks. According to some authors [8],

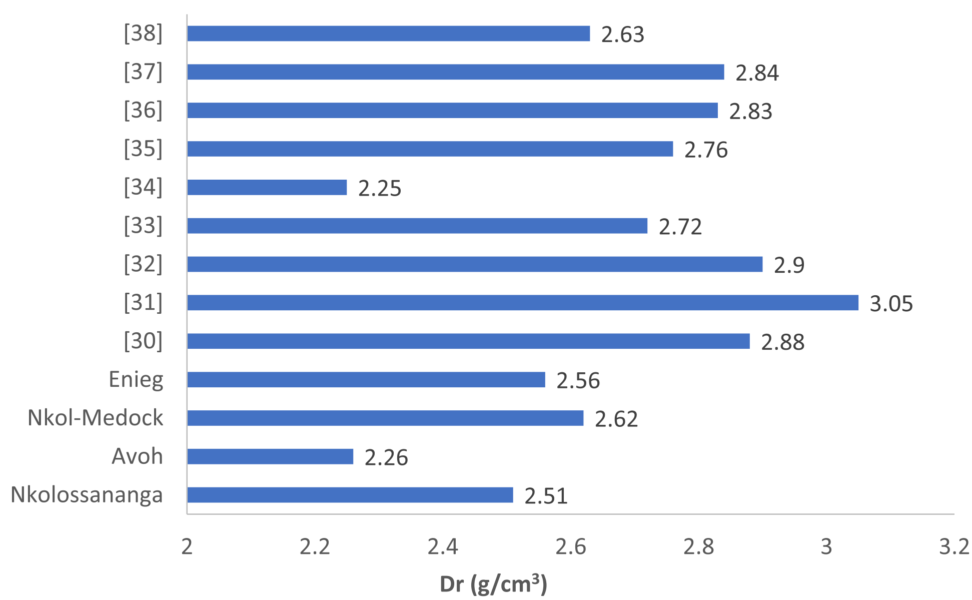


Fig. 5 Comparison of specific gravity (Dr) values with those of other authors in previous works

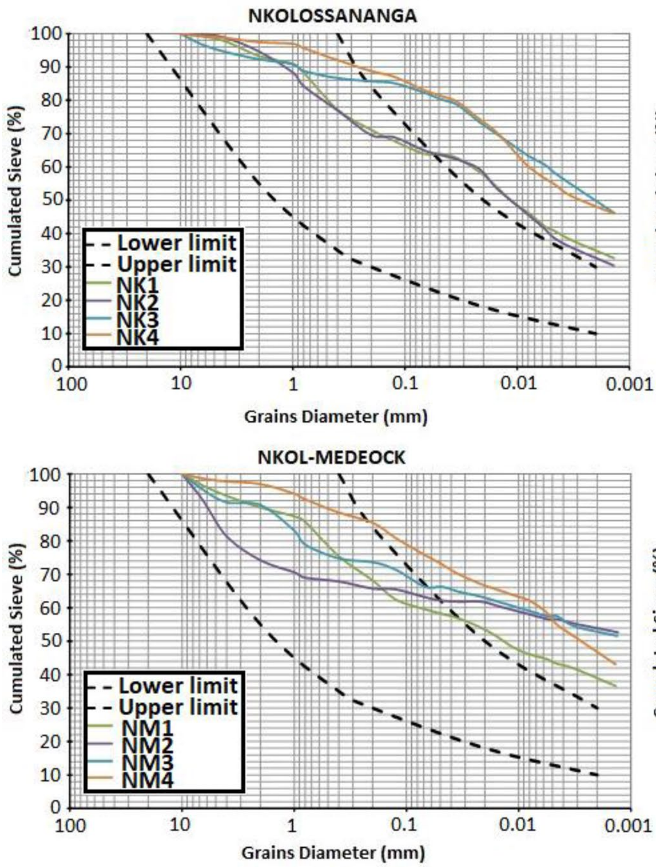


Fig. 6 Grains size distribution

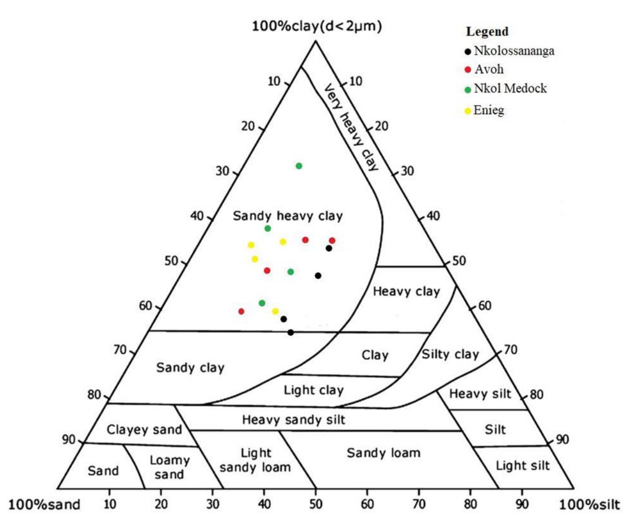


Fig. 7 Ternary diagram from the Belgian classification

the mechanical properties of compressed earth bricks are strongly related to the proportions of sand present inside the material (40–65%). The studies of Holtz and Kovacs [41] have shown that the plasticity of materials is strongly influenced by particle-size distribution. The technological parameters resulting from the drying and firing processes of the materials are influenced by the particle-size distribution of the material [42]. Furthermore, an analysis of the Pearson correlation matrix (Table 6) shows that there is a certain interdependence between the different granular classes present in the studied soils. This matrix shows a strong negative correlation (– 0.79) between the proportions of gravel and silt. This observation suggests that the proportions of silt tend to decrease when the proportions of gravel increase. The same is true for the proportions of sands and clays where the correlation coefficient obtained is – 0.68. Furthermore, the found correlation value (– 0.72) between the proportions of gravel and compressive strength (Table 4) indicates that an increase in the proportions of coarse particles or gravel tends to negatively affect compressive strength. This finding supports the analyses performed for specific gravity. On the other hand, in contrast to coarse fragments, a rise in the proportions of fines (silt) would have a favorable influence on mechanical resistance. A rather high and positive correlation coefficient emphasizes this impact (0.65).

Table 6 Correlation matrix of physical parameters (Pearson)

Variables	*W* (%)	Dr	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	VBS	Limit of liquidity (%)	Plasticity limit (%)	Plasticity index (%)
W (%)	1.00									
Dr	−0.06	1.00								
Gravel (%)	−0.28	0.04	1.00							
Sand (%)	−0.02	0.11	−0.40	1.00						
Silt (%)	0.66	−0.16	−0.79	0.22	1.00					
Clay (%)	−0.19	−0.04	−0.20	−0.68	−0.06	1.00				
VBS	0.51	−0.26	−0.36	−0.07	0.52	0.08	1.00			
Limit of liquidity (%)	0.37	−0.26	0.01	−0.13	0.11	0.01	0.45	1.00		
plasticity limit (%)	0.02	−0.17	−0.11	−0.11	0.14	0.13	0.54	0.70	1.00	
Plasticity index (%)	0.56	−0.16	0.11	0.00	0.03	−0.17	0.13	0.69	−0.01	1.00

3.4 The methylene blue value

Table 3 highlights that the soil blue values (VBS) are on average 2.9, 2.67, 2.03, and 1.8 for Nkolossananga, Avoh, Nkol-Medock, and Enieg, respectively. This indicates that overall the soils in the study area are moderately sensitive to water. The average value of the volume of blue of the soils allows, following the NF P94-068 standard [19], to classify the soils of the Avoh sites as silty soils with low plasticity, those of Nkol-Medock and Enieg as lateritic sandy-clay soils (SLSA) with values higher than 1.5; the soils of Nkolossananga are fine lateritic clay soils (SLFA) (VBS > 3). The blue values are related to the activity of fine particles (< 80 µm) and the adsorption capacity of clay minerals. Thus, the relatively high values would be due to the high proportions of clay particles in some materials. According to the Pearson correlation matrix in Table 6, there is some positive correlation (0.52) between the soil blue values and the proportions of silt in these materials. The more silt in the soil, the more methylene blue that soil absorbs. The same relationship is shown with the plasticity indices with a correlation coefficient of 0.54. The soils that absorb more tend to be the most plastic soils and this in the present case of study would be related to the proportions of silts contained in the materials. According to the Pearson correlation in Table 4, a substantial positive relationship (0.90) exists between blue values and compressive strength. This relation illustrates that increasing soil blue levels enhances burned brick compressive strength. Indeed, because methylene blue values are substantially correlated with the fraction of fine silt in the

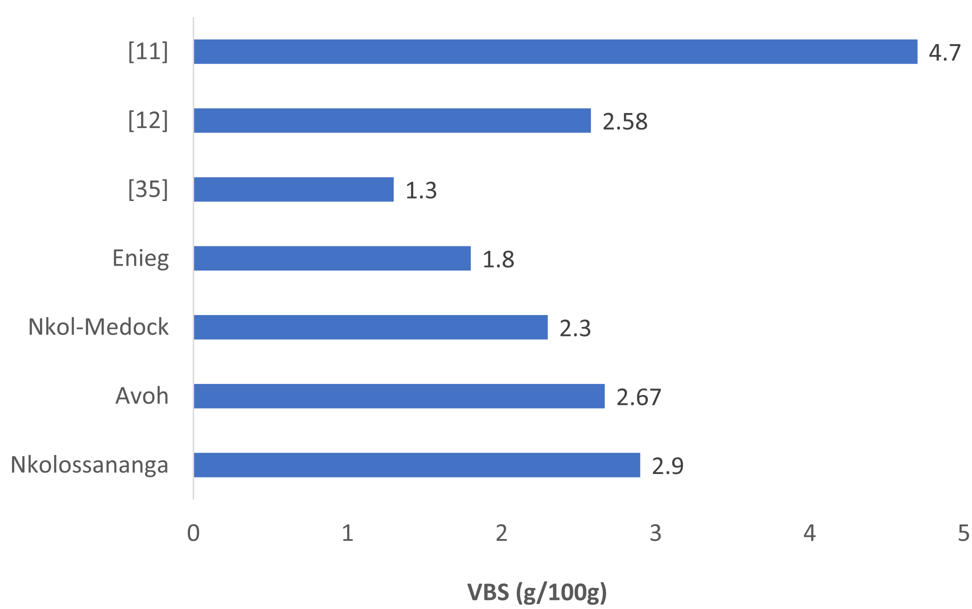


Fig. 8 Comparison of the methylene blue values (VBS) with those of other authors

material, the relationship between VBS and compressive strength implies that the content of silt present in the examined soils implicitly rises with compressive strength. The previous works carried out on Cameroonian lateritic soil and recorded in Fig. 8 show lower and higher VBS values than those obtained according to their clay content.

3.4.1 Compaction parameters

The results of the Proctor tests performed on the representative samples from each site are contained in Fig. 9. This test allows determining the values of water content for which compaction is optimal (w_{opt}) and the maximum dry densities (γ_{dmax}). For this work, the values of w_{opt} and γ_{dmax} obtained (see Table 3) are 20.2% and 1.41 t/m^3; 22% and 1.38 t/m^3; 23.2 and 1.41 t/m^3; 24.4 and 1.55 t/m^3 for Nkolossananga, Avoh, Nkol-Medock, and Enieg, respectively. These values show that better compaction of the soils in the study area is obtained for a water content corresponding to the respective Proctor optimums. For a better production of CEB, these values should be respected. According to the DSA [43], the water content must be sufficient to allow lubrication of the grains and to allow them to rearrange themselves to occupy as little space as possible, which has the effect of densifying the CTB and thus increasing the mechanical resistance. This water content must not be too high either, because the voids would be filled with water and, therefore, incompressible. This study is also supported in some ways by the more or less high and negative correlation coefficient observed between the optimal moisture content (w_{opt}) and the compressive strength (Table 4). This value demonstrates that, in general, the compressive strengths of the analyzed bricks tend to decrease as moisture content increases, implying that one of the factors that might negatively impact compressive strength during brick compaction is excessive moisture content. If this water content is very low compared to the optimum water content the soil is difficult to compact. However, although the compaction is high, the maximum dry density remains below 2 g/cm^3.

Previous work has identified soils that had lower optimum water contents than those obtained in this work, with at the same time higher maximum dry densities. These works are listed in Fig. 10.

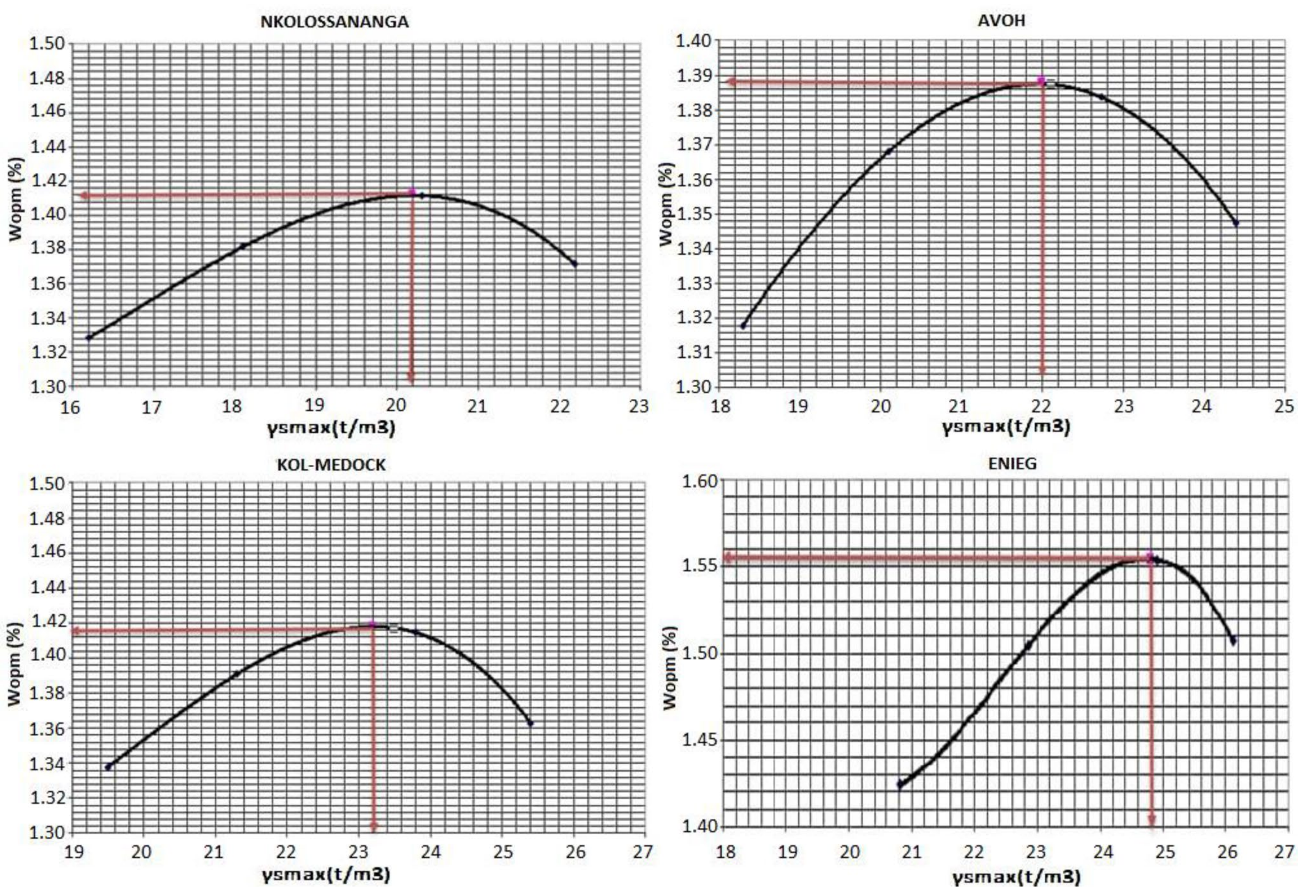


Fig. 9 Proctor curves

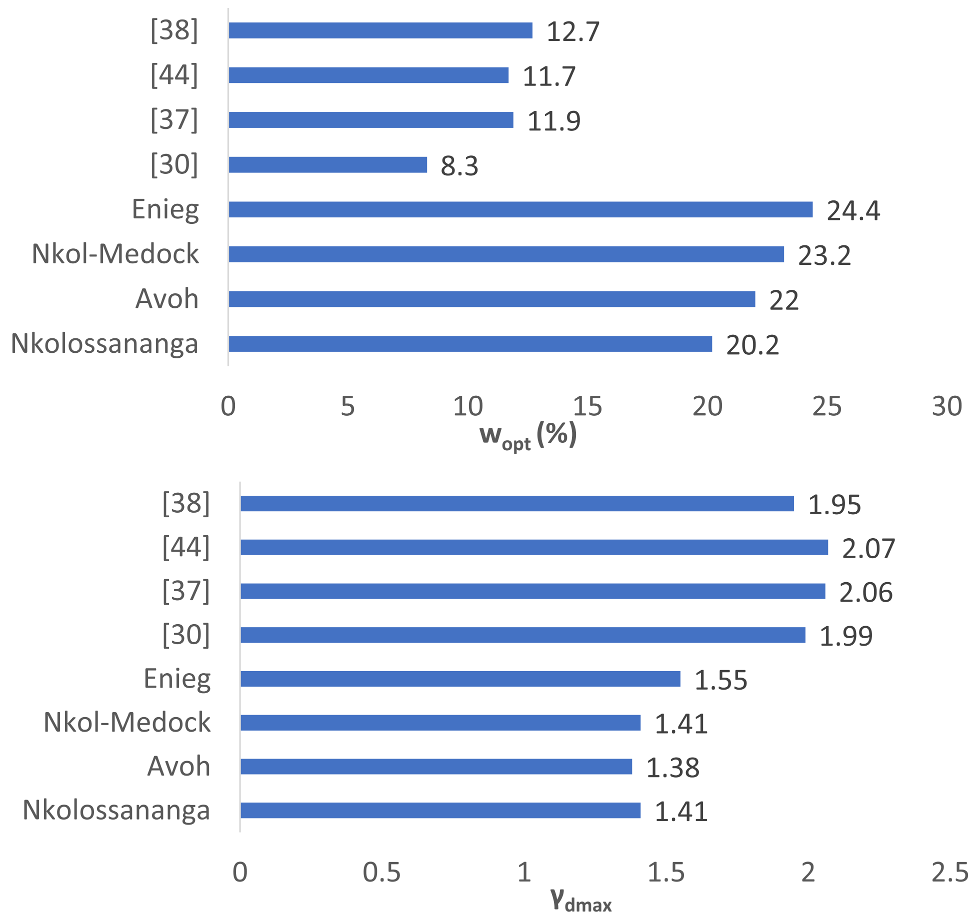


Fig. 10 Comparison of the compaction parameters (w_{opt} and γ_{dmax}) with those of other authors

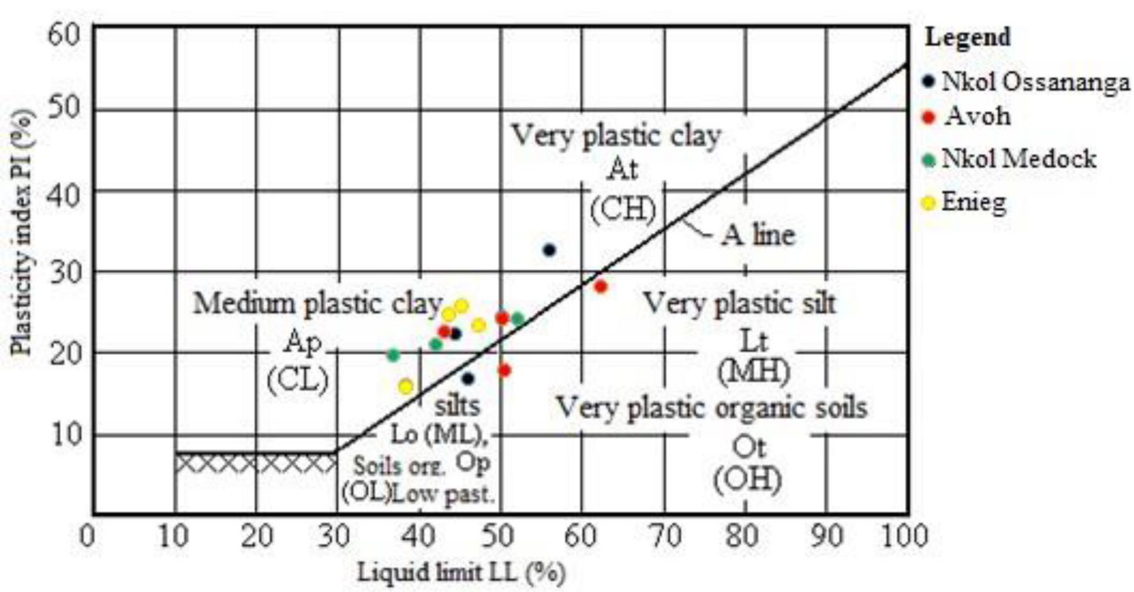


Fig. 11 Casagrande plasticity diagram

3.5 Mechanical parameters of raw materials

3.5.1 The Atterberg limits

This test evaluated the resulting liquid limit (W_L), plastic limit (W_P), and plasticity index (I_P) for the soils in the study area. The values obtained from this test are grouped in Table 3. The liquidity limits of the studied samples are globally between 36.9 and 62.48%, while the plasticity limits are between 19.04 and 34.73%. The resulting plasticity indices are between 15.46 and 32.31%. The highest plasticities are observed for the Nkolossananga site soil samples with a maximum value of 32.31% and a mean value of 23.83. In the Casagrande plasticity diagram (Fig. 11), the soils studied are composed almost entirely of medium and high plasticity clays (NK4 and AV2). Plasticity is one of the most important properties in the manufacture of ceramic products, because it facilitates molding and ensures a certain cohesion. The higher or lower plasticity observed in the studied soils could be the result of the relatively high proportions of clay in the particle-size composition. The more the soils are clayey, the more they tend to absorb water with direct consequence the increase of the liquidity limit and thus the plasticity of the material. Plasticity indices (PI) < 10% can be the cause of cracking during the extrusion process with a detrimental effect on the production of ceramics used in the building industry, due to possible variations in the amount of extrusion water [45, 46]. The studied soils have a plasticity index (PI) greater than 10%, and this suggests that these soils present abilities in the use in the raw state as structural ceramic products obtained by extrusion [46]. The soils studied with plasticity indices between 15 and 25% are the most suitable for the manufacture of compressed earth bricks stabilized with cement [47]. According to Pearson's correlation matrix (Table 6), there is a correlation between the parameters measured by the Atterberg limit test. A strong positive correlation exists between liquidity limits and plasticity limits (0.70) and also between plasticity indices and liquidity limits (0.69).

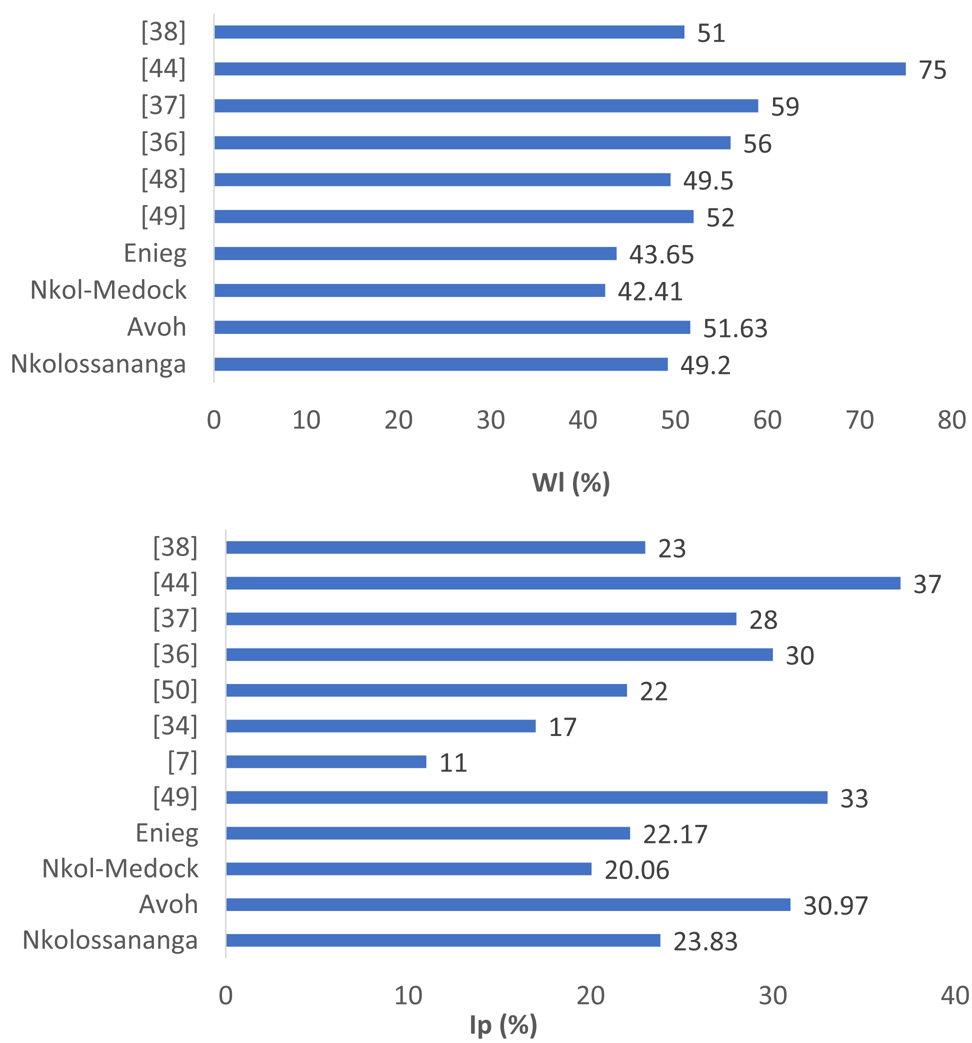


Fig. 12 Plasticity (Wl and IP) of soils from other research works

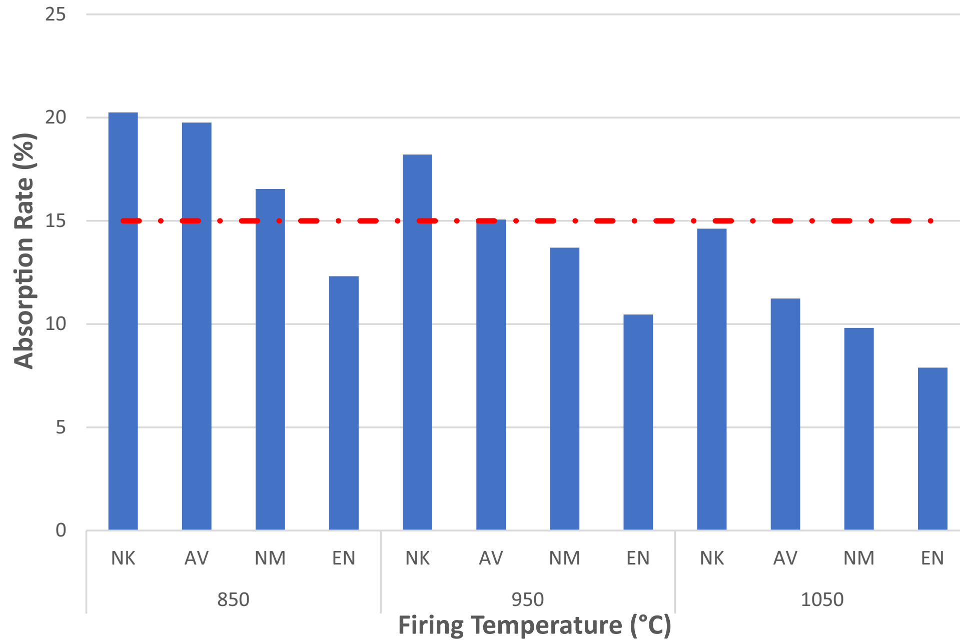


Fig. 13 Water absorption of fired samples

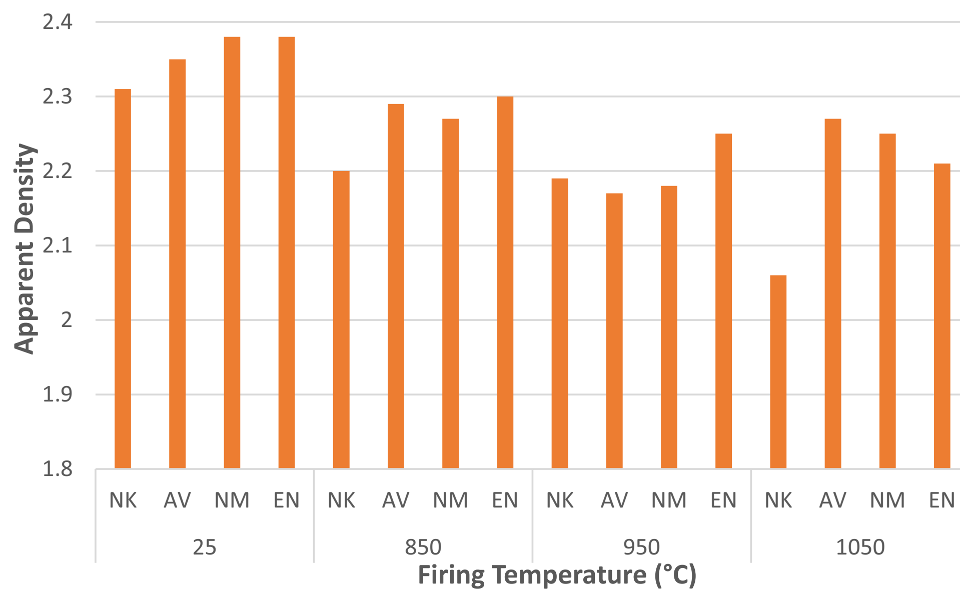


Fig. 14 Apparent density of CEBs

These correlations indicate that these parameters are intimately related although measured independently and by different procedures. The liquidity limits tend to grow with the plasticity limits as well as the plasticity indices evolve with the liquid limits. It should be observed that, just as the parameters of the Atterberg limits are interdependent, the Pearson correlation matrix reveals a reasonably strong and positive association between the values of the Atterberg limit and the mechanical resistances, particularly the compressive strength. With correlation values of 0.92, 0.97, and 0.56, the liquid limit, plastic limit, and plasticity index all have a positive impact on compressive strength values. The mechanical resistances rise as the values of the Atterberg limit increase. This might also imply that a material's plasticity or plasticity parameters have a major impact on the mechanical characteristics of the burnt brick. Plastic material with a high degree of fine particles would thus likely provide the best mechanical results after firing. The plasticity of some soils found in the literature is presented in Fig. 12.

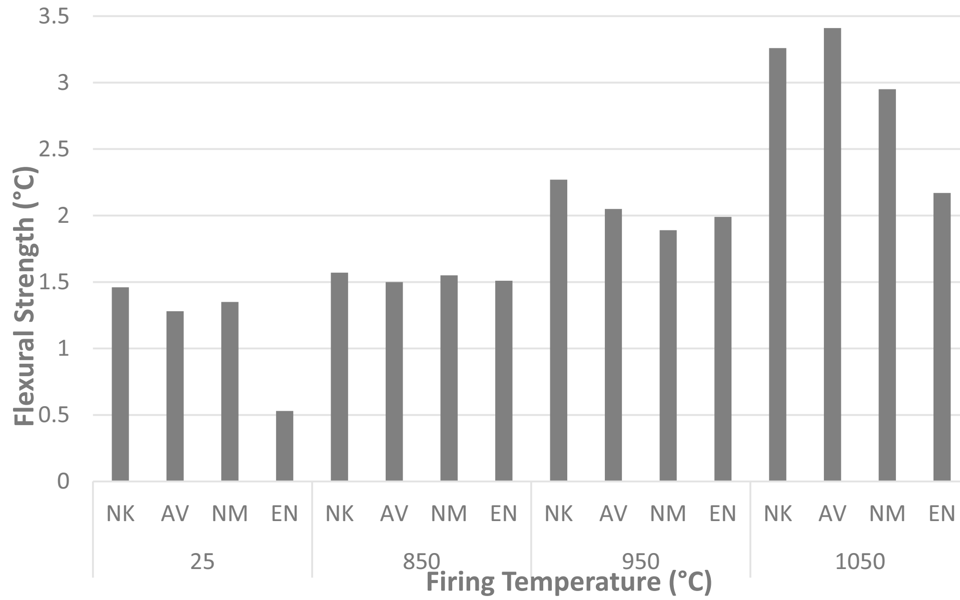


Fig. 15 Flexural strength

3.5.2 HRB classification

The results obtained from the particle-size test and the landing limits made it possible to classify these soils according to the Highway Research Board (HRB) classification system. Thus, according to the HRB, these soils are clayey and silty soils belonging to classes A-7–6 and A-5. The group indexes obtained are 2, 4, 5, and 6, respectively, for the soils of Enieg, Avoh, Nkolossananga, and Nkol-Medock.

3.6 Physical properties of CEBs

3.6.1 Absorption rate

Water absorption has a major influence on the strength and durability of CEBs. It depends on the clay content of the soil

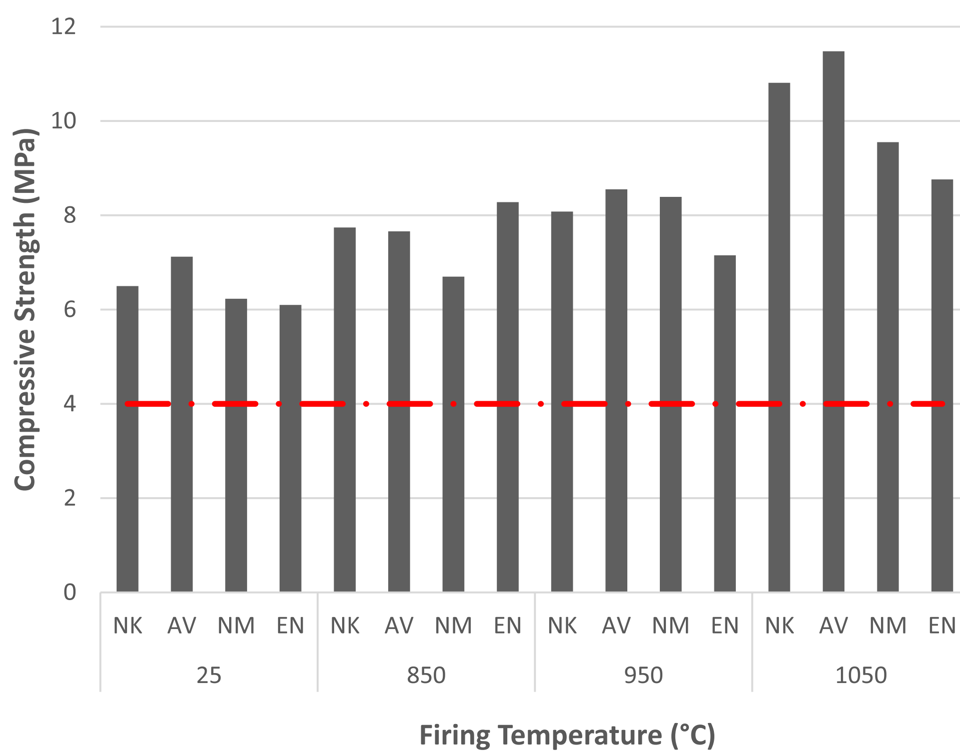


Fig. 16 Compressive strength

and the stabilization method. The results of the absorption test are shown in Fig. 13.

The absorption test on the unstabilized specimens showed that the specimens disintegrate after total immersion in water due to a relatively clay-rich composition of the materials used. Firing the specimens at 850 ℃, 950 ℃, and 1050 ℃ stabilized the CEBs and the water absorptions obtained are between 20.25 and 12.32; 18.21 and 10.46; 14.62 and 7.89, for each of the respective temperatures. These values almost entirely follow NC-102–115 [51] (which prescribes a water absorption of less than 15% for CEBs), starting at 950 ℃. In general, absorption decreases with increasing temperature. This decrease is associated with a glassy phase formation that penetrates pores closing them and isolating them from neighboring pores [52]. The decrease in water absorption translates into dehydration reactions, decarbonization, and combustion of organic matter [53]. These results are in agreement with those of Kagonbe et al. [54], who worked on the soils of Sekandé and Gashiga in the North Cameroon region.

3.6.2 Specimen bulk density

The results of the bulk density test are contained in Fig. 14. These results show that the values obtained for fresh samples (25 ℃) vary from 2.31 to 2.38. These values are higher than those recommended by the NC-102–115 standard [51], which prescribes values between 1.5 and 2 g/cm^3, and are far from the densities of soils from the Rhône-Alpes region of France used as building materials [55]. This indicates that the compaction was not optimal as obtained by the Proctor test due to a grading that deviates from the prescribed range of the standard [51] as shown in the grading curves. These results combined with the disintegration of the bricks after total immersion impose the need for a stabilization method to guarantee the quality of the CEBs. The method of calcination of the specimens used for the stabilization made it possible to reduce the densities to values ranging between 2.27 and 2.06, closer to the standard. This method, therefore, had a positive effect on the density. However, the most important properties remain the mechanical properties.

Table 7 Correlation matrix of CEB parameters (Pearson)

Variables	*t*°	density	*F*	*C*	abs
t°	1	−0.4304	0.8863	0.7728	−0.6753
Density	−0.4304	1	−0.3972	−0.3557	−0.1036
F	0.8863	−0.3972	1	0.9028	−0.4374
C	0.7728	−0.3557	0.9028	1	−0.3818
abs	−0.6753	−0.1036	−0.4374	−0.3818	1

3.7 Mechanical properties

3.7.1 Flexural strength of fired CEBs

The histogram in Fig. 15 shows the values of flexural strengths of the fired bricks. These results show that the strengths increase from 0.53 to 3.26 MPa as a function of sampling site and temperature. The Avoh soils show the best properties at 1050 ℃' (3.26 MPa), probably due to the higher clay percentage of the AV1 sample (51.7%). The Enieg sampling site shows the lowest resistance at 1050 ℃ (2.17 MPa), which may be due to a greater presence of impurities [56]. The sites of Nkol-Medock and Nkolossananga present values close to that of Avoh, because the clay content is close to that of this site. The work of other researchers [57] has also shown that between 950 and 1050 ℃, there was an increase in flexural strength and this varied from one soil sample to another depending on the clay content. In general, the higher the clay content of the sample, the better its flexural strength when calcined.

3.7.2 Compressive strength of fired CEBs

The results of the compression tests recorded in Fig. 16 show that the soils of the Monatélé locality tested are favorable for the production of compressed earth bricks, following standard NC-102–115 [51]. Indeed, all the samples offer compressive strengths at 14 days of curing, higher than 4 MPa, the threshold value of the standard. Stabilization of the bricks by firing at 850 ℃, 950 ℃, and 1050 ℃, increased the compressive strengths from 6.5 to 10.81 MPa for the samples from the Nkolossananga site, from 7.12 to 11.48 MPa for the Avoh samples, from 6.23 to 9.55 MPa for the Nkol-Medock samples, and from 6.1 to 8.76 for the Enieg site samples. These results are in line with those obtained for flexural strength and confirm the fact that the clay content plays an important role in the stabilization of CEBs by firing [56, 57]. Indeed, according to the literature, this firing has the effect of producing a glassy phase which reduces the porosity of the material by filling the pores. This mechanism induces the formation of a more coherent and resistant material [51, 52].

3.7.3 Statistical analysis and prediction model of mechanical behavior

The results of the mechanical tests carried out on the samples were analyzed with the statistical software XLSTAT on Microsoft Excel to have a descriptive statistical analysis: the mean, standard deviation, variance, median, and distribution of the samples were obtained. The Pearson correlation matrix between the mechanical parameters was performed and is presented in Table 7.

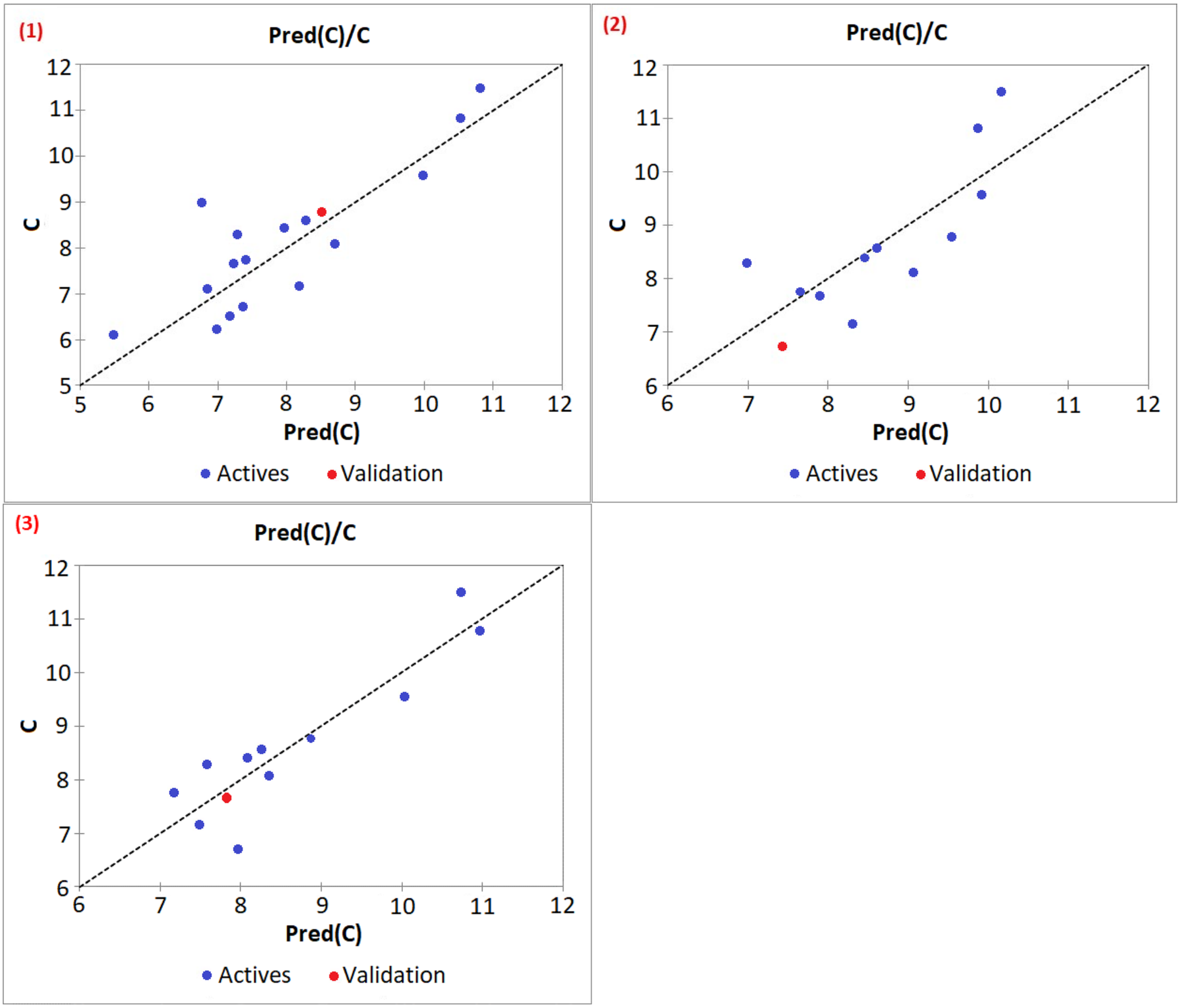


Fig. 17 Measured values versus predicted values; 1: linear modeling between compressive strength and flexural strength; 2: linear modeling between compressive strength, absorption rate, density, and temperature; 3: non-linear modeling between compressive strength, absorption rate, density, and temperature

The results of the correlation (Table 7) show that the most significant correlation coefficient is those obtained between compressive strength and flexural strength, temperature and flexural strength, temperature and compressive strength, temperature, and absorption rate, and the values are, respectively, 0.90, 0.88, 0.77, and − 0.67. These correlations show that the relationship between compressive strength and flexural strength, temperature and flexural strength, temperature, and compressive strength are positive, suggesting that the two parameters used for the correlation test tend to increase together. The correlation between temperature and absorption rate gives a negative value, indicating that when temperature increase, the absorption rate tends to decrease. Temperature and density have a poor relationship (−0.43), suggesting that the density tends to decrease when temperature increase. Linear and non-linear regression modeling was carried out on the samples and the models developed are:

First model linear modeling between compressive strength and flexural strength.

After the correlation between compressive strength (C) and flexural strength (F), regression analysis was carried out and expressed by the following linear equation with its corresponding coefficients and given by Eq. 1, illustrated in Fig. 17:

$$C = 4.50166 + 1.84862 * F$$
$$\text{with } R = 0.92 \text{ and } R^2 = 0.84. \quad (1)$$

The obtained models indicate that the values predicted by the models are very close to the measured values. This is verified by the R^2 value obtained for this prediction model and the residual values obtained by the difference between measured and predicted values.

Second model linear modeling between compressive strength, absorption rate, density, and temperature.

A multi-linear regression analysis was carried out between compressive strength (C), absorption rate (abs), density (d), and temperature (t) on specimens that have not been disintegrated after immersion in water by the absorption test. The expression of this analysis is given by Eq. 2 and illustrated in Fig. 17

$$C = -16.57249 + 0.12518 * \text{abs} + 0.01695 * t + 3.31436 * d \text{ with } R = -0.77 \text{ and } R^2 = 0.60. \quad (2)$$

This model shows that the values predicted are close to the measured values obtained. The relatively medium R^2 value obtained for this prediction model confirms this observation. Residual values obtained by the difference between measured and predicted parameters show very low values.

Third model Non-linear modeling between compressive strength, absorption rate, density, and temperature.

A non-linear regression analysis was carried out between compressive strength (C), absorption rate (abs), density (d), and temperature (t) on specimens that have not been disintegrated after immersion in water by the absorption test. The expression of this analysis is given by Eq. 3 and illustrated in Fig. 17

$$C = 157.77121 + 1.05134 * \text{abs} - 0.16667 * t - 83.96928 * d - 0.03143 * \text{abs}^2 + 0.00010 * t^2 + 20.03471 * d^2 \text{ with } R = 0.91 \text{ and } R^2 = 0.83. \quad (3)$$

This model shows that the values predicted are very close to the measured values obtained. The high R^2 value obtained for this prediction model confirms this observation, and the residual values obtained by the difference between measured and predicted parameters show very low values.

4 Conclusion

The present work focused on the identification of soils from the locality of Monatélé in central Cameroon and the statistical study of their properties for use in the manufacture of calcined stabilized CEBs. To do this, sixteen (16) samples were taken from four (04) sites, namely, Nkolossananga, Nkol-medock, Avoh, and Enieg. From the findings of this work, the following conclusions were made:

- The chemical and mineralogical tests showed that the soils sampled are composed of quartz, Kaolinite, Hematite, Muscovite, Calcite, Rutile, Pyroxene, Montmorillonite, and Illite, with varying proportions;
- The water content varied from 10.32 to 26.35% when the specific gravity was 2.51, 2.26, 2.62, and 2.5 for the soils of Nkolossananga, Avoh, Nkol-Medock, and Enieg, respectively;
- The particle-size analysis showed that the clay fraction was present in these materials in dominant proportions, ranging from 32.8% to 53.7%;
- The plasticity test indicated that the soils studied were almost essentially medium plasticity clays and high plasticity clays, as the case may be;
- The soils are classified as clayey and silty soils belonging to classes A-7–6 and A-5 according to the HBR classification;
- The physical–mechanical tests carried out on the specimens of fired bricks made with these soils showed that while the density decreased with the rise of the temperature, the water absorption, the flexural strength, and the compressive strength increased;
- The statistical study of the studied properties showed that there was a strong correlation (-0.79) between the proportions of gravel and silt, between sand and clay (-0.68), between the methylene blue and silt (0.52), between plasticity and silt (0.54), among others;
- The predictive models for compressive strength obtained was $C = 157.77121 + 1.05134 * \text{abs} - 0.16667 * t - 83.96928 * d - 0.03143 * \text{abs}^2 + 0.00010 * t^2 + 20.03471 * d^2$ with $R = 0.91$ and $R^2 = 0.83$.

This work is part of the study of soils, their development in construction, and the reduction of study costs by developing prediction models. The results made it possible to obtain an equation with a good correlation coefficient ($R^2 = 0.83$), but altogether perfectible. Based on these results and similar works, we recommend prediction using the regression method in soil studies and we propose to apply or develop a machine learning method to improve the accuracy of the prediction.

Author contributions YTL: validation, methodology, writing—review & editing, visualization, and original draft. TGGM: conceptualization, methodology, investigation, and writing—original draft. TDJ: validation, writing—original draft & editing, and visualization. SMAD: investigation, editing, and original draft. AT: methodology, investigation, and review & editing. NMS: investigation, methodology, and resources. MNLL: supervision, methodology, and resources.

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Code availability Not applicable.

Declarations

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

Consent to participate Not applicable.

Consent for publication Not applicable.

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