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Article

The clayey deposit from Bomkoul (Douala, Cameroon): a case study of the geotechnical appraisal and assessment of the characteristics of firing bricks

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Abstract

This study investigates two clayey facies from the Bomkoul area in the littoral region of Cameroon for their suitability as fired clay building products. The field study consisted of a geological survey and a geotechnical mission (G0). Assessment of the raw clayey materials included their mineralogy, particle size, determination of Atterberg limits, density and shear stress. Firing properties (shrinkage, water absorption and flexural strength) at 900–1100°C were also determined. The two main facies observed in the field are the mottled red/yellow grey clays from surface 'A' with a thickness of 2.0–2.5 m and the deep blackish fossiliferous schisteous grey clays 'B' with a thickness of 8–10 m. Estimation based on boreholes revealed a minimum of 1,400,000 tons of clayey materials. These reserves will supply a small brick-manufacturing unit for a minimum period of 25 years at an extraction rate of 50,000 tons per year. The main clay minerals of both samples are kaolinite (35% and 49%) and illite (1–11%). Both samples contain quartz (47% and 49%) as non-clay minerals, associated with a small amount of anatase (0.5–2.6%) and trace hematite (<1%). The major oxides are SiO_2 (71–76%) and Al_2O_3 (14%). The raw clayey material 'A' was finer and more plastic than the 'B' facies. The technological properties of the fired bricks obtained from the 'A' facies showed greater potential than the 'B' facies in terms of sonority and flexural strength. A mixture made of 40% 'A' and 60% 'B' yielded satisfactory brick properties at 1050°C.

Keywords: Cameroon; clayey deposit; Douala; firing properties; geotechnical mission (G0)

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Clayey materials are the basic raw materials for brick-making. For such ceramic applications, clayey materials should be neither too poor in fine particles nor too greasy. They should dry easily with limited shrinkage and should be able to be fired without problem. Pretreatment and the use of admixtures can improve the efficiency and utility of the clayey materials in various industrial processes (Konta & Künher, 1997; Reeves *et al.*, 2006; Christidis, 2011). The final mixture is often the result of careful and continuous research and the application of theoretical knowledge, but direct experience has also proven to be the highly valuable. In the first phase of processing of a raw material, it is sometimes necessary to reduce its particle size through crushing and grinding. The resulting powder is then mixed and homogenized. Key elements that should be considered when designing a production unit are: (1) the mineral and chemical characteristics of the raw materials, (2) the natural state and workability of the raw materials; and (3) the particle-size distribution curve, among other factors (Manning, 1995; Dondi, 1998; Reeves *et al.*, 2006). These characteristics vary according to the geological environment, which is controlled by the primary sources during *in situ* alteration of primary rocks (residual clays) or by transportation and deposition (sedimentary or alluvial clays; Wilson, 1998). The abundances of clay minerals (kaolinite, illite, smectite and chlorite) and non-clay minerals (quartz, feldspars, hematite, carbonates, etc.) present may differ among different clay types, and these differences will affect the technological properties of the derived products. In Cameroon's basement layer, various clays (sedimentary, residual and alluvial) are observed in various regions (Ngon Ngon *et al.*, 2012b; Nzeukou *et al.*, 2013). Residual

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clays, known as 'lateritic clays', are more frequently observed in the southern part of the country, consisting mainly of quartz, kaolinite and iron oxides (Thibault & Le Berre, 1985; Ngon Ngon *et al.*, 2012b). In this context, flux agents are necessary to improve the sintering behaviour of the fired products originating from these raw materials. Fired products obtained from the lateritic clays of Yaoundé presented matte sonority and have flexural strength values of between 2 and 8 MPa (Thibault & Le Berre, 1985). This could be improved to reach 20 MPa at 1050°C by adding alluvial clays with lower melting points (Ngon Ngon *et al.*, 2012b). In the northern regions of the country, the clayey deposits contain smectite, carbonates and some flux oxides (alkalis and alkali-earths), which impact the technological behaviour of these clays. Tsozue *et al.* (2017) obtained good technological properties (bulk density 1.8 g cm^{-3}, linear shrinkage <5%, flexural strength >5 MPa, water absorption <13%) of fired products (at 1000°C) from clayey materials of the Maroua area. In the coastal or littoral region of the country, the sedimentary clayey materials observed are essentially kaolinitic with minor quartz, illite and iron oxides, associated with minor carbonate and pyrite impurities (Ngon Ngon *et al.*, 2012b; Kankao *et al.*, 2022). The properties of derived ceramic products from these clays vary with the sintering temperature (Elimbi *et al.* 2014). In the Bomkoul area of Douala, where red and grey clay facies are observed, the relatively large amount of alkaline oxides favours clay maturation at lower temperatures (Elimbi & Njoupouo, 2002; Elimbi *et al.*, 2014). The mottled red clay facies is mainly used to produce floor and wall tiles, and despite its admixture with low-grade clay, the resulting ceramic quality is satisfactory (Elimbi *et al.*, 2014).

The first studies on the assessment of clayey materials for fired products in the littoral region of Cameroon were performed by the French Bureau de Recherche Géologique et Minière (BRGM) in 1980 as part of the project 'Study and Mining Prospection of South-West Cameroon' (Thibaut & Le Berre, 1985). The most important clay deposits in terms of quality and reserves were discovered at Mbanga, kilometric point 7.5 and 17 (PK7.5 and PK17), and at Koungue and Dizangue between Douala and Edea (Fig. 1). Except for the PK17 deposit at Bomkoul, the thickness of the sand cover (5 to >30 m) was the limiting factor for performing more detailed studies. In the framework of setting up an earth brick industry in Douala in 1982, the PK17 clayey deposit was quantitatively estimated to have ~1,000,000 m^3 of clayey material, with a possibility of supplying a unit using 30,000 m^3 of clayey material per year for a period of 30 years (Thibaut & Le Berre, 1985).

Some studies have also examined the use of these clayey materials as raw materials for ceramics (Thibaut & Le Berre, 1985; Ngon Ngon *et al.*, 2012a; Elimbi *et al.*, 2014). According to Thibaut & Le Berre (1985), Bomkoul's clayey materials have good extrusion properties and high flexural strength for unfired bricks. They could be exploited for the manufacture of clay bricks after firing at 900–1000°C, or for the manufacture of ceramic tiles after firing at 1200°C. The first geological studies of the Bomkoul clayey material (Ngon Ngon *et al.*, 2012a) demonstrated the presence of heterogeneous clayey materials on hills (80–120 m altitude) with variable colours (grey, dark-grey and mottled). The clayey deposits are thick at the upper slope and thin at the middle and lower slopes. Their textures vary from sandy-clay, clayey-silt and silty-clay to clay, and they demonstrated good potential for pottery and the manufacture of bricks, ceramic roofing tiles, wall tiles and floor stoneware tiles (Ngon Ngon *et al.*, 2012a). Previously, Elimbi & Njopwouo (2002) had suggested that the two facies of Bomkoul's clays have good firing characteristics. In addition, Elimbi *et al.* (2014) showed that adding at least 15% alkaline feldspar as a flux to the mottled red clay facies produced materials with good properties for terracotta when fired at temperatures between 1050°C and 1100°C. Addition of 25% fluxes and with a firing temperature of ~1200°C yielded ceramic products with low water absorption (0.25–0.70%). The addition of the grey clay facies (10–50%) or alkaline feldspars to the red clay facies produced a fluxing effect on compact ceramics at lower firing temperatures (Elimbi *et al.*, 2014).

A ceramics factory was established in 1975 in the northern suburbs of Douala in Bonendalé by the Industrial Ceramics Company of Cameroon (former CERICAM), and part of its clayey raw material came from the PK17 site in Bomkoul. However, the CERICAM quarry (at the Bomkoul site) is currently occupied by residential houses and other infrastructure, which makes industrial exploitation difficult and costly. A geological survey at this reference site helped to identify and map the areas that could be exploited for the industrial production of clay bricks. Instead of the physicochemical and mineralogical traits presented in Ngon Ngon *et al.* (2012a), this work examines the geological and geotechnical features obtained from these raw materials found around the old CERICAM quarry. It also presents an estimation of the reserves of clayey materials available, the various formulations and the ideal firing temperatures for obtaining fired bricks with good properties for building products.

Materials and methods

Geological and geotechnical survey

The study area is located at Bomkoul at PK17 in the Douala 3rd subdivision (Cameroon, Central Africa; Figs 1 & 2). Geologically, it belongs to the Douala sub-basin, which is part of the large coastal sedimentary basin of Douala–Kribi–Campo (Regnoult, 1986; Nguene *et al.*, 1992; SNH/UD, 2005; Ngon Ngon *et al.*, 2012a; Sobdjou *et al.*, 2023). Seven major formations constitute the lithostratigraphy of the Douala sub-basin (Fig. 3a). Bomkoul's sedimentary materials belong to the Matanda–Wouri formation of Upper Tertiary–Miocene–Pliocene age (SNH/UD, 2005; Ngon Ngon *et al.*, 2012a). The Matanda Formation is dominated by deltaic facies interstratified with volcanoclastic layers. The Wouri formation consists of gravels and sandy deposits with kaolinitic clayey materials (Regnoult, 1986; SNH/UD, 2005; Ngon Ngon *et al.*, 2012a; Sobdjou *et al.*, 2023).

A geological survey using a hand auger (S1–S10) at ~4 km from the former CERICAM Bomkoul clay extraction site (former CERICAM quarry) helped to identify a suitable clayey site for a detailed estimation of the reserve (Fig. 2 & Table S1). Three pits (P1–P3) ~10 m deep were dug and descriptions of the outcrop profiles were made. To better estimate the vertical coverage of the *in situ* materials, two mechanical boreholes (SPT1 and SPT2) up to 30 m deep were drilled as part of a geotechnical survey (G0), conducted by the National Civil Engineering Laboratory (Labogenie), in accordance with the classification of geotechnical tasks (Eurocodes 7 Part 2 (EN 1997-2)) on the 'Recognition of Land and Trials'. This survey helped to define the different formations, their nature, the *in situ* soil characteristics and the different groundwater levels. The reconnaissance was conducted using a 100 mm rotary drilling auger (Sedidrill 400) to 30 m deep so as to perform mechanical borehole activity at 1.5 m intervals (ASTM D 1586-99). The boreholes also enabled the collection of undisturbed samples of loose soil in Shelby tubes for identification. Boreholes S7 and S8 are towards the eastern limit of the deposit (Fig. 2), borehole

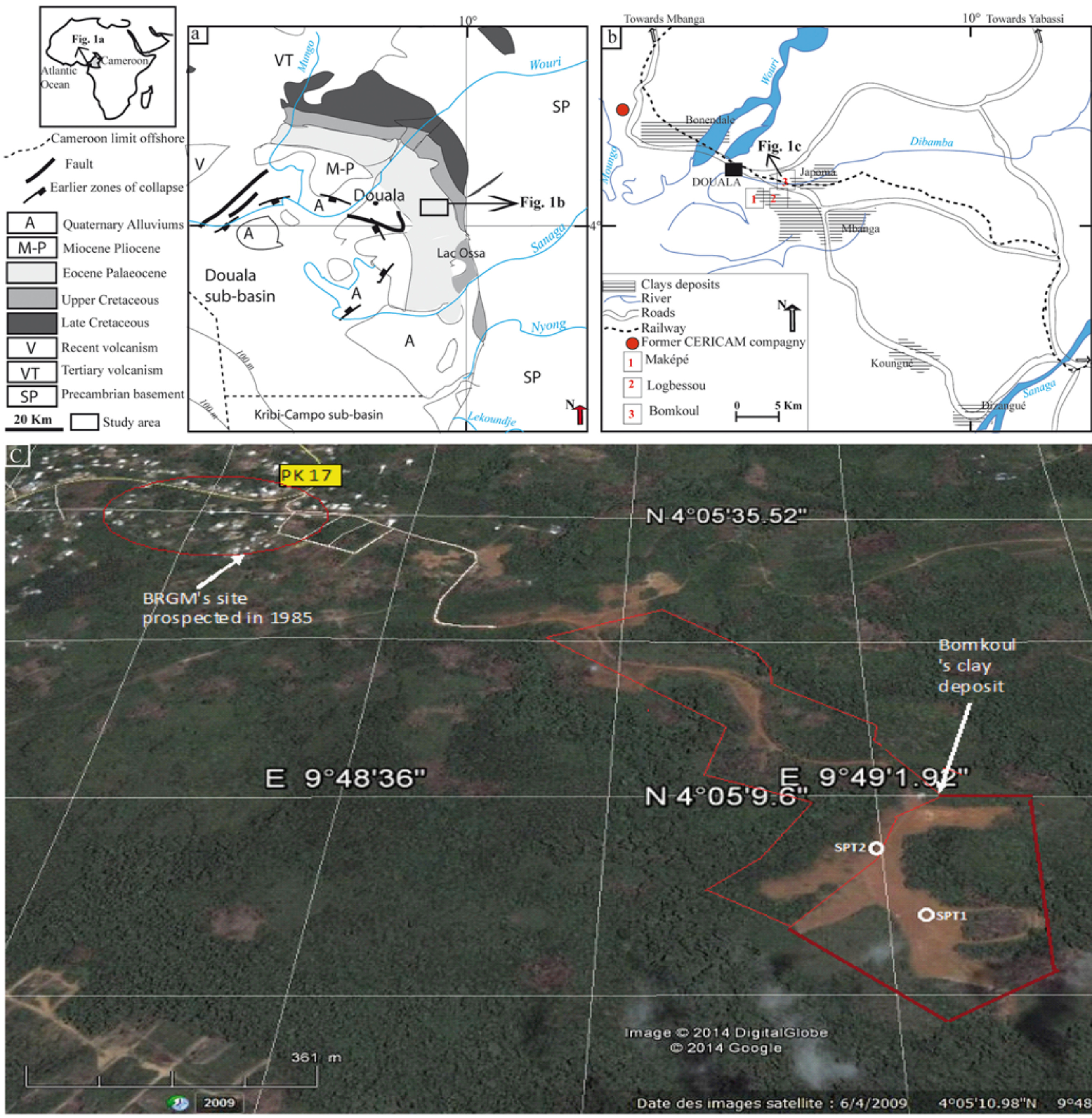

Figure 1. (a) Geological sketch map of the Douala sub-basin (SNH/UD, 2005; after Ngon Ngon *et al.*, 2012a). (b) Potential areas of clayey deposits in the Douala sub-basin (Thibault & Le Berre, 1985). (c) General view of Bomkoul's clayey deposits (Google Maps).

S1 is located in the old CERICAM quarry, and boreholes S2, S3 and S4 are towards the north-western limit on a different outcrop (a neighbouring hill) of the main site. Pit P3 and borehole S5 lie on the crest, at the centre of the main site. Pit P1 and boreholes S9 and S10 are located on the sides of the main site, enabling better estimation of the thickness of the exploitable clayey layer. Pit P2 was dug at the north-east of the deposit beyond the pathway.

The surveys carried out determined the following succession of formations from top to bottom (Table S1):

- A lateritic breastplate layer, compact and clayey at the base, 0–1.5 m thick
- A mottled red/yellow-grey clay, layered and laminated, fine in texture with nodules, thickness varying from 0.9 to 4.0 m
- A blackish-grey clay with laminated structure, fine and very compact, plastic and fairly homogeneous, with fossils, thickness varying from 3.5 to 14.5 m
- A sandy layer with various characteristics, thickness varying from 12.5 to 30 m

Two major facies characterize the Bomkoul clayey deposit: the mottled red/yellow-grey and the blackish-grey facies, in accordance with Ngon Ngon *et al.* (2012a) and Elimbi *et al.* (2014). However, Ngon Ngon *et al.* (2012a) in their study considered

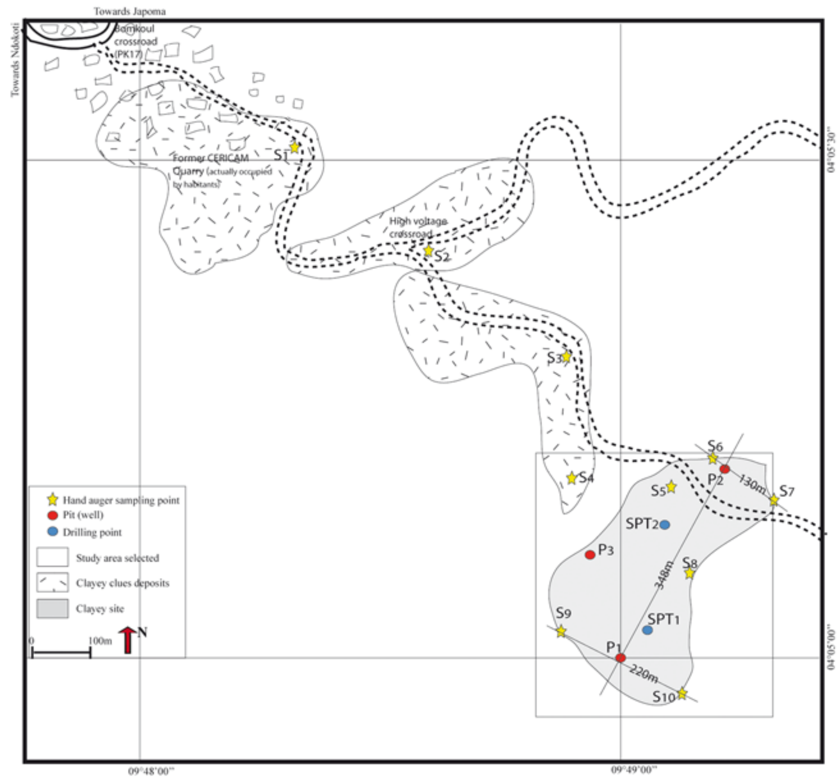

Figure 2. Sampling points and drilling positions (SPT1 and SPT2) at the new clayey site at Bomkoul.

there to be three clayey facies: mottled, grey and dark grey. The dark grey and grey clays probably correspond to the blackish-grey ones observed in this study, whereas the mottled clay corresponds to the mottled red/yellow-grey facies. Following the description terminologies of Miall (1990) and Walker (2006), the main sedimentary structures observed on the clayey layers are laminations. The collected sample tubes were sealed with wax and protected before being sent to the laboratory. Approximately 2–3 kg of samples were collected for analysis, which consisted of granulometric tests (NF P 94 041), moisture content tests (NF P 050), Atterberg limit tests (NF P 94 051), apparent density tests (NF P 94 053), specific density tests (NF P 94 054) and shear stress tests (NF P 94 071-1).

Bomkoul's clayey deposit: site topography, description and reserve estimation

The city of Douala is located in the sedimentary basin made up of Neogene ((Miocene–Pliocene) and Lower Quaternary deposits. Due to the very humid and hot climate, weathering is deep, and morphological differentiations are quite similar from one sector to another. The Cretaceous outcrops have yielded either friable, fine to coarse sandstones with intercalations of kaolinitic sandstones (calcareous or marly), which, after weathering, present sandy, sandy-clayey or clayish-sandy yellow or mottled surface textures (Ngon Ngon *et al.*, 2012a; Kankao *et al.*, 2022; Sobdjou *et al.*, 2023). Bomkoul's clayey deposit is bare and, for the most part, devoid of original vegetation. The site had been quarried for its laterite cover, thus leaving the underlying clayey layer nearly exposed. The altitude of the deposit varies between +26.00 and +20.00 m relative to mean sea level. The clayey site is a half-dome with its slope proceeding westward, consisting of a north–south-orientated main block (348 m long and 130–220 m wide), with an extension to another block at the north-west. Both blocks constitute an elongated low dome, with relative altitudes ranging from ~6 to 32 m (GPS data; Fig. 1c) above sea level.

The area of the deposit is ~6 ha. Following the morphology of the site, the spacing between pits and boreholes is ~200 m. Figure 2 shows the sampling points and drilling positions, and Fig. 3 presents a schematic cross-section of various profiles and their description. In general, field observations align with the literature data and the findings of the general geological study. The clayey materials observed in the field are shales altered that alter beyond a depth of 1 m, and they seem to belong to the Tertiary shale series of Douala's basin (Ngon Ngon *et al.*, 2012a; Sobdjou *et al.*, 2023). The clayey layers are generally covered by nodular breastplates that are argillaceous to varying degrees and ~1 m thick; these are lateritic layers that can be assessed for roadwork potential.

The subsoil of the Bomkoul clayey site therefore has a geological structure that can be described as globally homogeneous, with local inhomogeneity both on the surface and at depth. The profiles correlate very well. The average thickness of the mottled reddish/yellow-grey and black-greyish plastic clays of boreholes SPT1 and SPT2 is ~3.25 and 10 m, respectively. No other pits were deep enough to reach the bottom of the lower blackish (greyish) layer. However, the fairly good correlation between the SPT1 and SPT2 pits and boreholes enables confident extrapolation from the complete profiles of the latter. With the SPT1 and SPT2 mechanical drilling data, the thickness of the exploitable layer varied from 2.0 to 2.5 m for facies 'A' and from 8.5 to 11.5 m for facies 'B' (Fig. 3b). Following field observations and considering a minimum exploitable clayey material thickness of 2 m for facies 'A' and 8.5 m for facies 'B', for the average 6 ha of the Bomkoul clayey site the following minimum reserves were estimated: 120 000 m^3 from facies 'A' and 510 000 m^3 from facies 'B' (Table 1). Considering an average

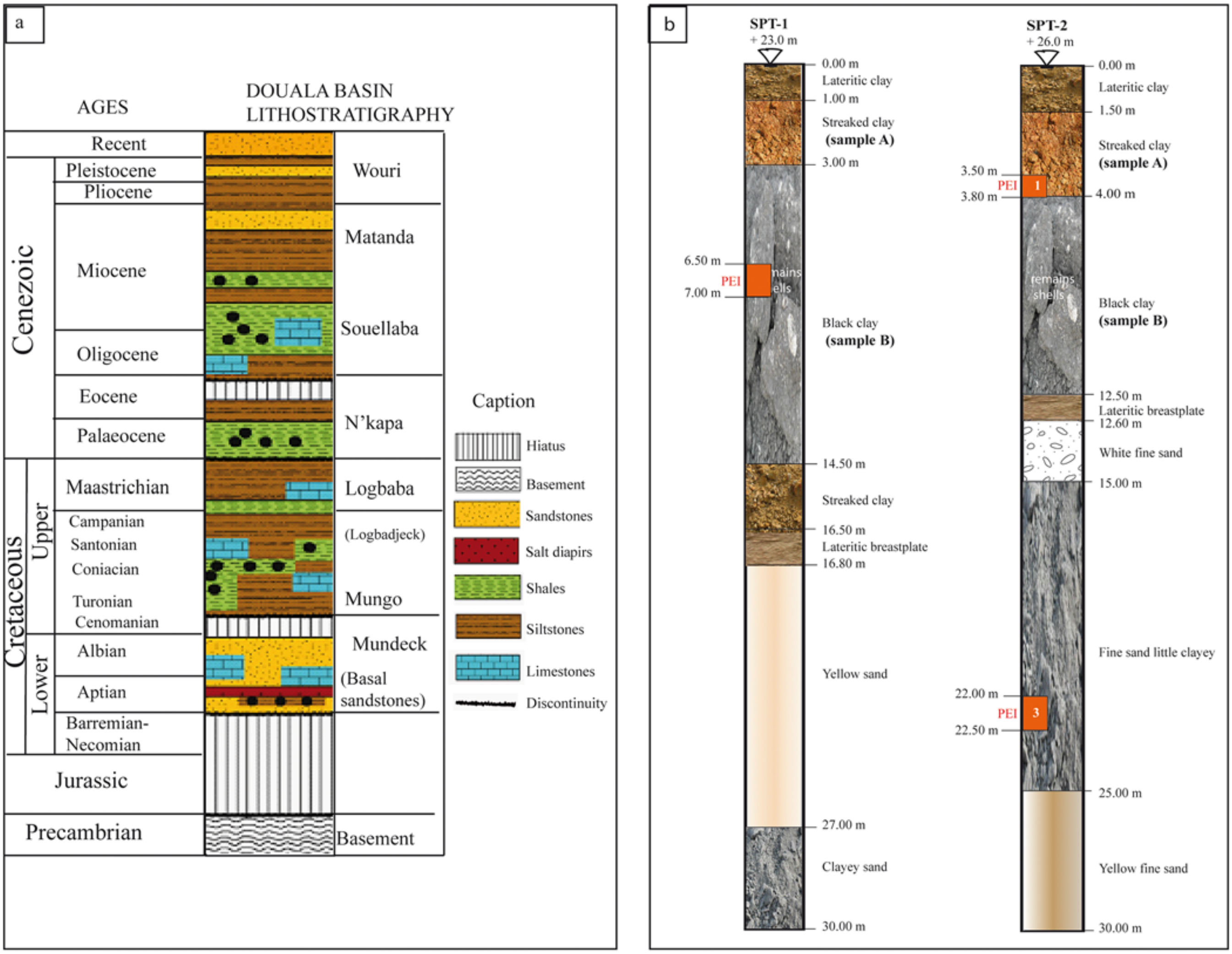

Figure 3. (a) Stratigraphic column of the Douala basin (from Sobdjou *et al.*, 2023). (b) Drilling log of Bomkoul's clayey materials (PEI = non perturbated sample; A and B are two major layers observed in the site and used for technological tests).

Table 1. Reserve estimation of Bomkoul's clayey materials.

	Thickness (m)	Average density[a] (tons m^{-3})	Average area (m^2)	Volume (m^3)	Deposit (tons)	Exploitation (tons $year^{-1}$)	Clay extraction time (years)
Facies 'A'	2.0	1.6	60,000	120,000	192,000	50,000	3.8
	2.5			150,000	240,000		4.8
Facies 'B'	8.5			510,000	816,000		16.3
	11.5			690,000	1,104,000		22.1

[a]The density of clayey material was considered to be 1.6 tons m^{-3}; facies 'A' and facies 'B' have densities of 1.6 and 1.7 tons m^{-3}, respectively.

of 1.60 tons m^{-3} of materials, the reserves are 192 000 tons of clayey materials from facies 'A' and 816 000 tons of clayey materials from facies 'B'. Considering a consumption rate of 50 000 tons $year^{-1}$, this deposit could operate for more than 4 years for facies 'A' and for more than 16 years for facies 'B' (Table 1).

Raw materials and brick-making preparation

Preparation of fired bricks with Bomkoul's clayey materials was carried out using the two major facies observed: the mottled reddish/yellow-grey facies (~5 m thick), denoted as sample 'A', and the blackish-grey facies (more than 10 m thick), denoted as sample 'B' (Fig. S1).

Mineralogical and chemical analyses

X-ray diffraction (XRD) analysis was carried out with a Bruker Advance D8 ECO diffractometer (Cu-$K\alpha_1$ radiation, $\lambda = 15{,}418$ Å, 40 kV, 30 mA) at the Argiles, Géochimie et Environnements sédimentaires (AGEs) laboratory (University of Liège, Belgium). Sample preparation followed the methodology of Moore & Reynolds (1989). After grinding (<80 µm), a small sample was placed on a sample holder by front-loading to reduce preferential orientation. The <2 μm fraction was separated by settling in a water column; the samples were mounted as orientated aggregates on glass slides, and three XRD traces were recorded for each sample: air-dried, glycolated (24 h) and heated (500°C for 4 h). The measurements were carried out in the 2θ range from 2° to 70°, with a step size of 0.02° and a time per step of 2 s. Mineral-phase identification and quantification were performed using Bruker® *Eva* and *Topas* software. The Rietveld refinement method, implemented in *Topas* software (Fig. S2), was applied to all of the mineral phases identified by XRD. The methodology, including reference standards and instrumental limitations, is according to Fagel (2024) and Fagel *et al.* (2024). Fourier-transform infrared (FTIR) spectroscopy was used to complement the XRD results. The FTIR spectra were recorded with a resolution of 4 cm^{-1} between 4000 and 400 cm^{-1} using a Bruker Nicolet Nexus apparatus at the Analytical Chemistry Laboratory in the University of Yaoundé I (Cameroon). The powdered samples were diluted in 180 mg of KBr and pressed to form pellets. The spectrum of each pellet was recorded by acquiring 200 scans at 1 cm^{-1}. Simultaneous thermal analysis was performed using a thermogravimetry and differential scanning calorimetry (TG-DSC) instrument (SETARAM) with a heating rate of 5°C min^{-1} from ambient temperature to 1200°C at the AGEs laboratory.

Chemical analyses were performed using X-ray fluorescence (XRF) spectroscopy with a Bruker S4 PIONIER XRF spectrometer on the <250 μm fraction of the samples. Powder pellets with a diameter of 34 mm and a thickness of 2.5 mm were compacted at 200 kN cold strength.

Brick preparation

Two mixtures (M1 and M2) were prepared for firing tests. M1 is a mixture of 40% facies 'A' and 60% facies 'B', and M2 contains 60% facies 'A' and 40% facies 'B'. Before mixing, samples were dried and then ground in a mortar to pass through a 1 mm sieve. Then, 12% water was added to obtain a paste with the desired consistency. After homogenization, specimens with dimensions 8 × 4 × 2 mm were prepared using a hydraulic press (10 tons). Thereafter, specimens were dried at room temperature for a few days, and then in an oven (105°C) for 24 h. Subsequently, samples were fired at 900°C, 950°C, 1000°C, 1050°C and 1100°C, with a heating rate of 5°C min^{-1} and a dwell time of 2 h at the maximum temperature. The colour, sonority, linear shrinkage, bending strength and water absorption were determined according to the NC 25-2010 standard. The sonority was assessed by knocking on the fired specimens with a metal rod or a metallic object.

Results and discussion

Bomkoul's clayey deposit: major characteristics for fired brick evaluation

Mineralogy and chemistry

Figure 4a shows the bulk XRD traces of samples A and B, and Table 2 lists their chemical compositions. The main minerals present were quartz (47% and 49%) and kaolinite (35% and 49%) for A and B samples, respectively, followed by illite (11% and 1%), muscovite (1.3% and 0.6%) and anatase (3.0% and 0.5%). K-feldspar (~2% microcline, 1.3% orthoclase and 0.4% sanidine) was detected only in facies 'A'. In the less than 2 μm fraction (Fig. 4b,c), no swelling minerals were observed in either sample. Illite and kaolinite were confirmed as the main clay minerals, with main peaks at 9.87 and 7.15 Å, respectively. The chemical composition matched the quantitative mineralogical data. The 48% of quartz content and 35–49% kaolinite content explain the SiO_2 and Al_2O_3 contents (Table 2). The small amounts of Fe_2O_3, alkali and alkali-earth oxides observed in both facies (Table 2) are in line with the mineralogical composition. These results contradict those of Ngon Ngon *et al.* (2012a), who also identified smectite (17%), goethite (8%), calcite (7%), ilmenite (5%), pyrite (4%), gibbsite (4%), chlorite (4%) and hematite (3%). This difference is ascribed to site heterogeneity and differences in sampling locations, as the present study was conducted away from the old CERICAM quarry area (Fig. 1c), which was the study area of Ngon Ngon *et al.* (2012a). Bomkoul's clayey materials are more kaolinitic and reflect the kaolinitic clayey materials from the Wouri formation mentioned by Regnoult (1986). The environmental conditions of the Douala sub-basin indicate multiple sedimentary formations, which may influence the mineralogical content of these clayey materials depending on their location.

The FTIR spectra (Fig. 5) are in accord with the XRD results. Samples A and B exhibited the stretching vibrations of structural OH groups of kaolinite at 3691 and 3620 cm^{-1} and the bending modes at 907 cm^{-1} (Saikia & Parthasarathy, 2010). The band at 1633 cm^{-1} in sample A, being absent in sample B, corresponds to deformation of the H–O–H bonds of water molecules. The bands at 1114, 1027 and 1001 cm^{-1} correspond to Si–O–Si and asymmetric Si–O–Al vibrations (Kakali *et al.*, 2001; Tchakouté *et al.*, 2013). The bands between 3500 and 3000 cm^{-1} and at 791, 748 and 678 cm^{-1} may be attributed to the deformation of O–H, which is associated with illite.

Figure 6 shows the thermal behaviour of samples A and B. Zone 1 shows a small endothermic peak at ~40°C for sample A and at 65°C for sample B, corresponding to the release of residual water during shaping (Baran *et al.*, 2001). According to the TG curves, the mass losses associated with this transformation are not significant, being ~1.5 and 0.5 wt.% for samples A and B, respectively. A small exothermic peak is observed at ~240°C for sample A (zone 2), which is characteristic of the degradation of organic matter (Pialy *et al.*, 2008).

The second endothermic event (zone 3), which is identical for the two clays studied, is observed between 480°C and 540°C, with very marked intensity. At this temperature range (400–600°C), kaolinite and illite undergo significant structural changes. Kaolinite transforms into nearly amorphous metakaolinite. This endothermic transformation is associated with significant weight loss: ~4.5 wt.% for sample A and 4.70 wt.% for sample B. The significant weight loss observed is due to the dihydroxylation of clay minerals. The weak endothermic peak at ~573°C corresponds to the transformation of α-quartz into β-quartz (Glover, 1995). The exothermic peak of zone 4 at ~977°C, which can be observed for both of these raw clay materials, is due to the structural reorganization of the clay minerals (progressive transformation of metakaolin into mullite).

Physical properties of the clays

The two major facies observed on the clayey deposit are: (1) the mottled red/yellow-grey facies of the surface (sample A); and (2) the blackish-grey deep facies (sample B), sometimes intercalated with a thinner transition facies rich in shells and nodules. The mottled red/yellow clay facies are layered and laminated silty to sandy-clays, with a fine texture (~80% fines) and few gravels

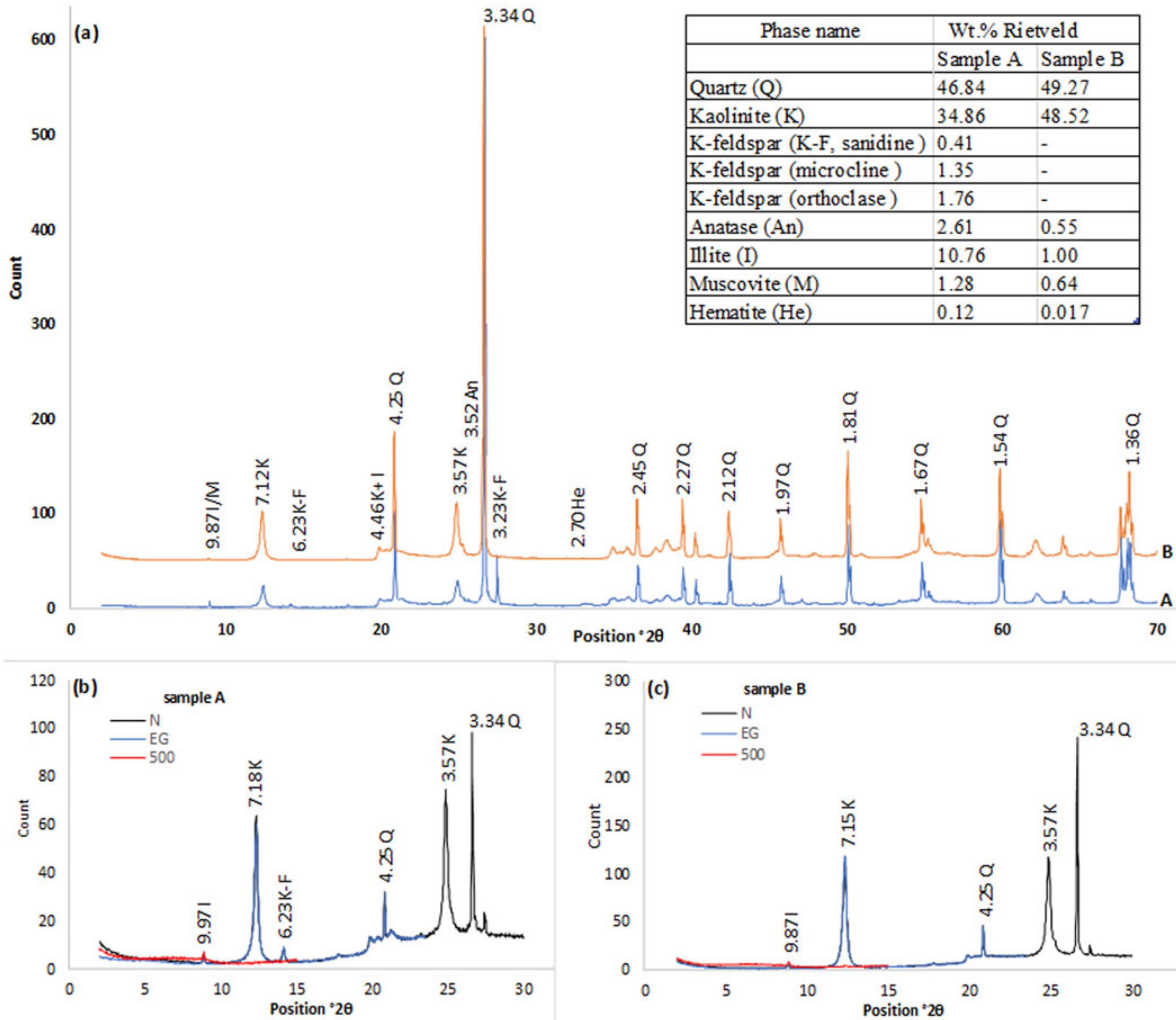

Figure 4. (a) XRD traces of the bulk samples. (b & c) XRD traces of clay fractions of Bomkoul's clayey materials. 500°C = heated samples; EG = ethylene glycol-solvated samples; N = air-dried samples.

Table 2. Major chemical composition (wt.%) of Bomkoul's clayey materials.

Colour	Facies	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total
Mottled red/yellow-grey	'A'	76.40	14.27	1.35	0.00	0.17	0.17	0.13	1.49	0.03	5.53	99.54
Grey/dark grey	'B'	71.15	13.62	2.86	0.36	0.22	0.18	0.85	1.47	0.06	8.55	99.32

LOI = loss on ignition at 1000°C for 2 h.

(~1.5%). The plasticity index (PI) of 20.4% and liquidity index of between 0 and 1 are likely to correspond to plastic materials. These facies correspond to the weathered materials with reddish-brownish spots/ferruginous nodules observed at the upper slope topography described by Ngon Ngon *et al.* (2012a). The blackish-grey facies overlain by weathered clays present a laminated structure, with a sandy-clay texture (~87% sand), a PI of 30% and a liquidity index of ~0.31, indicative of a plastic state at the sampling time. These facies correspond to the compact laminated grey or dark-grey clays with muscovite and scattered moulds of gastropods of Ngon Ngon *et al.* (2012a).

Table 3 lists the major technological characteristics of the two facies. The particle-size distribution and consistency play major roles in our understanding of the engineering properties of soils (Dondi *et al.*, 1998; Carretero *et al.*, 2002; Christidis, 2011). Consistency is significantly influenced by the amount of water present in the soil, according to its Atterberg limits. The undisturbed soil PEI-1 considered as 'sample A', taken between 3.5 and 3.8 m from the SPT2 drilling point, has a natural water content (ω) of 41.4 wt.%, whereas the water content should be, in the case of normal humid soils, equal to the plastic limit (Wp; i.e. 26.5 wt.%). The moisture and dry unit weight values were ~16 and

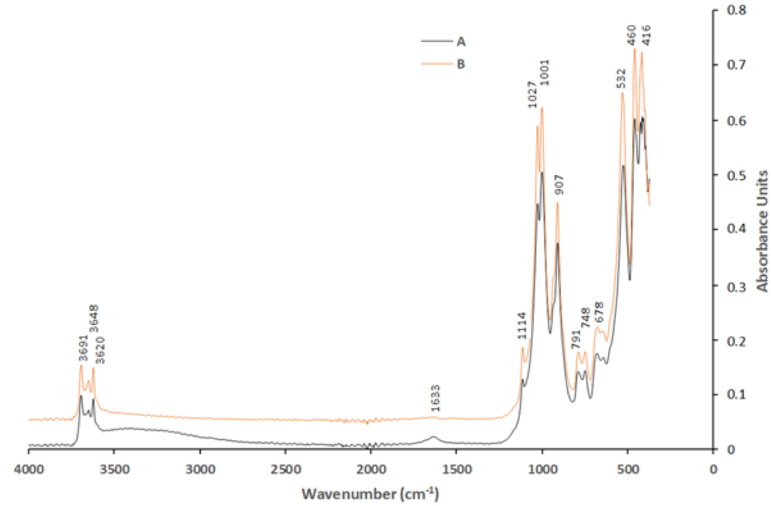

Figure 5. FTIR spectra of the studied clayey materials.

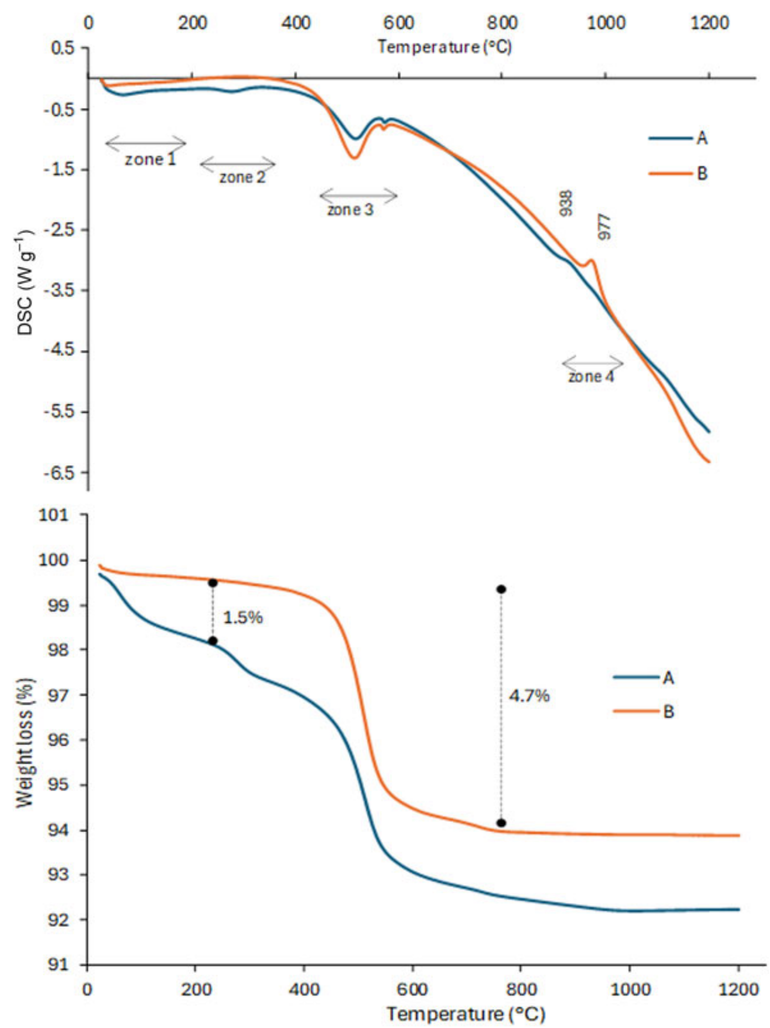

Figure 6. Simultaneous thermal analysis of the studied samples.

11 kN m^{-3}, respectively. The density here is expressed in terms of unit weight (kN m^{-3}) in the understanding that a weight is a force. It is quantifying the weight per unit volumeThe material was very hydrated at the sampling time (weight of water ~5 kN). According to the American Association of State Highway and Transportation Officials (AASHTO) classification, this soil is A-7-6 class. These are sensitive soils with high plasticity that can be very compressible and can undergo considerable volume change. The grading curve (Fig. 7a) covers a wide range of particle sizes, ranging from gravels to fines. The fine fraction (silt + clay) is ~80.5%, with the clay fraction (<2 μm) exceeding 75%. The sand and gravel fractions are 18.0 and 1.5 wt.%, respectively. Fine particles (diameter < 80 μm) were

Table 3. Geotechnical properties of Bomkoul's clayey materials.

Characteristic	Sample A (SPT-2)	Sample B (SPT-1)
Depth (m)	3.50–3.80	6.50–7.00
Nature of sample	Undisturbed	Undisturbed
Water content (%)	41.4	19.4
Volumetric weight (kN m^{-3})		
Unit weight (γ_h)	15.9	18.9
Dry unit weight (γ_d)	11.2	15.9
Specific unit weight (γ_s; tons m^{-3})	2.62	2.65
Particle size		
% passing <20 mm	100.0	100.0
<10 mm	99.3	100.0
<5 mm	98.6	100.0
<2 mm	93.4	100.0
<1 mm	91.0	97.2
<0.315 mm	89.3	70.7
<80 μm	80.6	13.5
Gravel (%)	1.40	0.00
Sand (%)	18.0	86.5
Fine (%)	80.6	13.5
Plasticity (%)		
Liquidity limit	46.9	40
Plasticity index	20.4	30
Liquidity index	0.732	0.313
Direct shear strength (unconsolidated–undrained test)		
Cohesion: Cu (kPa)	13.1	17.4
Friction angle: φ_u (°)	41.3	34.1
AASHTO classification	A–7–6(13)	A–2–4(0)
	Plastic material	Sandy material

AASHTO = American Association of State Highway and Transportation Officials.

~80%, suggesting a heavy sandy clay, which could be the cause of problems such as unsuitable agglomeration during processing (Carretero *et al.*, 2002) or of cracks appearing and excess shrinkage in firing products (Reeves *et al.*, 2006).

The undisturbed soil (PEI-2), denoted as 'sample B', which was collected 6.5–7.0 m from the SPT1 drilling point, has a natural water content (ω) of 19.4 wt.%, whereas the water content should be, in the case of normal humid soils, equal to the plastic limit (Wp; i.e. 10 wt.%). The moisture and dry unit weight values were ~19 and 16 kN m^{-3}, respectively. The material was very hydrated (weight of water ~4 kN) at the sampling time. According to the AASHTO classification, this soil is A-2-4 class. These are sandy soils that are sensitive to small variations in water content, potentially losing their cohesion in the event of an uncontrolled increase in water content. Figure 7a shows that the particle-size distribution curve of sample B did not include all of the particle-size fractions. The total of fines (<80 μm) is 13.5%, and this probably includes only the silt fraction. Some 86.5% of sample B consists of the sand fraction, which can be considered as a coarse-grained soil or as sandy material. It is a poorly/uniformly graded sample, with a high plasticity value of 30%. This high plasticity may be attributed to the presence of illite in this material (Fig. 7b), in accordance with the SiO_2/Al_2O_3 ratio, which exceeds 2, suggesting the presence of a 2:1 phyllosilicate of illite type (Tsozué *et al.*, 2017). Low-plastic (PI < 10%) or highly plastic (PI up to 35%) materials are not suitable for extrusion (Carretero *et al.*, 2002; Jeridi *et al.*, 2008; Wang *et al.*, 2023). In addition, a satisfactory grading curve is one that shows adequate proportions of each size fraction (Dondi *et al.*, 1998). Sample A, with Wp ≈ 27% and PI ≈ 21%, may be suitable for extrusion, and sample B, with Wp ≈ 10% and PI ≈ 30%, might also be acceptable (Fig. 7c). Sample A included particle sizes from gravel to clay, but the proportions of silt and sand need to be adjusted to achieve adequate texture for the extrusion process. In addition, in sample B, the proportions of silt and clay also need to be adjusted to achieve adequate texture for the extrusion process.

Sample A is a plastic material with a plastic limit of ~20 wt.% and a liquidity index of 0.7. This material needs at least 47 wt.% water before starting to behave as a liquid. At this liquid stage, the material is not consistent with there being poor cohesion between the soil particles. When the water content changed the clay from the a liquid to a plastic state, the shear strength values were 13 and 17 kPa for sample A and sample B, respectively (Fig. 8). The dynamic penetrometer test gives a continuous relative soil strength value with depth (Abdulrahman, 2015). The variation of this resistance curve with depth also confirms the heterogeneity of the site's materials. Facies 'A' is a less resistant and less cohesive material than facies 'B' (Fig. 8). The PI also confirms the lower cohesion of facies 'A' (PI = 20%) compared to facies 'B' (PI = 30%). Overall, the materials studied are of very dense consistency from 3.5 m in depth relative to material from ground level.

Assessment of fired bricks

The Fe_2O_3 and TiO_2 contents (~1–3 and 1.5 wt.% respectively) are responsible for the pink colour of the ceramic specimens after firing (Fig. S3).

The sonority of fired specimens obtained from the subsurface blackish-grey facies 'B' remained dull from 900°C to 1100°C, while that obtained with 100% of the mottled facies 'A' as well as mixtures M1 and M2 was metallic at all firing temperatures. The cohesion is very good for all of the specimens (Fig. S4). The metallic sound in general reflects maturity of the fired products, showing that chemical transformation occurs during the sintering stage (Dondi *et al.*, 2001; Nzeukou *et al.*, 2013; Wang *et al.*, 2023). The sound is produced when cohesion is high due to partial glass formation during sintering reactions, and it can be used to help assess the sintering maturity of a product (El Boudour El Idrissi *et al.*, 2018; El Ouahabi *et al.*, 2019). Facies 'A' could achieve sintering maturity at lower temperatures than facies 'B'.

On drying (at 105°C), clayey materials of facies 'A' shrink four to five times more than their counterparts from facies 'B' (Fig. 9 & Table 4). The Brick Industry Association (BIA) recommends drying shrinkage values of 2–8% for unfired bricks specimens (El Idrissi *et al.* 2022). The values obtained from the studied samples were ~4–6% for surface mottled clayey material and 1–2% for subsurface blackish-grey clayey material. The specimens from the M1 and M2 mixtures have almost the same drying shrinkage values, and, after firing, the shrinkage values are <2% at temperatures lower than 1050°C and 4% at 1100°C. The recommended values for firing shrinkage from the BIA are 2–10% for fired masonry bricks (El Idrissi *et al.*, 2022). Facies 'A' is rich in fine-grained material (80%); it is therefore more plastic than facies 'B'. This property is beneficial for hand-moulding, shaping or extrusion processes (Jeridi *et al.*, 2008; Christidis, 2011; Wang *et al.*, 2023). After firing, the facies 'A' surface clayey material exhibited greater shrinkage (3–5%) than the facies 'B' subsurface clayey material, which exhibited very low shrinkage (<1%), and it even exhibited negative shrinkage values at 900°C, 950°C and 1050°C. No cracks can be observed on fired brick specimens (Fig. S4). Inasmuch as the linear shrinkage indicates firing efficiency,

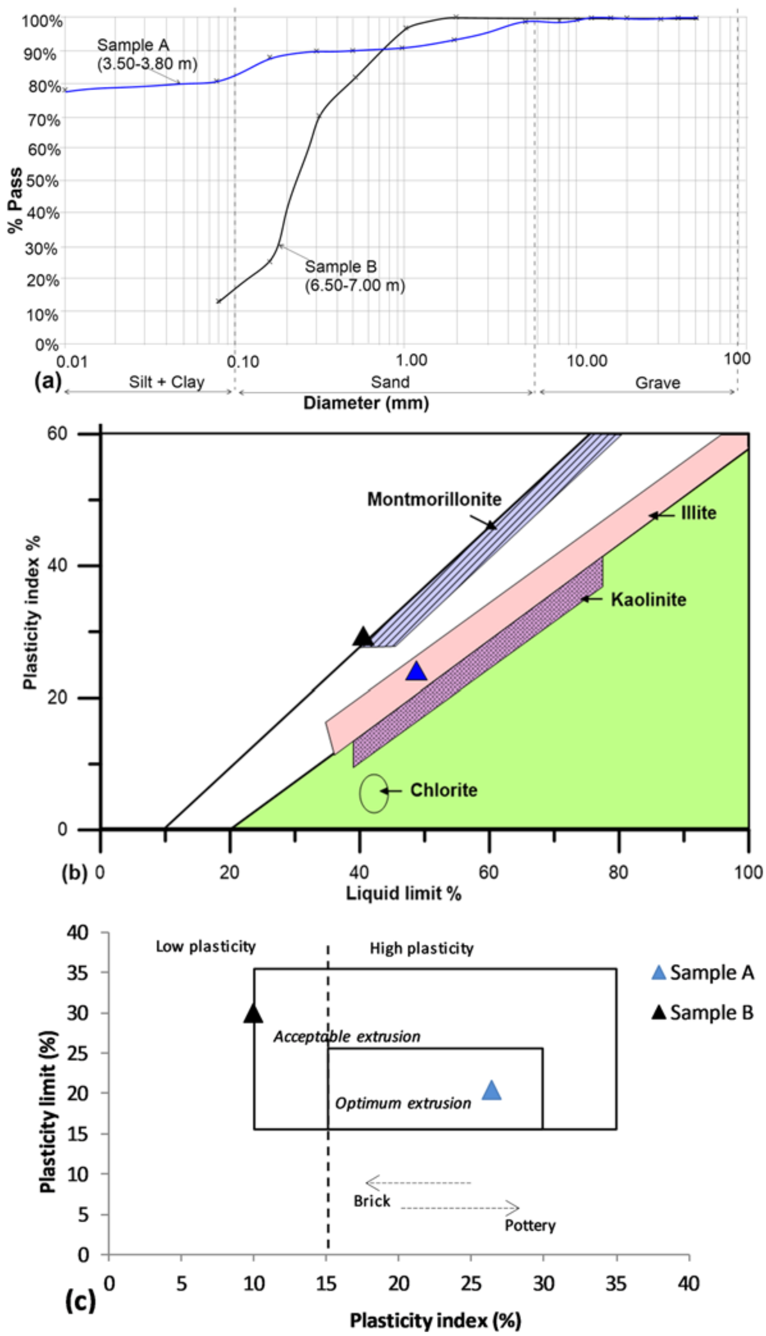

Figure 7. (a) Particle-size curves of Bomkoul's clayey materials. Projection of samples in (b) a Holtz and Kovacs diagram and (c) a Bain & Highley (1978) diagram.

the low values obtained from facies 'B' suggest it would have poor performance and strength for the production of fired bricks. This is probably due to the lack of liquid-phase formation that would improve densification reactions during sintering (Elimbi *et al.*, 2014; Arianpour & Arianpour, 2022). The kaolinite content of this sample may be responsible for its refractory character. Suitable amounts of flux mineral (K-feldspar) may improve its fusibility. The shrinkage values of facies 'A' and mixtures M1 and M2 are lower than 8%. According to Wang *et al.* (2023), bricks with firing shrinkage values of less than 8% may be considered of good quality. Furthermore, Boussen *et al.* (2016) proposed firing shrinkage values of less than 3% for good-quality fired bricks.

The flexural strength values of the fired specimens as a function of firing temperature are shown in Fig. 9. As the firing temperature increased, the flexural strength of the pieces also increased due to densification. The flexural strength varied between 0.6 and 7.2 MPa, achieving their maximum values at 1100°C. The clayey material B showed the lowest flexural strength values (<1 MPa), while the surface mottled clayey material A showed the highest flexural strength values (6–7 MPa). The flexural strength values of the M1 and M2 mixtures were 2.5–3.5 MPa, with the M2 values being slightly higher than those of M1 at 950–1100°C. This performance is probably due to the transformation reactions that take place from 950°C, with the proportion of surface mottled clayey material, which reacts at lower temperatures, being higher in M2

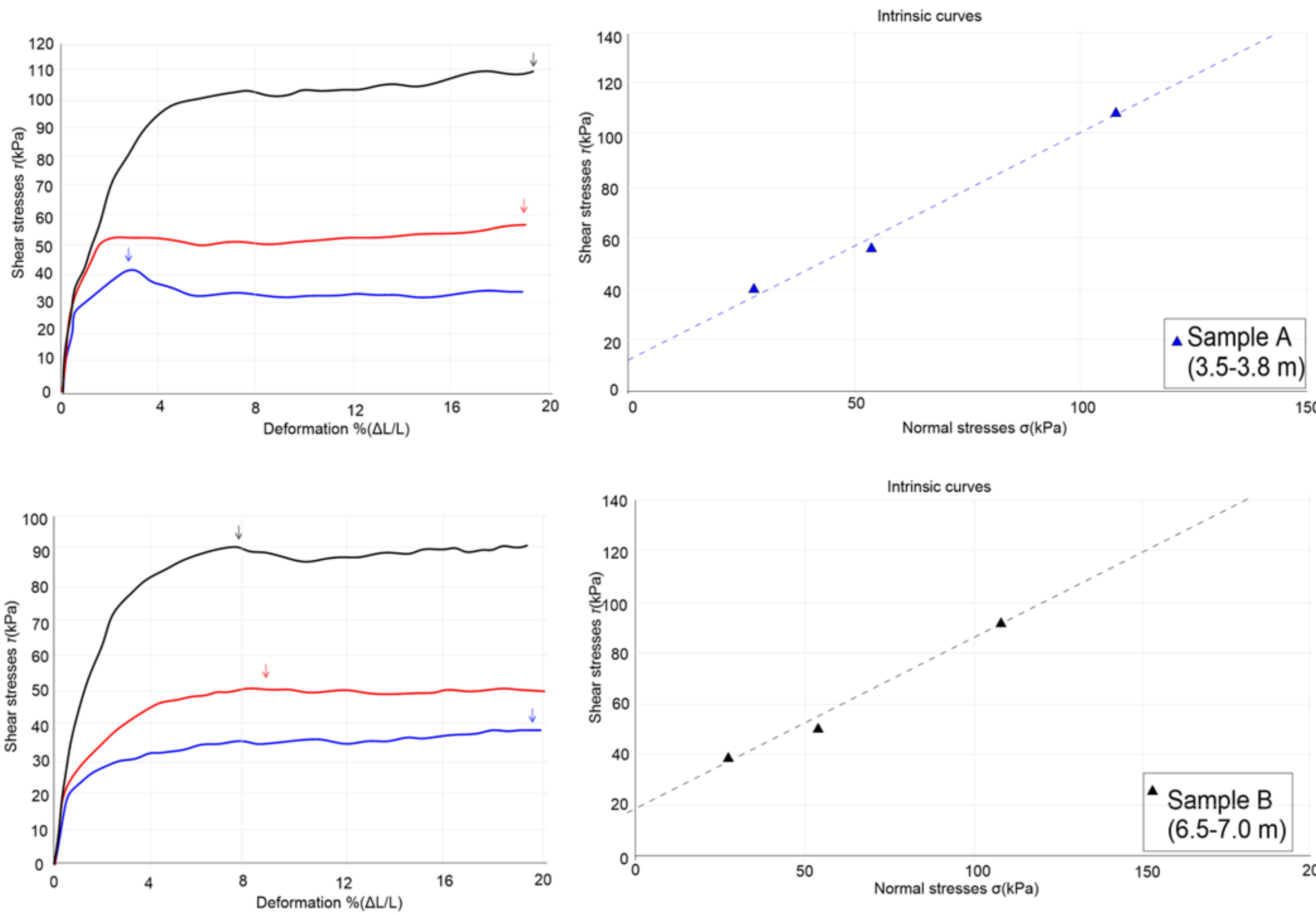

Figure 8. Shear stresses *vs* volume deformation. The left-hand graph depicts the shear stresses *vs* deformation for normal stresses of 28 kPa (blue), 58 kPa (red) and 110 kPa (black). The right-hand graph depicts the shear stresses *vs* normal stresses from which we can obtain the values of undrained cohesion (Cu) and the friction angle (ϕ).

(60%) than in M1 (40%). The presence of illite, with fluxing oxides such as K_2O, Na_2O and possibly Fe_2O_3 (Table 2), in the raw clay promoted sintering, which increased melt formation and densification of the fired products (Elimbi *et al.*, 2014; Arianpour & Arianpour, 2022; Lemougna *et al.*, 2024). Iron generally affects sintering kinetics and may increase vitrification (Andji *et al.*, 2009). The water absorption of fired specimens obtained with the surface mottled clayey material A showed a decreasing trend with increasing firing temperature for both the M1 and M2 mixtures (Fig. 9). The evolution of water absorption is related to the densification of fired products because porosity controls water absorption and affects the strength of fired bricks (Arianpour & Arianpour, 2022). Sintering of the ceramic specimens was accelerated above 900°C as the glassy phase formed. The glassy phase penetrated the open pores, closing and isolating them from neighbouring pores. This explains the significant decrease in water absorption after sintering at higher temperatures. However, from 1000°C to 1050°C, the water absorption values of specimens from facies 'A' increased from 16% to 18%, before decreasing again between 1050°C and 1100°C. For subsurface blackish-grey facies 'B', the water absorption value increased to 21% at 1000°C, before decreasing thereafter. In the temperature range from 1000°C to 1050°C, structural reorganization occurs, which may increase the porosity of firing products. Good-quality ceramic products may be obtained at 1050°C (El Idrissi *et al.*, 2022). Lower water absorption values (20–22%) were obtained with mixtures of M1 and M2 at 1000°C. Water absorption is an important parameter to consider for fired bricks, and this also depends on the target application and the weathering conditions. ASTM C62-99 recommends water absorption below 17% for bricks exposed to severe weathering. Cameroon's norm NC 23-2010 recommends a water absorption value of $<$20% for ordinary masonry and of $<$15% for foundation masonry. Water absorption may also be reduced according to the shaping method. Application of high pressure during shaping improves densification from the unfired bricks until the sintering stage. Recommended values of water absorption for building, facing and hollow bricks are given by BIA (2017). The maximum values recommended are 20%, 25% and no limit, respectively, for bricks exposed to severe, moderate and no weathering.

Conclusion

This study focuses on raw clayey material for fired bricks located in Bomkoul-PK17, Douala, Cameroon, where two main clayey facies have been observed: surface mottled reddish-brown/yellow-grey clayey material from facies 'A' and the subsurface blackish-grey clayey material from facies 'B'. Reserve estimation is at ~1,400,000 tons of clayey material, which could supply a small brick-production unit for more than 25 years.

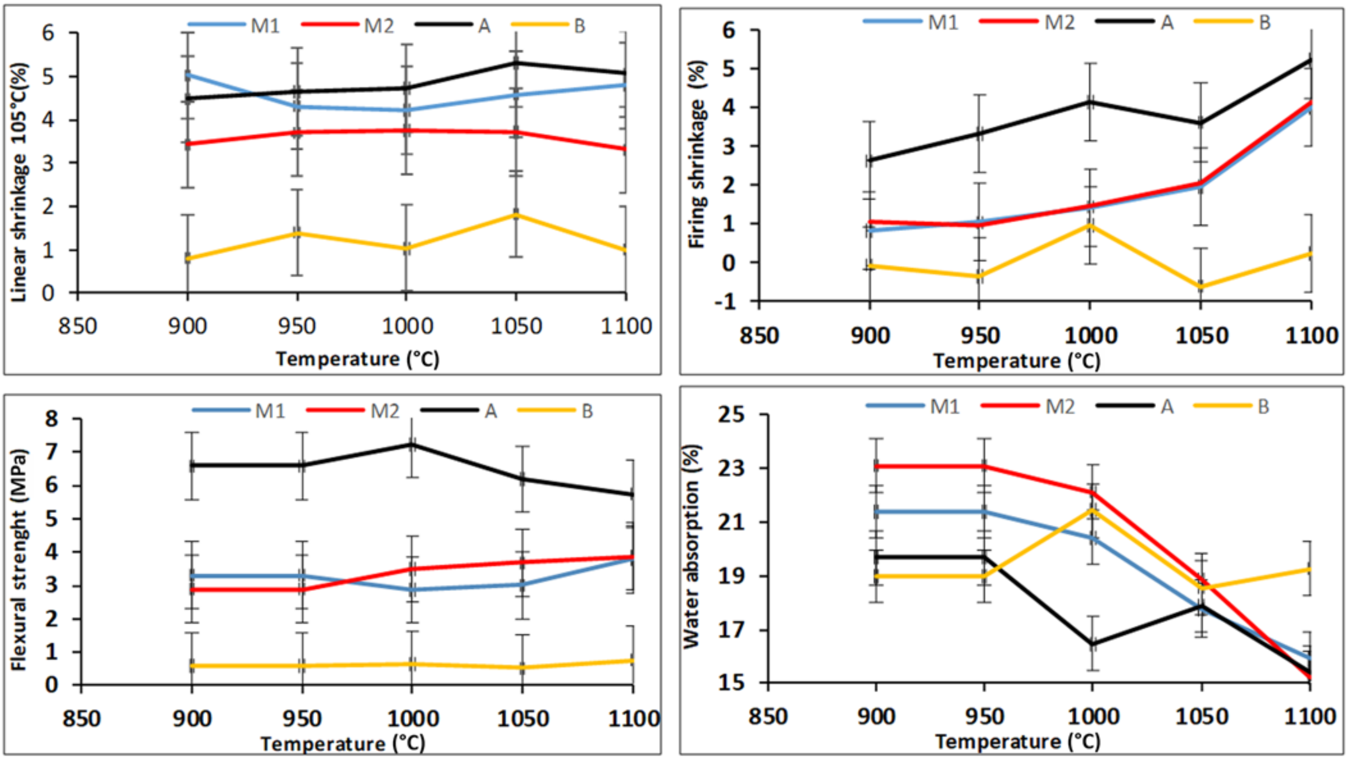

Figure 9. Evolution of various firing properties of the clayey specimens with increasing temperature.

Table 4. Technological properties of fired bricks from Bomkoul's clayey materials.

Firing temperature (°C)	Mixture sample	Linear shrinkage (%)	Colour and cohesion	Sonority	Firing shrinkage (%)	Flexural strength (N mm^{-2})	Water absorption (%)
900	M1	5.0	Pink and good	Metallic	0.8	3.3	21.3
	M2	3.4		Metallic	1.1	2.9	23.1
	100% sample A	4.4		Metallic	2.6	6.6	19.7
	100% sample B	0.8		Dull	−0.061	0.6	18.9
950	M1	4.3	Pink and good	Metallic	1.0	3.3	21.4
	M2	3.7		Metallic	0.9	2.9	23.1
	100% sample A	4.6		Metallic	3.3	6.6	19.7
	100% sample B	1.4		Dull	−0.3	0.6	18.9
1000	M1	4.2	Pink and good	Metallic	1.4	2.1	20.4
	M2	3.7		Metallic	1.5	3.5	22.1
	100% sample A	4.7		Metallic	4.1	7.2	16.5
	100% sample B	1.0		Dull	0.9	0.6	21.4
1050	M1	4.6	Pink and good	Metallic	1.9	3.0	17.7
	M2	3.7		Metallic	2.1	3.7	18.8
	100% sample A	5.3		Metallic	3.6	6.2	17.1
	100% sample B	1.8		Dull	−0.6	0.5	18.6
1100	M1	4.7	Pink and good	Metallic	4.0	3.8	15.9
	M2	3.3		Metallic	4.1	3.9	15.2
	100% sample A	5.4		Metallic	5.2	5.8	15.4
	100% sample B	1.0		Dull	0.2	0.8	19.3

The two facies are dominated by quartz (47–49%) and kaolinite (35–49%), associated with illite (1–11%). Minor K-feldspar (~3.5%) and traces of hematite (<1%) are also present in facies 'A'. Facies 'B' is richer in sand than facies 'A'. Chemical analysis agrees with the mineralogical composition, indicating the presence of SiO_2 (71–76%), Al_2O_3 (14%) and Fe_2O_3 (1–3%).

The fired products obtained from facies 'B' produced a dull sound and presented flexural strength values of <1.5 MPa, linear shrinkage values of <1% and irregular water absorption (i.e. evolving in a sawtooth pattern with temperature).

Firing products obtained from facies 'A' and mixtures obtained from facies 'A' and 'B' produced a metallic sound and presented linear shrinkage values of 1% and 6% and flexural strength values of 1.5 and 7.0 MPa). The water absorption characteristics of the mixtures are suitable for the manufacture of bricks after firing at 1050°C. At this temperature, the firing products present moderate flexural strength (2.0–3.6 MPa). The M1 mixture (40% of facies 'A' + 60% of facies 'B') represents a satisfactory mixture for the utilization of the various facies of the Bomkoul clayey deposit.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1180/clm.2025.8.

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Competing interest. The authors declare none.

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