Research article

Evaluation of lateritic soils of Mbé for use as compressed earth bricks (CEB)

Japhet Taypondou Darmana,*, Jules Hermann Keyangue Tchouataa, Gilbert François Ngön Ngön b, François Ngapguec, Bachirou Lindou Ngakoupaina, Yannick Tchedele Langolloa

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ABSTRACT

This work was carried out on the lateritic soils of Mbé in the Adamawa region of Cameroon. For this study, twenty (20) soil samples were taken from four (04) sites (Kabaa, Ndom, Mbé Norwegian camp, and Nyèssé). To assess their suitability for the production of compressed earth bricks, physical parameters were obtained by geotechnical tests to determine particle size distribution, water content, atterberg’s limits, specific gravity, methylene blue value, maximum dry density (MDD), and optimum moisture content (OMC). Chemical and mineralogical properties were obtained by X-ray fluorescence and X-ray diffraction, respectively, followed by the determination of technological parameters (water absorption and mechanical properties) on compressed earth brick specimens. The results show that the studied lateritic soils contain mainly sand (52.8–90.3 wt%) and clay particles (8.4–42.1 wt%), gravel particles are slightly represented (1.1–16.3 wt%). The plasticity index of the studied materials is average (5–38%), about their methylene blue values (1–5), these soils correspond to clayey-silty soils. The materials studied are classified by the USCS as clayey sands/silty clays; according to the Highway Research Board (HRB), they are classified as A-7-5 or A-7-6 clayey soils with group index of 1 for Kabaa, 7 for Ndom, 9 for Mbé Norwegian Camp, and 12 for Nyèssé. These soils are rich in silica (SiO₂, 62.6–78.1 wt%), followed by aluminum (Al₂O₃, 11.8–18.2 wt%) and iron oxides (Fe₂O₃, 3.2–8.1 wt%); other oxides are in lower proportions (<1 wt%). The mineralogical content consists mainly of clay minerals such as kaolinite, illite, smectite (montmorillonite), and non-clay minerals such as quartz, muscovite, biotite, gibbsite, and hematite. The bulk density and mechanical properties of the specimens are within the standard NC 102-115 (2007) of compressed earth bricks (CEB), which recommends minimum compressive strengths of 2 Mpa for unstabilized CEB and 4 Mpa for stabilized CEB. Water absorption of CEB and physical parameters of soils have a significant impact on the mechanical behavior of CEB. According to the test results, Mbé lateritic soils are suitable for engineering applications in the production of stabilized compressed earth bricks.

1. Introduction

Lateritic soils, which occupy 33% of the intertropical zone (Tardy, 1992), are among the most widely used raw materials, particularly for road construction (Attoh-Okin, 1995; Kassogue et al., 2002; Millogo et al., 2008) as subsoil and as building materials (Nzeukou Nzeugang et al., 2013; Tsouzé et al., 2017, Kagonbé et al., 2020) for the production of compressed earth bricks or adobe. Lateritic soils are reddish-brown and are residual soils formed after weathering of a pre-existing basement rock under tropical climate conditions (Maignien, 1966; Gidigasu, 1976). Civil engineering studies on lateritic materials are particularly interested in their use in the production of stabilized or unstabilized compressed earth bricks (CEB). The definition of CEBs according to Stulz et al. (1993) is “small-sized masonry units with regular and verified characteristics, obtained by static or dynamic compression of the soil in a wet state followed by immediate de-molding”.

More than 95% of the traditional habitat in Mbe is made up of precarious dwellings, generally built of the earth with a thatched roof (PNPD, 2014). In this locality, lateritic soils are extracted by the local population for the production of building materials (adobes) due to their low cost as building materials and the easier implementation process than concrete block construction. However, the lack of compliance with

* Corresponding author.
E-mail address: japhet8darman@gmail.com (J. Taypondou Darman).

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geotechnical standards, due to the lack of evaluation and prior testing of the materials studied, leads to inefficient exploitation of lateritic materials, which hurts the constructions carried out by giving them low durability. The behavior of lateritic soils depends on the mineralogy and chemical content, combined with geotechnical properties (particle size distribution, plasticity, etc.) (Ngon Ngon et al., 2009; Nzeukou Nzeugang et al., 2021). Several authors have done extensive work on Cameroonian lateritic or clay soils for use in engineering applications such as ceramics, fired bricks, compressed earth bricks, stabilized earth bricks, and porcelain (Ngon Ngon et al., 2005; Kamseu et al., 2007; Ngon Ngon et al., 2009; Nzeukou Nzeugang et al., 2013; Nzeukou Nzeugang et al., 2014; Tsozué et al., 2017; Nzeukou Nzeugang et al., 2021; Kagonbé et al., 2021). Many studies another way carried out soil properties using statistical analysis methods in other parts of the world (Osinubi et al., 2015; Gadzama et al., 2017, 2018; Babatunde et al., 2020; Yohanna and Nwaiwu Okechukwu, 2021). The lateritic soils used in the locality of Mbé, despite their abundance, have little known geotechnical properties because the Adamawa region has so far benefited from few geological investigations (Lasserre, 1958; Humbel, 1966; Le Marechal et al., 1971; Tchameni et al., 2006; Atougour et al., 2019; Nguetnkam et al., 2020; Temga et al., 2021).

This paper aims to evaluate the suitability for earthen constructions of soil samples collected from four sites and improve the properties of those that do not offer desired results. This evaluation consists in the determination of the physical, geochemical and mineralogical properties of soils. In addition, an evaluation of the mechanical behavior, a statistical analysis of correlated parameters and a strength prediction model of the compressed earth bricks manufactured from the lateritic material of Mbé, are carried out to optimize their use in construction.

2. Experimental methods

2.1. Location and sampling

2.1.1. Location

The study area is located in the Adamawa region of Cameroon, in the Vina division. The Mbé subdivision is located between 13°20’ and 13°50’ East longitude, and 7°34’ and 7°68’ North latitude, covering an area of approximately 3000 km². Figure 1 shows the location map of the study area.

2.1.2. Sample

The lateritic materials studied were collected at four different sites (Ndom, Kabaa, Norwegian Camp, and Nyessé) in the Mbé subdivision; GPS coordinates are presented in Table 1. Five sampling wells were dug at each study site; the sampling wells were described according to the observations made at the site. Sampling was conducted manually using a pickaxe, shovel, and GPS, followed by labeling of collected samples. Sampling wells averaging 1.5 m in depth were dug at a sampling interval of 50–100 m using a square sampling grid staggered according to the accessibility of the sampled point at each sampling site. Quantities of approximately 50 kg were collected from the sample wells for laboratory analysis.
analysis. The sample sites generally have two types of lateritic soils based on their color. On the lithologic sections in Figure 2, two soil horizons can be distinguished:

- Horizon A is a thin layer of soil made up mainly of humus, notably of plant debris. This layer is blackish in color and measures 15 cm from the surface;
- Horizon B is a lateritic soil consisting of fine-grained soil combined with some gravel particles. The color observed varies from reddish to brown depending on the sampling point, with an average depth ranging from 15 cm to about 150 cm.

### Table 1. Coordinates of sampling wells in Mbé locality.

| Sampling sites | wells | Latitude (x) (UTM) | Longitude (y) (UTM) | Elevation (m) |
|----------------|-------|-------------------|-------------------|--------------|
| Ndom           | 1     | 337721            | 857110            | 588          |
|                | 2     | 337678            | 857200            | 586          |
|                | 3     | 337632            | 857158            | 584          |
|                | 4     | 337692            | 857070            | 582          |
|                | 5     | 337682            | 857143            | 584          |
| Kabaa          | 1     | 337750            | 858446            | 576          |
|                | 2     | 337699            | 858441            | 575          |
|                | 3     | 337707            | 858386            | 575          |
|                | 4     | 337762            | 858409            | 573          |
|                | 5     | 337728            | 858423            | 575          |
| Norwegiane camp of Mbé | 1 | 345479 | 870165 | 604 |
|                | 2     | 345417            | 870181            | 607          |
|                | 3     | 345423            | 870130            | 605          |
|                | 4     | 345467            | 870106            | 604          |
|                | 5     | 345448            | 870147            | 606          |
| Nyessé         | 1     | 345253            | 868650            | 635          |
|                | 2     | 345321            | 868724            | 633          |
|                | 3     | 345352            | 868607            | 635          |
|                | 4     | 345328            | 868666            | 635          |
|                | 5     | 345407            | 868674            | 632          |

2.2. Experimentation

2.2.1. X-ray fluorescence spectrometry (XRF)

The X-ray fluorescence spectroscopy (XRF) analysis was performed on the raw materials using a Niton XL3t980 hXRF analyzer (X-ray tube: 50 kV; anode: silver; silicon detector: 8 mm). The analysis provides raw data in the form of a spectrum with the specific fluorescence energy (in keV) on the x-axis and the photon number (in CPS) on the y-axis. The instrument has been calibrated and configured in mining/mineral mode. The materials studied were crushed and sieved to 80 μm and then analyzed to obtain the base oxides contained in the materials.

2.2.2. X-ray diffractometry (XRD)

X-ray diffractometry (XRD) was performed at the AGEs laboratory of the University of Liege (Belgium) using a Bruker-AXS D8 diffractometer with Cu radiation (KαCu = 1.54056 Å) at an intensity of 40 mA and a voltage of 40 kV. It is configured with a step size of 0.013°/2θ for a measurement time of 30 s and data are collected over the interval of 2°–70° (2-θ). Mineral phase identification was performed using X’Pert HighScore Plus software associated with PDF-2 2007 release software. Prior to analysis, the analyzed samples were ground and sieved to 80 μm.

2.2.3. Physical analysis

The physical analyses were carried out at the National Civil Engineering Laboratory (Cameroon). The natural water content calculated by formula (1) was determined according to the NF P94-050 (1995) standard by twice weighing, the first for the raw sample (W) and the second after drying in the oven (at 105 °C) to a constant mass (Wd). The specific gravity, which is the volumetric weight of the solid grains excluding the pore spaces, was determined by the pycnometer method according to the NF P94-054 (1991) standard. Dry particle size analysis was performed by sieving for a fraction of ≥ 80 μm and sedimentometry was obtained after sedimentation test on a fraction of <80 μm according to NF P94-056 (1996) and NF P94-057 (1992) standards, respectively. The methylene blue test measures the capacity of the clay to absorb the cations of a solution. It was carried out according to the NF P94-068 (1998) standard

![Figure 2. Lithological profiles of the sampling wells.](image)
and calculated by formula (2). The compaction parameters (the optimum moisture content and the maximum dry density) were determined by the modified Proctor test according to the NF P94-093 (1999) standard. The Atterberg limits (plastic limit-PL, liquid limit-LL, and plasticity index-PI) were determined by the Casagrande approach according to the standard NF P94051 (1993). The absorption rate was determined by immersing the specimen in water for 24 h and using the successive weighing methods outlined in formula (3) in accordance with ASTM (1972) standards.

\[
w = \frac{W - W_d}{W_d} \times 100; \quad (1)
\]

with: \(w\): water content; \(W\): wet mass; \(W_d\): dry mass

\[
VBS = \frac{\text{volume of methylene blue used}}{\text{mass of dry sample}} \quad (2)
\]

\[
\text{Abs} = \frac{\text{mass of wet specimen} - \text{mass of dry specimen}}{\text{mass of dry specimen}} \times 100 \quad (3)
\]

2.2.4. Preparation of specimens and mechanical test on CEB

The samples produced were made according to the method prescribed by the Cameroonian standard NC 102-115 (2007), which consist in: extraction, preparation (drying, crushing, sieving, mixing with water), compaction using a hydraulic press, followed by de-molding, and finally air drying. The soil powders of a size less than 1 mm were obtained after grinding. For stabilized specimens, 4%, 6%, and 8% by weight of Portland cement were added to the natural material mixture. After 28 days of maturation in a plastic envelope, all the specimens were tested to determine their physical and mechanical parameters.

Compressive and flexural strengths were measured on prismatic soil specimens of dimensions \(4 \times 4 \times 16\) cm. The standards NF P94-420 (2000) and NF P94-422 (2001) were used to measure the compressive and flexural strengths, respectively.

3. Results and discussion

3.1. Mineralogical and chemical composition

The mineralogy of the studied soils, presented in Figure 3, is characterized by clay minerals such as kaolinite, illite, and smectite (montmorillonite), and non-clay minerals such as quartz, muscovite, biotite, gibbsite, and hematite. To determine the nature of clay minerals in the samples, oriented clay slides was performed (Figure 4) on two soil samples (Norwegian camp and Kabaa) whose diffractograms are similar to those of the samples from the other two sites. The presence of smectite was verified using diffractograms of Mbé Norwegian camp soils (Figure 4a) by the change of the diffraction peak from 13.85 Å to 16.19 Å after ethylene glycol solvation. Furthermore, the ethylene glycol solvation treatment had no effect on the kaolinite (\(d = 7.14\) Å) and illite (\(d = 9.98\) Å) main peaks. Moreover, the primary diffraction peak of kaolinite is missing from the diffractograms after the \(500^\circ\)C firing, but that of illite is still evident. These elements confirm the presence of kaolinite and illite in the clay samples studied. The intensity of the illite diffraction peak increased after the heat treatment at \(500^\circ\)C for Norwegian camp soil. This increase in intensity, according to Fadil-Djenabou et al. (2015) could be attributed to the collapse of the smectite diffraction peak to illite peak (\(d = 10.0\) Å), which also confirms the existence of these expansive 2:1 clay minerals (smectite and illite). The presence of clay minerals has significant effects on the geotechnical properties of soils since some swelling clay minerals such as smectites absorb more water than others (kaolinite) (Guorui, 1996; Logmo et al., 2013). The kaolinite mineral in the studied lateritic soil has a positive effect on the manufacture of compressed earth bricks because it increases the molding properties of the soil material (Morin and Todor, 1975). The presence of illite and smectite as clay minerals is the result of the Sudanian climate that prevails in the study site. The presence of hematite in the soils of Mbe is dependent on the iron oxide (Fe₂O₃) content and is responsible for the reddish-brown color of the soils studied (Bell, 1993). The presence of gibbsite is due to the high alumina content of the Mbé soils. The presence
of illite in the studied soils contributes to improving the plasticity of clays (Kamseu et al., 2007; Nzeukou Nzeugang et al., 2013). According to some authors (Pedro, 1966; Nguetnkam et al., 2014), weathering processes by bissiallitization dominate in the North Cameroon region and favor the presence of smectite in soils. Conversely, monosiallitization is a crystallization process that favors the presence of kaolinite and generally dominates in areas with abundant rainfall.

The studied materials are mainly characterized by relatively high contents of SiO$_2$, followed by Al$_2$O$_3$ and Fe$_2$O$_3$, as shown in Table 2. Other elements such as potassium, sodium, calcium, and magnesium oxides, are present in minor proportions (<1%). The SiO$_2$ content of these lateritic soils shows a good relationship with the presence of quartz particles; thus, the highest amount observed for all samples corresponds to the highest proportion of the sandy fraction in the particle size distribution analysis and higher proportions of quartz minerals in its mineralogical composition. The proportion of alumina (Al$_2$O$_3$) reflects the presence of aluminosilicates in these soil materials. The silica (SiO$_2$ > 60% by weight), iron (Fe$_2$O$_3$ < 10% by weight), and alumina (Al$_2$O$_3$ < 35% by weight) content of Mbé soils is suitable for tile and brick making (Djedid et al., 2001; Ngon Ngon et al., 2012). The geotechnical characteristics of the soil (compaction parameters, dry density) can be improved by a reasonably high proportion of quartz (Gokalp, 2009). Nevertheless, amounts of basic elements (<2 wt% (oxides of calcium, magnesium, sodium, and potassium) may induce low flexural strength (Ngon Ngon et al., 2013) since these elements are cementitious compounds. The presence of free forms of silica and 2:1 clay mineral types is related to a high SiO$_2$/Al$_2$O$_3$ ratio > 3, indicating an excess of SiO$_2$ (Nguetnkam et al., 2014; Tsozu et al., 2017) and suggesting a high chemical maturity of the studied samples (Maignien, 1958; Tsozu et al., 2017). Weathering ratios such as RR (Ruxton Ratio), CIA (Chemical Index of Alteration), WIP (Weathering Index of Parker), and MWPI (Modified Weathering Potential Index) are weathering index showing that these soil materials are the result of a relatively extensive weathering process of the basement rock.

### 3.2. Physical parameters

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

#### 3.2.1. Natural water content

The arithmetic mean natural water content values are 17.95%, 11.29%, 16.24%, and 14.79% for the Norwegian Camp, Kabaa, Ndom, and Nyessé. Overall, these moisture content values are relatively low compared to those obtained by Keyangue Tchouata et al. (2019) at Meiganga, even though the sampling was conducted at the same time (during the rainy season). This can be explained by the low proportions of the clay fraction (<35%) in the Mbé samples, which have adsorptive properties to retain water. The higher water content values observed in some samples may also reflect the presence of some expansive clay minerals such as smectites (Guorui, 1996; Logmo et al., 2013).

#### 3.2.2. Specific gravity

The average specific gravity values are 2.54, 2.53, 2.51, and 2.30, respectively, for the soils of the Norwegian Camp of Mbé, Kabaa, Ndom, and Nyessé. Specific gravity values above 1.5 indicate that the soils studied are very heavy with coarse textural fragments (Nzeukou et al.,

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**Table 2. Chemical composition of Mbé clayey materials (wt%).**

|         | KABAA | NDOM | NYESSE | NORWEGIAN CAMP |
|---------|-------|------|--------|----------------|
| LOI     | 4.65  | 9.4  | 7.67   | 7.2            |
| SiO$_2$ | 78.16 | 62.61| 63.26  | 64.12          |
| Al$_2$O$_3$ | 11.84 | 17.77| 18.09  | 18.29          |
| Fe$_2$O$_3$ | 3.27  | 7.89 | 6.25   | 8.11           |
| CaO     | 0.14  | 0.5  | 1.35   | 1.23           |
| MgO     | 0.14  | 0.5  | 0.4    | 0.77           |
| SO$_3$  | 0.03  | 0.04 | 0.04   | 0.25           |
| Na$_2$O | 0.14  | 0.43 | 0.11   | 1.47           |
| K$_2$O  | 4.12  | 2.1  | 4.71   | 2.21           |
| P$_2$O$_5$ | 0.04  | 0.05 | 0.04   | 0.07           |
| TOTAL   | 102.53| 100.29| 101.92 | 103.72        |
| RR      | 6.60  | 3.52 | 3.50   | 3.51           |
| WIP     | 3411.56| 2052.70| 4068.16| 2869.27       |
| CIA     | 72.91 | 85.43| 74.57  | 78.84          |
| MWPI    | 4.64  | 3.85 | 6.98   | 5.90           |
The specific gravity of laterites depends on their chemical composition. Lower specific gravity values would be characterized by high alumina content, while higher specific gravity values would be due to high iron content (Maignien, 1958). Lateritic soils in the equatorial zone have specific gravity values ranging from 2.5 to 3.6 (Mahalinga-Iyer and Williams, 1985). The specific gravity values of the studied soil are close to 2.5, indicating that the alumina content is higher than the iron content in the studied soil, as shown by the chemical composition. In addition, it is observed in the Pearson correlation matrix (Table 4) that in general, the compressive strength of CEBs is highly related to the values of specific gravity with a correlation coefficient $R = -0.71$. This high and negative correlation coefficient value suggests that the specific gravity would have a negative influence on the compressive strength of CEBs. This could be due to the fact that Gs also negatively influences the values of MDD, which is an important parameter in the soil compaction process as observed in Table 4 and corroborated by the work of Gadzama et al. (2018). In addition, since the increase in alumina tends to decrease the Gs of the soil (Maignien, 1958), the increase in alumina content would be favorable for the compressive strength. Because alumina is dependent on clay minerals like kaolinite, this correlation shows that increasing the kaolinite content in the material has a positive effect on compressive strength.

### 3.2.3. Grains size distribution

The particle size analysis is presented in Figure 5. These curves were projected into the particle size envelope of soil materials used for the production of compressed earth bricks (CB) according to NC 102-115 (2007) and CRATerre- et al. (1998).

The grading patterns show much steeper slopes on the sand portion and shallower slopes on the clay and silt portions. The particle size distribution indicates that the soils studied are clayey sands. For some authors (Guettala et al., 2002; Kwon et al., 2010), the compressive strength of earth bricks increases with a high percentage of sand, with a better result for a proportion of sand between 40 and 65%. A certain high proportion of coarse grains is necessary because they constitute the skeleton of the earth brick and ensure the stability of its structure. Soils with a clay content of 15–30% are suitable for mud brick production (Kwon et al., 2010). The soils of Mbe have relatively high proportions of sand (52.8–90.3%). The proportion of sand (52.8–59.9%) in the Nyessé soil samples is within the range given by Guettala et al. (2002) and Kwon et al. (2010). The other soil samples are closer to the higher values obtained by these authors, except for the Kabaa sample, which shows an excessive proportion of sand (63.2–90.3%). The texture of the soil is one of the most important parameters for their use as construction materials (Carmen Jime Nez Delgado and Ignacio, 2005). The correlation analysis between the soil parameters of the Mbe locality and the compressive strength values (Cs) of CEBs shows a strong positive correlation of Cs with Gs (0.71) and a weak correlation of Cs with Sa (–0.3) and Cs with Cl (0.18). Thus, it is observed that the mechanical behavior of specimens, especially the compressive strength, is greatly influenced by the grain size of the material in general and by the Gs in particular.

#### 3.2.4. The value of methylene blue

The methylene blue values of the investigated materials range from 0.66 to 5.0. According to the interpretation of the standard on the values of methylene blue NF P94-068 (1998), the soils studied are essentially silty soils and silty clay soils. This indicates that overall, the soils in the study area are moderately sensitive to water. The soil samples from Kabaa are mainly loamy soils with low blue values ranging from 0.66 to 1.66 while high blue values (between 3 and 5) can be observed in some samples from other sites. Furthermore, the Pearson correlation matrix (Table 4) shows that, in general, the compressive strength of CEB has a rather poor relationship with methylene blue values, with a correlation coefficient of $R = 0.42$. This poor correlation value indicates that methylene blue value has little effect or does not have a direct effect on the compressive strength of CEB. Thus, according to the blue values, silty soils and silty clay soils have no significant impact on the compressive strength of CEB. Nonetheless, the positive value of R implies that the compressive strength of the CEB improves with soil clay concentration. This is explained by the fact that the clay in the material acts as a natural cement, tending to bind the soil particles together and therefore enhancing the mechanical characteristics of the CEB.

#### 3.2.5. Compaction parameter

The main objective of the proctor compaction test in this study is to determine the optimum moisture content needed to achieve the best compression of the soils studied. The results show that at the Norwegian Camp, Kabaa, Ndóm, and Nyessé sites, the maximum dry densities (MDD) are 1.97, 2.20, 2.04, and 2.12, respectively, for optimum moisture contents (OMC) of 10.01%, 9.62%, 9.42%, and 11.34%. The optimum moisture content values of the studied soils are lower than the values obtained by Mengue et al. (2017) (17.8%), while the maximum dry densities obtained are higher (1.79). These relatively low moisture

| Study sites       | Norwegian Camp of Mbe | Kabaa |
|-------------------|------------------------|-------|
| Wells             | Well1                  | Well2 | Well3 | Well4 | Well5 | Mean |
| W (%)             | 11.11                  | 27.11 | 20.24 | 11.52 | 19.76 | 17.95 | 12.14 | 9.68 | 13.2 | 10.29 | 11.11 | 11.28 |
| Gs (g/cm²)        | 2.55                   | 2.55  | 2.49  | 2.56  | 2.55  | 2.54  | 2.32  | 2.54  | 2.57  | 2.64  | 2.58  | 2.53  |
| Gr (φ ≤ 20mm)     | 4.30                   | 10.83 | 6.44  | 2.66  | 7.43  | 6.33  | 7.44  | 2.20  | 13.00 | 1.10  | 9.60  | 6.67  |
| Sa (φ ≤ 2mm)      | 68.37                  | 65.48 | 60.9  | 54.6  | 68    | 63.47 | 69.5  | 85.1  | 62.33 | 90.34 | 77    | 77.03 |
| Cl (φ ≤ 2μm)      | 27.02                  | 23.2  | 32.5  | 42.1  | 24.2  | 29.80 | 23.1  | 12.3  | 23.7  | 8.45  | 13.3  | 16.17 |
| VBS               | 2.00                   | 2.33  | 3.33  | 2.20  | 2.66  | 2.50  | 1.66  | 0.66  | 1.66  | 0.66  | 1.00  | 1.13  |
| OMC (%)           | 11.00                  | 9.55  | 10.10 | 10.00 | 9.40  | 10.01 | 8.20  | 8.00  | 9.30  | 12.22 | 10.40 | 9.62  |
| MDD               | 1.98                   | 1.97  | 2.02  | 1.96  | 1.92  | 1.97  | 2.23  | 2.20  | 2.25  | 2.15  | 2.15  | 2.20  |
| LL (%)            | 36.19                  | 40.64 | 44.18 | 42.45 | 41.61 | 41.01 | 26.86 | 33.67 | 44.38 | 43.99 | 36.5  | 37.08 |
| PL (%)            | 21.5                   | 26    | 26.8  | 18.1  | 25.6  | 23.6  | 20.8  | 21.5  | 32.2  | 24.3  | 22    | 24.16 |
| PI (%)            | 14.7                   | 14.7  | 17.4  | 24    | 15.1  | 17.18 | 6     | 12.1  | 12.2  | 18.8  | 14.5  | 12.72 |
| HRB classification | A-7.5                  |       |       |       |       |       |       |       |       |       |       |       |
| USGS classification| Sandy Elastic Silt (MH)| SM    |       |       |       |       |       |       |       |       |       |       |

Table 3. Physical parameters of the studied soils.
The average values obtained are closer to the results of Carmen Jime Nez Delgado and Ignacio (2005) suggesting in their work that the plasticity index should be between 16% and 28% and the liquid limits between 32% and 46% for the soils to be suitable for construction as raw material. Other authors (Ngapgue et al., 2020) studying the sandy and silty soils of Fongo Tongo in West Cameroon found an average plasticity index of 16.1%. This value is lower than the average value (19.47%) of silty soils of Fongo Tongo in West Cameroon.

### 3.2.6. Atterberg limits

The average values obtained are closer to the results of Carmen Jime Nez Delgado and Ignacio (2005) suggesting in their work that the plasticity index should be between 16% and 28% and the liquid limits between 32% and 46% for the soils to be suitable for construction as raw material. Other authors (Ngapgue et al., 2020) studying the sandy and silty soils of Fongo Tongo in West Cameroon found an average plasticity index of 16.1%. This value is lower than the average value (19.47%) of soils in the study area. Thus, the more clayey soils will tend to absorb more water, increasing the liquid limit and plasticity index of these soils. As shown by Bergaya et al. (2006) and Hajjaji et al. (2010) the particle size distribution has a great influence on the plasticity properties of soils. Thus, the difference observed between the Fongo Tongo soils and the Mbé soils could be due to the presence of clay particles in the Mbé soils in higher proportions; or to the presence of 2:1 clay minerals such as illite, which has the effect of improving the plasticity of clay soils (Kamseu et al., 2007; Nzekou Nzeugang et al., 2013). A plasticity index of between 15 and 25% is more appropriate for the production of compressed earth bricks (Murmu and Patel, 2018). According to the correlations established, PI and LL seem to be the atterberg limit parameters that most influence the compressive strength, with correlation coefficients of 0.46 and 0.57, respectively, for OMC and MDD.

### Table 4. Correlation matrix variables.

| Variables | Ce | Cs | Fs | Abs | Gr | Sa | Cl | Go | VBS | OMC | MDD | LL | PL | PI |
|-----------|----|----|----|-----|----|----|----|----|-----|-----|-----|----|----|----|
| Ce        | 1.00 | 0.51 | 0.89 | -0.14 | 0.03 | 0.04 | -0.05 | 0.05 | 0.05 | -0.11 | -0.06 | -0.03 | -0.16 | -0.02 | -0.18 |
| Cs        | 0.51 | 1.00 | 0.27 | -0.59 | 0.72 | -0.30 | 0.19 | -0.71 | 0.43 | 0.57 | 0.46 | 0.61 | 0.52 | 0.60 | -0.61 |
| Fs        | 0.89 | 0.27 | 1.00 | -0.03 | -0.15 | 0.24 | -0.24 | 0.24 | -0.15 | -0.32 | -0.02 | -0.24 | -0.21 | -0.23 | -0.03 |
| Abs       | -0.14 | -0.59 | -0.03 | 1.00 | -0.23 | 0.07 | -0.03 | 0.47 | 0.10 | -0.55 | -0.62 | -0.30 | -0.89 | -0.25 | 0.97 |
| Gr        | 0.03 | 0.72 | -0.15 | -0.23 | 1.00 | -0.64 | 0.51 | -0.94 | 0.82 | 0.78 | 0.25 | 0.92 | 0.36 | 0.92 | -0.27 |
| Sa        | 0.04 | -0.30 | 0.24 | 0.07 | -0.64 | 1.00 | -0.99 | 0.72 | -0.92 | -0.83 | 0.46 | 0.87 | 0.03 | -0.88 | 0.08 |
| Cl        | -0.05 | 0.19 | -0.24 | -0.03 | 0.51 | -0.99 | 1.00 | -0.60 | 0.85 | 0.76 | -0.57 | 0.78 | -0.11 | 0.79 | -0.04 |
| Go        | 0.05 | -0.71 | 0.24 | 0.47 | -0.94 | 0.72 | -0.60 | 1.00 | -0.77 | -0.93 | -0.28 | -0.96 | -0.55 | 0.95 | -0.49 |
| VBS       | 0.05 | 0.43 | -0.15 | 0.10 | 0.82 | -0.92 | 0.85 | -0.77 | 1.00 | 0.73 | -0.35 | 0.90 | -0.10 | 0.93 | 0.06 |
| OMC       | -0.11 | 0.57 | -0.32 | -0.55 | 0.78 | -0.83 | 0.76 | -0.93 | 0.73 | 1.00 | 0.10 | 0.94 | 0.54 | 0.92 | -0.55 |
| MDD       | -0.06 | 0.46 | -0.02 | -0.62 | 0.25 | 0.46 | -0.57 | -0.28 | -0.35 | 0.10 | 1.00 | 0.01 | 0.83 | -0.03 | -0.62 |
| LL        | -0.03 | 0.61 | -0.24 | -0.30 | 0.92 | -0.87 | 0.78 | -0.96 | 0.90 | 0.94 | 0.01 | 1.00 | 0.33 | 1.00 | -0.33 |
| PL        | -0.16 | 0.52 | -0.21 | -0.89 | 0.36 | 0.03 | -0.11 | -0.55 | -0.10 | 0.54 | 0.83 | 0.33 | 1.00 | 0.28 | -0.87 |
| PI        | -0.02 | 0.60 | -0.23 | -0.25 | 0.92 | -0.88 | 0.79 | -0.95 | 0.93 | 0.92 | -0.03 | 1.00 | 0.28 | 1.00 | -0.28 |
| P         | -0.18 | -0.61 | -0.03 | 0.97 | -0.27 | 0.08 | -0.04 | 0.49 | 0.06 | -0.55 | -0.62 | -0.33 | -0.87 | -0.28 | 1.00 |
3.2.7. HRB and USCS classification of the studied soils

According to the Highway Research Board (HRB) classification, the soils studied are classes A-7-5 and A-7-6 with a group index value of 1; 7; 9; and 12 respectively for Kabaa; Ndom; the Norwegian camp of Mbé; and Nyéssé. According to the Unified Soil Classification System (USCS), the soils of Mbé are elastic sandy loam (MH) and silty sand (SM). From these two classification systems, it appears that these soils are mainly fine soils with a sandy-clay composition, which makes them suitable for use as construction materials.

3.3. Physical and mechanical properties of brick specimens

3.3.1. Physical properties

One of the most important parameters to control soil strength is density which is related to compressive strength (Kwon et al., 2010). The densities of manufactured brick specimens are presented in Table 5. The densities obtained (2.04–2.08) are close to those obtained at the Proctor optimum (1.95–2.26). This implies that the compaction of these specimens was well done. The particle size distribution affects the density of...
the brick specimens. It has been shown that the density increases with an increase in coarse grains content (Kwon et al., 2010). The relatively high density observed for the test specimens may be due to the high proportion of coarse grain in the soil studied. These density values ensure good mechanical behavior by improving the compressive strength of the bricks.

### 3.3.2. Mechanical properties

The compressive strength values recorded in Tables 5 and 6 are overall between 5.04 and 10.04 MPa (see Figure 8 and 10), while the flexural strength is between 0.55 and 3.29 MPa. The influence of the stabilizer contents on the mechanical properties of the tested samples is shown by histogram which clearly indicates the increase in the mechanical strength (compressive and flexural strength) when the cement content increases. Some authors (Meukam et al., 2004) show that the compressive strength of bricks of stabilized lateritic soil is between 2 and 10 Mpa with a cement content of 3–10%. The values obtained for the Mbé soils are greater than those recommended by the Cameroonian standard NC 102-115 (2007) for earth brick construction. These high values of compressive strength could be characteristic of compaction that resulted in higher densities, resulting in increased compressive strength of the compressed earth bricks. The compressive strength of stabilized compressed earth bricks depends on the soil properties (Guettala et al., 2002; Kwon et al., 2010), and the amount of stabilizer.

### Table 5. Physical and mechanical parameters of the specimens.

| Sampling site          | density | Compressive strength (MPa) | Flexural strength (MPa) | Absorption rate          |
|------------------------|---------|----------------------------|-------------------------|--------------------------|
| Kabaa                  | 2.04    | 5.04                       | 1.22                    | Destructed by immersion  |
| Nyèssé                 | 2.08    | 6.01                       | 0.55                    |                          |
| Norwegian Camp         | 2.08    | 5.36                       | 1.33                    |                          |
| Ndomb                  | 2.04    | 5.53                       | 1.43                    |                          |

Figure 7. Mean values of Atterbergs limits projected in clay workability chart (Bain and Highley, 1978).

Figure 8. Compressive strengths of unstabilize bricks specimen.
Analysis of the mechanical results presented in Figures 9 and 11 indicates that the flexural strength of the bricks is lower than their compressive strength. In addition, the percentage of clay present in the particle size distribution of these soils may act as a natural binder (Office of International Affairs D. W. C. B., 1970). The increase in mechanical strength of stabilized compressed earth bricks would be due to the increase in the quantity of C2S and C3S, which once hydrated are likely to improve the mechanical properties of CEB. Table 6 shows the compressive strength increases as the porosity and water absorption decrease. This relationship demonstrates that the percentage of void in a compressed earth brick specimen has a significant influence on mechanical behavior.

### 3.3.3. Water absorption

The water absorption test consists of a full immersion test of the brick that allows water to be absorbed into the pores, which are easily filled under cold conditions. The results presented in Table 6 for water absorption are illustrated by the histograms in Figure 12. Water absorption strongly influences the strength and durability of earth bricks. Total water absorption is an important parameter that can be used to obtain the total void volume in CEB (Kerali, 2001). The results presented in Figure 12 show a decrease in the rate of water absorption as the cement content increases. At the start of the water absorption (0% cement content), total disintegration of the bricks by immersion in water is observed. The very high water absorption rate observed for some samples would be linked to the mineralogical nature of the clay particles contained in the soil. Indeed, smectite and illite are clay minerals whose presence would cause high absorption rates. Because of their swelling property and their great capacity to retain water, the presence of these clay minerals can lead to inhibition of the stabilizing action of cement (Walker and Stace, 1997). The absence of smectite coupled to the predominance of sandy particles could explain relatively low absorption rates of the Kabaa site CEBs. Smectite-containing materials, such as Ndom and Norwegian camp, have the highest absorption rates. The Cameroonian earth construction standard NC 102-115 (2007) prescribes absorption rates less than 15%. It was found that at 6% stabilization, all the specimens except those from Ndom had absorption rate that meets the standard. Due to the high clay mineral content in the Ndom soils, the absorption rate, even at 8%, is still unsatisfactory according to NC 102-115 (2007).

### 3.4. Statistical analysis and prediction model of mechanical behavior

#### 3.4.1. Principal component analysis (PCA)

PCA is a statistical analytic approach that may be used to explore and analyse correlations between variables. This methodology reduces data by evaluating data tables in which observations are defined by numerous intercorrelated dependent quantitative variables (Gadzama et al., 2018). According to Herve and Lynne (2010), Principal component analysis is based on the decomposition of positive semidefinite matrices and the
singular value decomposition (SVD) of rectangular matrices. The purpose of this analysis is to extract essential information from the data table and represent it as a new collection of orthogonal variables known as principal components.

According to the PCA results (Table 7) on soil and CEB data, the liquid limit (LL), plasticity index (PI), soil blue volume (VBS), proportion of gravel (Gr), and percentage of clay (Cl) are the characteristics that have a significant influence on the behavior of the material investigated for the principal component 1 (F1). As a result, these parameters must be closely monitored during the manufacturing process to ensure optimal performance of these soils in the manufacturing of CEBs. Additionally, in principal component 2 (F2), the maximum dry density (MDD) and plasticity limit have a significant influence on soil behavior. Figures 13 and 14 show the correlation circle of variables and biplot of the principal component analysis between compressive strength (Cs) and soil factors. According to the PCA, principal component 1 (F1) has a 51.46% influence on the examined soils. This means that the liquid limit, plasticity index, soil blue volume, gravel proportion, and clay percentage all have an estimated 51.46% effect on the behavior of the examined soil. Changes in these variables have a substantial influence on the quality of manufactured bricks.
3.4.2. Data modeling

Eqs. (4) and (5) show the mathematical relationships established for the mechanical strengths and water absorption. According to Eq. (1), compressive strength (Cs) has a substantial link with the proportion of cement (Ce), gravel (Gr), optimal moisture content (OMC), and plasticity index (PI). The coefficients of determination discovered for this model are $R^2 = 82\%$, indicating the strength of the relationship formed between the parameters used in this model.

$$Cs = -8.02238 + 0.31186Ce + 0.81026Gr + 1.12511OMC - 0.20875PI$$ (4)

$R^2 = 82\%$

$$Abs = -0.48408 + 0.59708P$$ (5)

$R^2 = 90.12\%$

According to Eq. (4), the variables Ce, Gr, and OMC have positive coefficients, implying that these factors increase the characteristics of the strength to compression of the earthen brick. However, it is also found that only PI has a negative coefficient, indicating that this parameter has a negative impact on compressive strength. As a result, a rise in the plasticity index of the soil influences the mechanical strength of the soil and thus constitutes a parameter that must be carefully monitored during the field fabrication of CEBs. The laboratory results, when compared to the regression model’s predicted values (Figure 15), show a high correlation and the residual values have absolute values between 0.2 and 0.5 (Table 8).

In Eq. (5), it is observed that the porosity (P) has a positive coefficient, which indicates that the increase in porosity has the effect of increasing the absorption rate of the manufactured bricks. This can be explained quite simply by the voids caused by the porosity that will retain water once the brick is immersed. A comparison of the results from the model with those measured in the laboratory (Table 9) shows that the distance between the predicted and measured values (Figure 15) is acceptable and

Table 7. Correlations between variables and factors.

|             | F1       | F2       | F3       |
|-------------|----------|----------|----------|
| Ce          | 0.00     | 0.16     | 0.97     |
| Cs          | 0.69     | 0.45     | 0.45     |
| Fs          | -0.23    | 0.18     | 0.91     |
| Abs         | -0.46    | -0.79    | 0.02     |
| Gr          | 0.89     | -0.02    | 0.07     |
| Sa          | -0.82    | 0.51     | -0.03    |
| Cl          | 0.74     | -0.57    | 0.01     |
| Gs          | -0.98    | -0.10    | 0.05     |
| VBS         | 0.82     | -0.53    | 0.15     |
| OMC         | 0.97     | 0.03     | -0.13    |
| MDD         | 0.12     | 0.90     | -0.17    |
| LL          | 0.98     | -0.15    | 0.00     |
| PL          | 0.46     | 0.82     | -0.30    |
| PI          | 0.97     | -0.20    | 0.02     |
| P           | -0.48    | -0.78    | -0.01    |
demonstrates a strong association of the parameters with residual values ranging from 0.03 to 0.6 in absolute value.

4. Conclusion

This study focused on the evaluation of the suitability for earthen construction of soil samples collected in Mbe district in the Adamawa region of Cameroon. Physical and mechanical tests were carried out on the twenty samples collected from four sites, followed by soil classification.

1. The results of the physical tests show that these soils are of sandy clay texture and have medium to high plasticity; these soils are silty clays according to their methylene blue value. The correlations show that the physical parameters (LL, PI, VBS, Gr, and Cl) have a more or less significant influence on the compressive strength of CEBs.

2. Mineralogically, these soils are essentially constituted by clay minerals such as kaolinite, illite, smectite (montmorillonite), and non-clay minerals such as quartz, muscovite, biotite, gibbsite, and hematite. The chemical composition shows relatively high contents of SiO₂, followed by Al₂O₃ and Fe₂O₃.

3. The tests carried on CEB specimens show that the densities obtained (2.04–2.08) on the compressed earth brick specimen are within the standard of compressed earth bricks. The water absorption shows a poor result without stabilization. The mechanical properties of the test specimens gave compressive strengths varying between 5.04 and 10.04 MPa, with flexural strengths between 0.55 and 3.29 MPa.

4. According to the statistical analysis, there is a good relationship between compressive strength and absorption and between compressive strength and physical parameters of soil. According to the Cameroonian standard NC 102-115 (2007), compressed earth bricks made with Mbe soils have a good mechanical behavior since the compressive strengths are higher than the recommendations with or without stabilizers.

5. For potential use, it is recommended to stabilize these soils at a percentage between 4 to 8% to improve the durability and mechanical properties.

Table 8. Validation table of model 4.

| Observations | Gr  | Gr  | OMC | PI   | Cs   | Pred(Cs) | Residual |
|--------------|-----|-----|-----|------|------|----------|----------|
| Obs1         | 0.00| 6.67| 9.62| 12.72| 5.04 | 5.54     | -0.50    |
| Obs2         | 4.00| 8.12| 9.94| 18.44| 6.74 | 6.54     | 0.19     |
| Obs3         | 6.00| 6.33| 10.01| 17.18| 5.97 | 6.65     | -0.68    |
| Obs4         | 8.00| 9.87| 11.34| 29.54| 10.31| 9.06     | 1.24     |

Table 9. Validation table of model 5.

| Observations | P   | Abs | Pred(Abs) | Residual |
|--------------|-----|-----|-----------|----------|
| Obs6         | 28.17| 15.74| 16.33     | -0.59    |
| Obs7         | 30.25| 17.61| 17.57     | 0.03     |
| Obs11        | 20.46| 11.66| 11.73     | -0.07    |
| Obs15        | 20.33| 12.27| 11.65     | 0.61     |

1. The results of the physical tests show that these soils are of sandy clay texture and have medium to high plasticity; these soils are silty clays according to their methylene blue value. The correlations show that the physical parameters (LL, PI, VBS, Gr, and Cl) have a more or less significant influence on the compressive strength of CEBs.

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5. For potential use, it is recommended to stabilize these soils at a percentage between 4 to 8% to improve the durability and mechanical properties.
properties of the compressed earth bricks. Physical parameters (LL, PI, VBS, Gr, and CI) must be monitored during the manufacturing of CEBs in the field.

Declarations

Author contribution statement

Japhet Taypondou Darman: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Jules Hermann Keyangue Tchouata; Gilbert François Ng-non: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. François Nganguie: Analyzed and interpreted the data; Wrote the paper. Bachirou Lindou Ngakoupain: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Yannick Tchedele Langollo: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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