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ORIGINAL PAPER

Assessment of Lateritic Gravelled Materials for Use in Road Pavements in Cameroon

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Abstract Early surface and structural deterioration of new pavements are becoming increasingly perceptible in Cameroon. This raises serious concerns regarding the nature, spatiotemporal evolution, and quality of materials used. Therefore, this study uses geotechnical identification, X-ray diffractometry, and statistical methods to optimize the durability of lateritic gravelled material (LGM) pavements. The CBR values within the study sites are dispersed and present low variability (coefficient of variation-CV < 15%), to high variability (CV > 35%). Three groups of LGM were distinguished at the Bamileke Plateau: firstly, LGM at the BAN site were characterized by CBR (31%). Secondly, LGM of Bamendjou 1 and Bamendjou 2 sites, characterized by CBR varying between 25 and 27%, CI between 1.3 and 1.5, gravel content among 62.7 to 64.7%, and MDD between 1.76 and 1.82 g/cm^3. Thirdly the Sekakouo and Chenye sites LGM are dominated by fines with C80µm between 38 and 44%. Swelling clay minerals are absent in these materials. It results that, these materials are suitable for use as a subgrade layer for any type of traffic, and as a sub-base for low-volume traffic T1 to T3, except those at the Sekakouo and Chenye sites. Prospecting of LGM deposits should be directed towards those with high proportions of Gm, gravel content, MDD, CI, SG, and low proportions of Pm, C80µm, C400µm, Pp, εs and C2mm.

Keywords Bamileke plateau · Lateritic gravelled materials · Californian bearing ratio · Mineralogical composition · Road construction · Subgrade · Sub-base layer

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1 Introduction

Lateritic soils are substantial and significant materials for substructures construction (Goodary et al. 2012; Taallah et al. 2014). They are highly weathered tropical soils with various amounts of particle size ranging from clay to gravel (Oyelami and Van Rooy 2016a, b). There are huge varieties of lateritic soils in relationship with the climate, parent rocks, topography, and/or time under which they have been formed. Lateritic gravelled materials (LGM) correspond to lateritic soils that contain a high amount of aluminous and/or ferruginous encrusted nodules embedded into fine silty-clay soil (Bagarre 1990; Millogo 2008; Onana et al. 2015).

The Bamileke Plateau is dominated by lateritic soils (69% of the total surface). LGM occupies about 54% of lateritic soils' total surface. Regarding petrography, the main parent rock of LGM at western Cameroon are basalts, which cover about 660 km^2, representing about 77% of the total area. In this region,

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altitudes vary from 1400 to 2045 m with slopes between 7 and 36% (Olivry 1973). LGM are generally considered as well raw materials for subgrade, sub-base, and occasionally base course (Nyemb et al. 2013; Manefouet 2016; Hyoumbi Tchungouelieu et al. 2018; Katte et al. 2018; Takala and Mbessa 2018; Keyangue Tchouata et al. 2019). The Bamileke Plateau lateritic gravelled materials (BPLGM) have plasticity indexes between 7 and 40%, maximum dry densities between 1.50 and 2.20 g/cm^3, and CBR values varying between 11 and 60% (Sikali and Mir-Emirati 1986; Nyemb et al. 2013; Manefouet 2016; Hyoumbi Tchungouelieu et al. 2018; Takala and Mbessa 2018; Keyangue Tchouata et al. 2019). They are mainly made up of gibbsite, goethite, hematite, anatase, and kaolinite (Momo Nouazi et al. 2012; Manefouet 2016; Ngueumdjo et al 2020). BPLGM may also contain ilmenite, illite; florencite; montmorillonite; plagioclase, and quartz (Hyoumbi Tchungouelieu et al. 2018); vermiculite, smectite, halloysite, and phlogopite (Tematio et al. 2017).

Few works exist regarding the causes of early structural and superficial degradations of LGM pavements. Generally, the African road network and especially that of Cameroon is subjected to rapid deterioration (Combere 2008; Diop et al. 2015; Onana et al. 2015; Issiakou Souley 2016; Kanda Sandjong et al. 2020). Previews studies attempting to explain the causes of this early degradation of road pavements can be classified into two groups. According to the first authors, early degradation of road pavements may be attributed to the unstable behavior of LGM linked to their mineralogical composition diversity, and also their character as an evolving residual material (Issiakou Souley 2016). While the second author concluded that the under-dimensioning of the pavement structure could be responsible for that early degradation (Combere 2008; Onana et al. 2015).

Moreover, the CBR and traffic are considered as the key parameters used to design pavement structures in tropical areas (CEBTP 1984). The CBR is the most useful geotechnical parameter for the dimensioning of flexible pavements in tropical countries. Low CBR implies thicker pavement and inversely. However, variations in the nature and intensity of most pedogenetic processes result in heterogeneities and discontinuities of the soil cover (Tabbagh et al. 2000). Thus, this heterogeneity, both vertical and lateral, may have an impact on the determination of geotechnical parameters and also CBR. The character of residual evolving materials of LGM is also influenced by the presence of swelling minerals. In this case, it has been found out that the LGM behavior on the field is different from that determined by conventional geotechnical tests (Tockol 1994; Millogo 2008; Onana et al. 2015; Issiakou Souley 2016). Therefore, the objective of this study is to optimize the durability of LGM pavements using geotechnical identification, X-ray diffractometry, and statistical methods.

2 Study Area Setting

The Bamileke Plateau, in which this study was conducted, extends between longitude 09° 44’ to10° 33’ E and latitude 04° 10’ to 05° 56’ N in the Cameroon western Highlands. More especially, on an experimental area of about 354 km^2, located on the northern flank of Mount Bangou, between parallels 05° 18’ to 5° 45’ N and meridians 09° 56’ to 10° 20’ E (Fig. 1).

The climate of the Bamileke Plateau is sub-equatorial, characterized by high altitudes, with annual average rainfall varying between 1600 and 2000 mm; and annual average temperature fluctuating between 18 and 20 °C (Momo Nouazi et al. 2016).

Geomorphologically, the Bamileke Plateau is a vast monotonous region of plus or minus elongated, low-lying croups modeled in the volcanic cover. It is mostly covered by an old weathered and cuirassed basaltic mantle (Tematio 2004). The main morphological feature of the study area is Mount Bangou, culminating at an altitude of 1,924 m at the top of a residual lava butte. It was formed during the Eocene (ages 40 K–40 Ar from 44.7 to 43.1 ± 1 Ma). It is the oldest dated volcano in the Cameroon Line. In this region, the basements are made up of granitoid and gneisses, probably of the Pan-African age (Fosso et al. 2005). The volcanic rocks consist of aphyric basalts, tuffs, sub-aphyric basalts, porphyritic basalts, rhyolites, quartz-trachyte, rhyolites with aegirine plus or minus arfvedsonite (Fosso et al. 2005; Kuepouo et al. 2006; Nono et al. 2009; Kwékam et al. 2010). Basalts are known to be the main parent rock of BPLGM. These basalts cover almost three-quarters of this plateau with minerals such as olivine, plagioclase, pyroxene, and opaque minerals (Nono et al. 2009). However, in almost all lavas, xenoliths and xenocrysts of quartz from the Pan-African

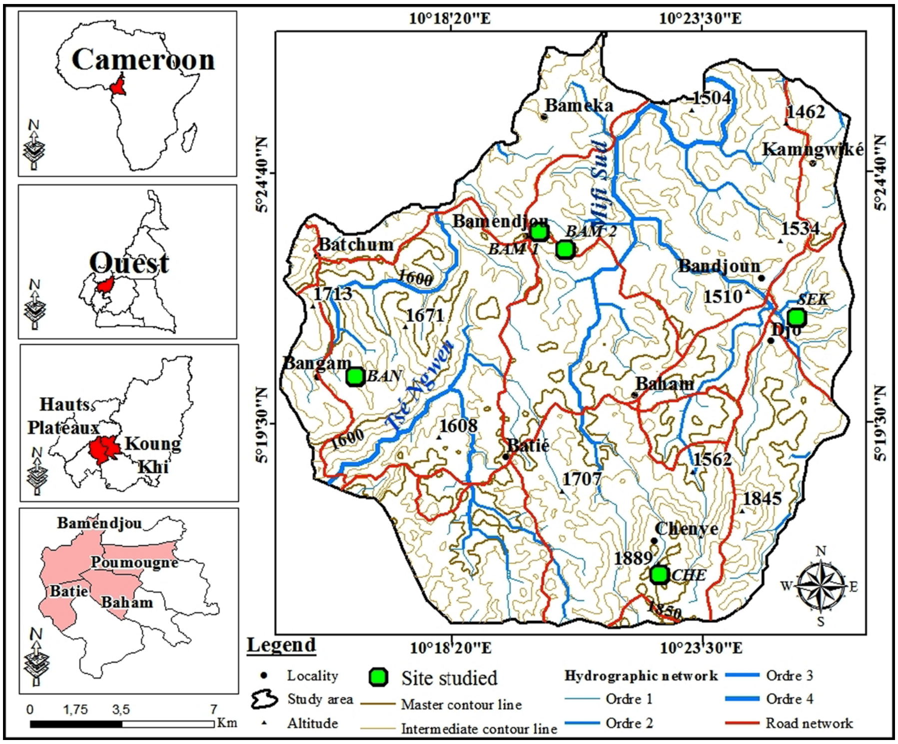

Fig. 1 Location map. *SEK* Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou 1 site, *BAM2* Bamendjou 2 site, *BAN* Bangam site

Granito-gneissic basement are present (up to 1% of the modal composition) as observed by Fosso et al. (2005).

The LGM sites studied are mainly located on the upper part of the conical interfluves, also on very steep slopes and at the break of slopes. They are distributed between the *Kong-khi* and *Hauts plateaux* departments. The following sites: Sekakouo, Chenye, Bamendjou 1, Bamendjou 2, and Bangam are located at 1685 m; 1873 m; 1648 m; 1638 m, and 1668 m of altitude, respectively. Their surface areas are 143,509 m^2; 51,786 m^2; 157,462 m^2; 16,126 m^2 and 78,519 m^2, respectively. The study area is occupied by red or red-brown ferrallitic soils, developed on the basement rocks and plateau basalts (Segalen 1967). However, hydromorphic soils are found in lowlands (Olivry 1973). The soil profiles are composed of an organo-mineral horizon (HA), a thick gravelled mineral horizon, and a clay mineral horizon (HB), structured in successive strata. Nevertheless, the HA is absent in some places. The proportion of nodules predominates in the upper part of the gravelly mineral horizon and decreases gradually to its base. The soil profile types are: organo-mineral-A horizon/mineral-B horizon/alteration-C horizon (A/B/C), organo-mineral-A horizon/structural mineral-B horizon/alteration-C horizon (A/(B)/C) and organo-mineral-B horizon/alteration-C horizon (B/C).

3 Methods of Study

Disturbed LGM samples were taken at several points of the study area. Twenty (20) manual pits with an average depth of 6 m, were excavated. The locations of these pits were chosen based on the topo-sequential method. Only one disturbed sample was collected from each pit, along the gravelled mineral horizon. Twenty (20) disturbed LGM samples of approximately 70 kg each, were packaged in polyethylene bags for laboratory analyses (Fig. 2).

The mineralogical analyses were carried out at the *Argiles, géochimie et environnements sédimentaires* laboratory (AGES) in Belgium. The LGM mineralogy was determined by powder X-ray diffraction using a Brucker D8 Advance diffractometer, using monochromatic CuKα1 radiation with 26 ranges from 2° to 70° in 0.020° steps operating at 40 kV and 25 mA using Cu–Kα1 radiation (I = 1.5406 Ä). Mineral proportions were determined using the Match 3 software 2020.

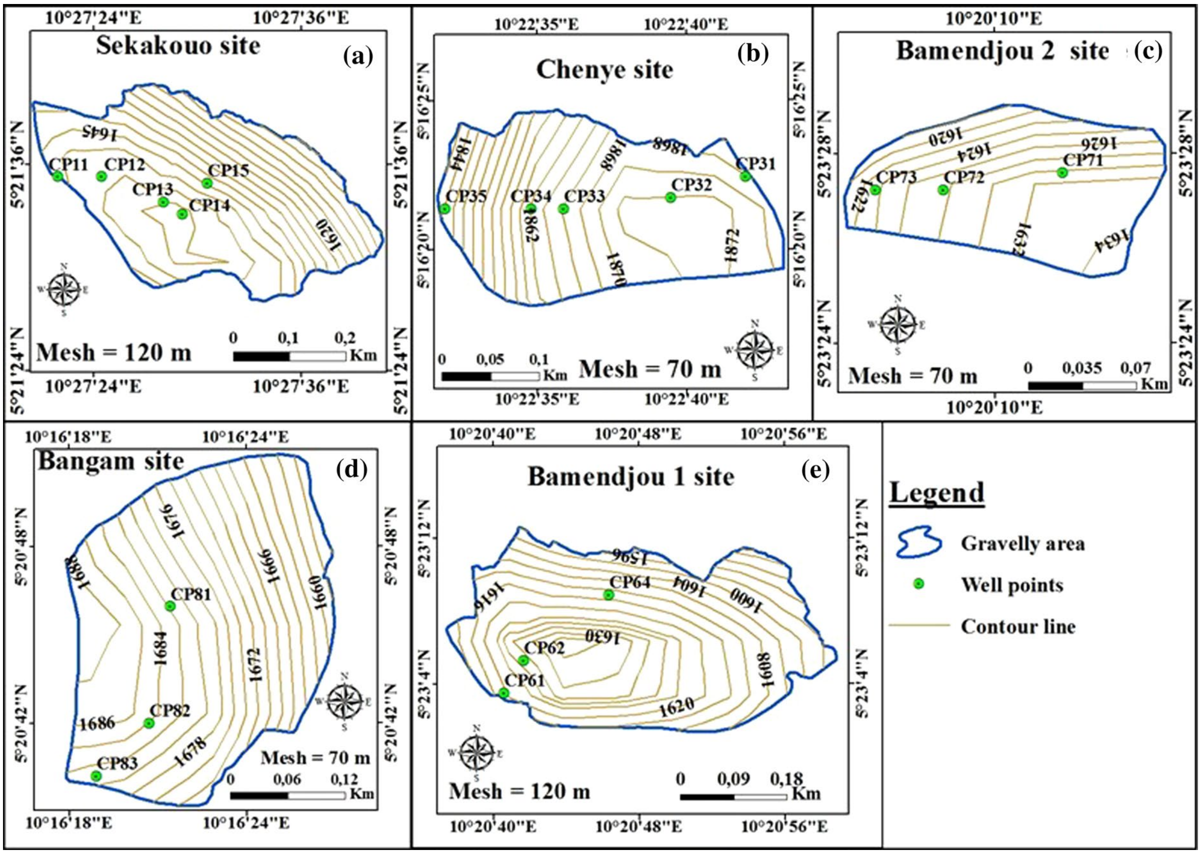

Fig. 2 Sampling map of the studied sites. **a** Sekakouo, **b** Chenye, **c** Bamendjou 1, **d** Bamendjou 2, **e** Bangan

Geotechnical analyses of disturbed LGM samples collected during field campaigns were performed at the *Bureau d'investigation géotechnique* (BIG) of Cameroon. Their grain size distribution was determined through dry sieving and sedimentometry, according to the NF P 94-056 (1996) and NF P94-057 standards, respectively (ANFOR 1992). The liquid limit (LL) was determined using the Casagrande apparatus, according to the NF P 94-051 standard (ANFOR 1993). The plastic limit (ω_p) was determined using the roller method following also the NF P 94-051 standard (ANFOR 1993). The consistency index (CI), plasticity index (PI), and group index (GI) were determined from the Atterberg limits. The methylene blue value (MBV) was determined according to the NF P94-068 standard (AFNOR 1998). The natural water content (ω_{nat}) was determined by successive weighing of raw soil samples before and after drying in an oven at 105 °C based on the NF P 94-050 standard (AFNOR 1991). The specific gravity (SG) was determined using pycnometers according to the NF P 94-054 standard (AFNOR 1991). The maximum dry density (MDD) and the optimum moisture content (OMC) were determined through the modified Proctor test following the NF P94-093 standard (AFNOR 1999). The Californian bearing ratio (CBR) was determined using the NF P94-078 standard (ANFOR 1997). For determining CBR, representative soil samples were compacted to a predetermined optimum moisture content and maximum dry density for a given soil compaction energy (Katte et al. 2018).

Statistical analyses were performed using all the 20 samples, from the five representatives LGM sites studied. Fifteen meaningful, geotechnical variables were selected for statistical analyses. These are Specific gravity (SG), size fractions less than 2 mm (C2mm), size fractions less than 400 µm (C400µm), size fractions less than 80 µm (C80µm), gravel content (gravel), consistency index (CI), liquid limit (LL), plasticity index (PI), grading modulus (Gm), plasticity modulus (Pm), plasticity product (Pp), swelling potential (εs), optimum moisture content (OMC), maximum dry density (MDD) and CBR index determined at 95% (CBR95).

The consistency index is the ratio defined by the following formula:

$$CI = \frac{LL - \omega_{nat}}{PI} \quad (1)$$

CI: consistency index; LL: liquid limit; ω_{nat} : naturalwater; PI: plasticity index;

The grading modulus was determined by formula (2):

$$Gm = [300 - (\%\ C2mm + \%\ C400\mu m + \%\ C80\mu m)]/100 \quad (2)$$

C2mm: Size fractions less than 2 mm, C400µm: Size fractions less than 400 µm, C80µm: Size fractions less than 80 µm (fines),

Each of the plasticity-based derived parameters represents the effective contribution of the plasticity of the fines to the performance of the whole materials, which depends on the proportion of fines (Charman 1988; Nwaiwu et 2006). Plasticity modulus was determined by the formula (3)

$$Pm = PI \times \text{percentage passing } 400\mu m \text{ test sieve} \quad (3)$$

Pm: Plasticity modulus;

As for the plasticity product, it was by formula (4)

$$Pp = PI \times \text{percentage passing } C80\mu m \text{ test sieve} \quad (4)$$

Pp: plasticity product;

The swelling potential of the LGM was determined at the immersion phase of the CBR test. A tripod carrying a comparator was placed on the edge of the mold during the immersion of the samples. Subsequently, the comparator rod was adjusted so that the feeler of the comparator came to rest on the edge of the swelling disk. The initial reading of the comparator was thus noted. Thus, the swelling potential was calculated by the following formula:

$$\varepsilon s = \frac{100Xlf - li}{Hi} \quad (5)$$

εs: swelling potential; lf: initial reading; li: Final reading; Hi: initial height (Hi = 127 mm).

These variables were analyzed using Statistica 7 and Microsoft Excel 2013 software. The correlation matrix was used to evaluate the degree of correlation pairwise between the 15 significant geotechnical variables. A standardized principal component analysis (PCA) was also performed on these variables. The individual factor maps identified the contribution of the LGM of the study sites in defining the different factor axes that constitute the principal component. These factorial axes differentiate the LGM according to the most influential geotechnical parameters. Variations of BPLGM properties were evaluated using their coefficient of variations (CV), following the Wilding and Dress (1983) classification, summarized as followed: (a) if the CV is less than 15, then the parameter has low variations, (b) if the CV is between 15 and 35, the variable has medium variations, and (c) otherwise, the parameter has high variations.

4 Results

4.1 Macroscopic Organization of the Lateritic Gravelled Materials

The LGM studied are sometimes covered by the organo-mineral horizon. They are also deposited on the clayey mineral horizon. These materials are contained in the gravelled mineral horizon with thicknesses between 72 and 305 cm with a light red (7.5R 5/3) color. The LGM studied are mainly characterized by the presence of nodules of a millimeter to multicentimeter size. The proportion of these nodules decreases from the top to the bottom of this horizon (Fig. 3b, Fig. 3c, and d). These nodules are remains of strongly altered basalts. Nevertheless, other nodules are fragments of cuirass and quartz, which have resisted weathering. They are rounded, angular, and fragile to shocks (Fig. 3e and f). They are progressively transformed into a reddish yellow clayey B horizon (7.5YR6/5).

4.2 Mineralogical Composition

The interpretation of LGM powder diffractograms allowed us to determine the following mineral phases, classified by descending order of their percentages: kaolinite, gibbsite, goethite, hematite, ilmenite, rutile, anatase, maghemite, and quartz (Fig. 4).

Kaolinite content varies from 21.6% (Sekakouo site) to 36.6% (Bamendjou 1 site). Gibbsite content

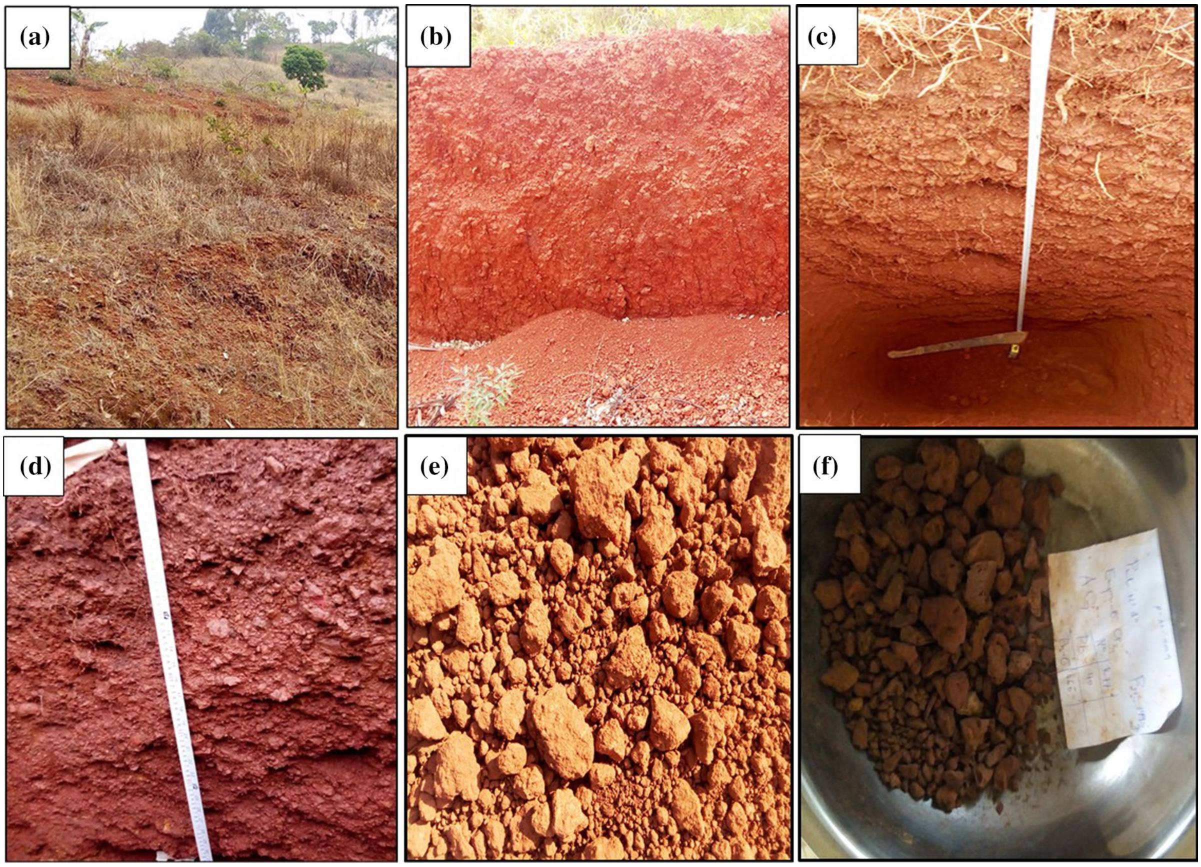

Fig. 3 Morphology of lateritic graveled materials of the Bamileke Plateau. **a** surface view of the lateritic graveled material site at Sekakouo on a rounded-top interfluve; **b** decrease of nodules in a matrix of fine soil observed on talus at Chenye; **c** soil profile showing lateritic graveled material observed at Bangam; **d** soil profile on the slope of the site at Bamendjou 1; **e, f** nodules of millimetric to multi-centimeter size in the lateritic graveled materials studied

ranges from 14.7% (Bamendjou 1 site) to 27.7% (Chenye site).

Goethite content fluctuates between 6.6% (Chenye site) to 19.4% (Bangam site). Hematite content varies from 2.9% (Bamendjou 2 site) to 14.8% (Chenye site). Ilmenite content ranges between 1.8% (Bamendjou 1 site) and 15% (Bamendjou 2 site). Rutile (3.1% to 8.9%), anatase (2.4% to 6%), maghemite (4.4% to 5.7%), and quartz (0.1% to 5.8%) are the less represented minerals at the sites studied. However, rutile was not identified in LGM from the Chenye, Bamendjou 1, and Bamendjou 2 sites (Table 1).

4.3 Specific Gravity (SG)

The mean values of SG are 2.73; 2.60; 2.72; 2.70 and 2.81 for the Sekakouo (SEK), Chenye (CHE), Bamendjou 1 (BAM1), Bamendjou 2 (BAM2), Bangam (BAN) sites, respectively. Their coefficients of variation are less than 15% and are thus classified as low variation (Table 2).

4.4 Granulometric Size Characteristics

The granulometric curves of BPLGM are shown in Fig. 5. These curves show that the gravel content varies from 41.4% (CHE) to 68.8% (BAM1). The LGM gravel contents at the SEK and CHE sites are

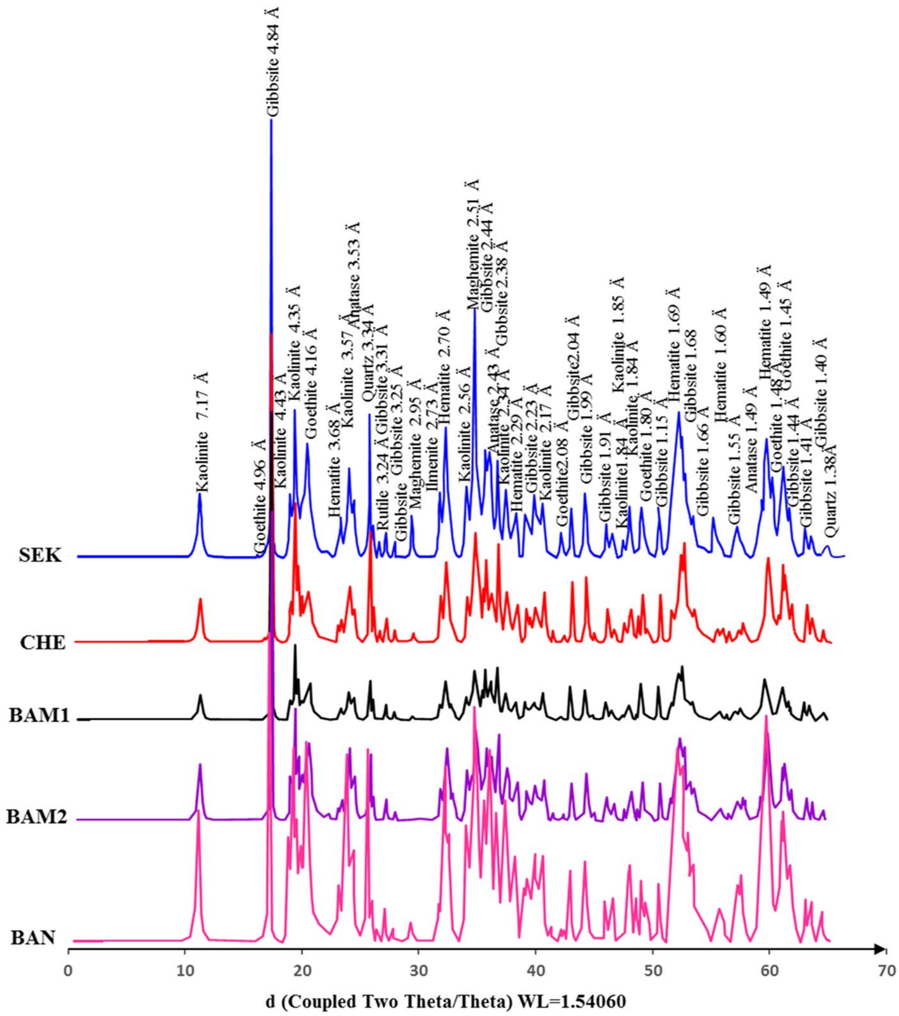

Fig. 4 X-RD diffractogram of all samples. *SEK* Sekakouo site, *CHE* Chenye site, *BAM1* Hamidou 1 site, *BAM2* Bamendjou 2 site, *BAN* Bangam site

Table 1 The relative proportion of minerals (%)

Samples	Kaolinite	Gibbsite	Goethite	Hematite	Ilmenite	Rutile	Anatase	Maghemite	Quartz
SEK	21.6	16.3	15.0	11.5	13.6	8.9	2.4	5.7	5.1
CHE	32.3	27.7	6.6	14.8	2.4	Nd	6.0	4.4	5.8
BAM1	36.6	14.7	17.5	13.8	1.8	Nd	6.0	4.8	4.7
BAM2	28.9	27.3	17.7	2.9	15.0	Nd	5.2	3.0	0.1
BAN	25.1	17.9	19.4	5.9	11.7	3.1	5.9	4.4	4.1

Sd Standard deviation, *Nd* No data, *SEK* Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou 1 site, *BAM2* Bamendjou 2 site, *BAN* Bangam site

classified as medium variation (CV > 15%). While gravel contents at the BAM1, BAM2, and BAN sites, are classified as low variation (CV < 15%).

The values of the size fractions less than 2 mm (C2mm), vary from 17.5% (BAM1) to 52.0% (CHE). These values of size fractions less than 2 mm of the BAN site have a high variation (CV > 35%). While those of the SEK, CHE, and BAM1 sites have a medium variation; and that of the BAM2 site has a low variation (CV < 15%).

Table 2 Average geotechnical properties (%)

S	Gravel	C2mm	C400µm	C80µm	C2µm	Gm*	Pm*	P_P*
SEK	47.4 ± 12.75[b]	44.6 ± 12.84[b]	42.0 ± 10.93b	38.0 ± 3.52[a]	8	1.85	1083	677
CHE	41.6 ± 12.46[b]	52.0 ± 11.52[b]	46.7 ± 10.93b	44.0 ± 10.57[b]	7	1.58	919	859
BAM1	68.8 ± 6.85[a]	17.5 ± 4.35[b]	12.9 ± 3.10b	14.0 ± 2.38[b]	2	2.56	316	327
BAM2	62.7 ± 5.51[a]	31.2 ± 3.51[a]	26.4 ± 4.88b	22.0 ± 1.73[a]	4	2.20	600	502
BAN	64.7 ± 8.08[a]	24.6 ± 8.62[C]	19.9 ± 6.53b	18.0 ± 4.93[b]	3	2.38	406	361

S	SG	LL (%)	ω_p(%)	PI* (%)	CI*	GI*	MBV	Ac	Ɛs	OMC (%)	MDD (g /cm^3)	CBR (%)
SEK	2.73 ± 0.11[a]	60.8 ± 4.49[a]	34.9 ± 3.30[a]	25.8 ± 3.52[a]	1.3 ± 0.30[b]	5	0.90	1.12	0.103 ± 0.03[b]	11.6 ± 1.85[a]	1.73 ± 0.12[a]	21 ± 2.35[a]
CHE	2.60 ± 0.08[a]	57.8 ± 3.29[a]	38.3 ± 2.52[a]	19.5 ± 1.97[a]	1.5 ± 0.10[a]	5	1.10	0.83	0.092 ± 0.01[a]	16.4 ± 2.41[a]	1.69 ± 0.15[a]	22 ± 6.42[b]
BAM1	2.72 ± 0.12[a]	60.1 ± 6.16[a]	36.1 ± 4.37[a]	24.0 ± 3.17[a]	1.8 ± 0.24[a]	0	0.41	2.55	0.088 ± 0.01[a]	13.0 ± 2.54[b]	1.76 ± 0.06[a]	25 ± 5.56[b]
BAM2	2.70 ± 0.08[a]	57.1 ± 4.71[a]	34.2 ± 3.27[a]	22.9 ± 1.54[a]	1.7 ± 0.16[a]	1	0.82	1.63	0.080 ± 0.01[a]	14.6 ± 1.31[a]	1.82 ± 0.03[a]	27 ± 10.50[C]
BAN	2.81 ± 0.05[a]	58.6 ± 4.10[a]	38.4 ± 3.08[a]	20.2 ± 1.83[a]	1.9 ± 0.27[a]	0	0.82	1.53	0.087 ± 0.01[a]	13.6 ± 1.36[a]	1.89 ± 0.03[a]	31 ± 2.52[a]

Gm = [300 – (% C2mm + % C400µm + % C80µm)]/100, Pm = PI × percentage passing 400 µm test sieve, Pp = PI × percentage passing C80µm test sieve, *C2mm* Size fractions less than 2 mm, *C400µm* size fractions less than 400 µm, *C80µm* size fractions less than 80 µm (fines), *C2µm* size fractions less than 2 µm (Clay), *gravel* gravel content, *Gm* grading modulus, *Pm* plasticity modulus, *Pp* plasticity product, *calculate parameter, [a]low variation, [b]medium variation, [c]high variation, *Nd* no data, ± **n:** standard deviation, *SG* specify gravity, *S***:** samples, *SEK* Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou1 site**,** *BAM2* Bamendjou 2 site, *BAN* Bangam site**,** *MBV* (g/100): Methylene Blue Value, *LL* liquid limit, $\boldsymbol{\omega_p}$: plasticity limit, *PI* plasticity index, *CI* consistency index, *CV* coefficient of variation, *GI* Group index, $\mathcal{E}_s$: swelling potential, *Ac* clay activity; *OMC* optimum moisture content, *MDD* maximum dry density and *CBR* California bearing ratio

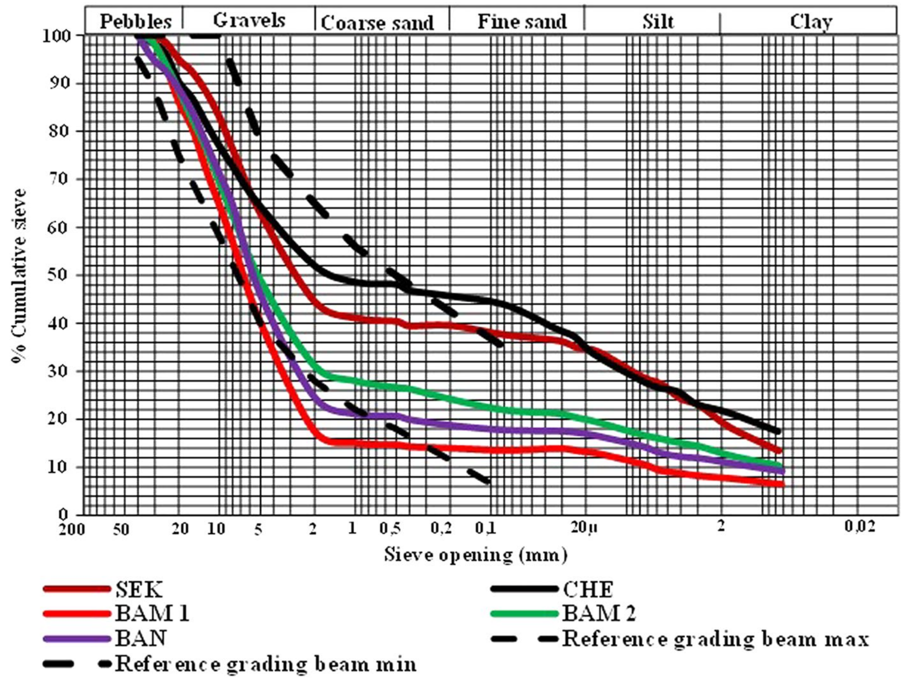

Fig. 5 Grain size curves of the samples. *SEK* Sekakouo site, *CHE* Chenye site, *BAM1* Bamendjou 1 site, *BAM2* Bamendjou 2 site, *BAN* Bangam site

The values of the size fractions less than 400 µm (C400µm) ranged from 12.9% (BAM1) to 46.7% (CHE). The C400µm values of the sites studied are classified as medium variation (CV > 15%).

Moreover, the BAM1 site has the lowest fine particle content value (C80µm) of 14.0%, and the CHE site has the highest C80µm value of 38.0%. The CV of fine particle contents of the CHE, BAM1, and BAN sites is greater than 35% and thus are classified as a high variation. The fine particle contents of the SEK and BAM2 sites are classified as a low variation (CV < 15%).

The clay content (C2µm) varies from 2% (BAM1) to 8% (SEK). The values 8%; 7%; 2%; 4% and 3% are noted for the SEK, CHE, BAM1, BAM2 and BAN sites, respectively.

4.5 Atterberg Limits and Swelling Potential of LGM

The Atterberg limits, MBV, and swelling potential results are summarized in Table 2. The average values of LL vary from 57.1% (BAM2) to 60.7% (SEK) (Table 2). Their coefficients of variation are lower than 15% and are classified as a low variation. The ω_p values vary from 34.2% (BAM2) to 38.4% (BAN). Their coefficients of variation are less than 15% and are classified as a low variation. PI values range from 19.15% (CHE) to 25.8% (SEK). The plasticity indices are classified as low variation (CV < 15%). These PI values allow us to classify BPLGM with PI < 25%, as moderately clayey soils (CHE, BAM1, BAM2, and BAN sites); and those with PI > 25% as clay soils (SEK), according to the *Guide des Terracements Routiers*, fascicule I (1992).

The average methylene blue values (MBV) of the BPLGM range from 0.41 (BAM2) to 0.90 g/100 g (SEK). These materials have an average MBV between 0.2 and 2.5 g/100 g. Therefore, they belong to the silty soil category according to Duplain et al. (2000).

The swelling values range from 0.080 (BAM2) to 0.103 (SEK). The BPLGM are therefore classified as low-swelling materials, according to Seed et al. (1962).

4.6 Derived Parameters

The BAM1 site has the highest Gm value of 2.56 and the CHE site has the lowest Gm value of 1.58 (Table 2). The CHE site has the highest plasticity product (Pp) of 859% and the BAM1 site has the lowest Pp of 327% as can be seen in Table 2. The SEK site has the highest Pm (1 083%) and the BAM1 site has the lowest Pm (316%). The clay activity (Ac) values of BPLGM range from 0.83 (SEK) to 2.55 (BAM1) as can be seen in Table 2. Therefore, they belong to the normal soil category, according to Skempton and Northe (1952). However, the materials at the BAM1 site have an average activity between 1.25 and 2. They are thus classified as active soils. The consistency index (CI) values range from 1.26 (SEK) to 1.94 (BAN) as can be observed in Table 2. The BPLGM have CI > 1 and belong to the very consistent soil category. The GI values are very low and range from 0.03 (SEK) to 5.36 (CHE).

4.7 Compaction Characteristics

The maximum dry density (MDD) values ranged from 1.69 (CHE) to 1.89 g/cm^3 (BAN) and for optimum water contents (OMC) of 16.4 and 13.6%, respectively. The OMC values vary from 13.0 (BAM1) to 16.4% (CHE) as can be seen in Table 2. Furthermore, gravels were shown to be brittle under the compaction force of the compaction drop hammer Proctor, since they were considerably fragmented during these tests.

The CBR95 values ranged from 21% (SEK) to 31% (BAN) as seen in Table 2. Thus, the BPLGM have a bearing index of class S4 at SEK, CHE, BAM1, BAM2 sites, and S5 the BAN site.

5 Discussion

5.1 Lateritic Gravelled Materials and Mineralogical Diversity

The BPLGM are contained in the B-nodular horizon. They are silty-clay and mainly light red. These materials are characterized by a great proportion of nodules (40 to 70%). These nodules are concretions, fragments of cuirass, and quartz gravels. They were formed in situ. They are composed of kaolinite, gibbsite, goethite, hematite, quartz, maghemite, ilmenite, rutile, and anatase. Swelling clay minerals are absent in these materials. These mineralogical assemblages are generally present in lateritic soils as also observed by Ekodeck (1984); Mbumbia et al. (2000); Millogo et al. (2008) and Onana et al. (2015); except for maghemite, ilmenite, and rutile. This mineralogical composition is similar to those of fine lateritic soils of Bafang investigated by Hyoumbi Tchungouelieu et al. (2018). The same mineralogical assemblages were also observed in the eastern and central Cameroon LGM, as concluded by Nzabakurikiza et al. (2012); Onana et al. (2015), and Ngo'o Ze et *al*. (2019). Similar observations were made by Manefouet (2016), regarding lateritic gravelled soils of the southern slopes of the Bamboutos Mountains base areas. However, the BPLGM have in addition maghemite, rutile, and a higher proportion of gibbsite.

The great kaolinite content combined with low quartz content could be linked to an optimal drainage environment, allowing the leaching of soluble cations, some silica, and the crystallization of 1:1 clay mineral, as concluded by Yongue-Fouateu et al. (2009). The quartz in these materials may derive from quartz xenoliths in the parent rock as reported by Fosso et al. (2005). The great rutile content (3.60 to 3.64%) in these LGM parent rocks (basalts), supports the presence of rutile as noticed by Fosso et al. (2005) and Nono et al. (2009). Hematite and ilmenite present in these materials, highlight their ferrallitic character as also conclude by Tematio et al. (2009). The light red color dominance can be explained by the presence of hematite in these soils. The great gibbsite content (14.7–27.3%) in these materials, suggests humid climatic conditions and high degrees of weathering as also concluded by Tassongwa et al. (2017).

5.2 Coefficient of Variation

LL, ω_p, εs, SG, CI, Pl, OMC, and MDD are the geotechnical parameters showing a low variation. However, the εs and CI of the Sekakouo site have medium variations. The OMC at the Bamendjou 1 site also has a medium variation.

Size fractions less than 80 µm (C80µm), gravel content, size fractions less than 2 mm (C2mm), size fractions less than 400 µm (C400µm), and California bearing ratio (CBR) are those geotechnical parameters, showing a medium variation. Nevertheless, the C80µm of the SEK, BAM2, and BAN sites; is classified as a low variation. The C2mm of the BAN site has a low variation. The gravel content of the BAM1, BAM2, and BAN sites; has a low variation. While the CBR of the SEK and BAN sites have a low variation.

The geotechnical parameters of granularity (C80µm, gravel content, C2mm), show high variation as well as CBR. They are consequently the most dispersed. This trend had also been noted on LGM

Table 3 Correlation matrix

	SG	C2mm	C400µm	C80µm	Gravel	LL	PI	Gm	Pm	P_P	Ɛs	CI	OMC	MDD	CBR
SG	1														
C2mm	− 0.666	1													
C400µm	− 0.631	**0.997**	1												
C80µm	− 0.668	**0.991**	**0.992**	1											
Gravel	0.654	**− 0.986**	**− 0.986**	**− 0.999**	1										
LL	0.341	− 0.132	− 0.074	− 0.021	0.004	1									
PI	0.224	− 0.156	− 0.095	− 0.113	0.135	0.697	1								
Gm	0.699	**− 0.998**	**− 0.992**	**− 0.990**	**0.986**	0.157	0.197	1							
Pm	− 0.488	**0.932**	**0.955**	**0.936**	**− 0.926**	0.143	0.192	**− 0.911**	1						
PP	**− 0.774**	**0.987**	**0.978**	**0.984**	**− 0.978**	− 0.162	− 0.182	**− 0.993**	**0.891**	1					
Ɛs	− 0.071	0.548	0.596	0.633	− 0.648	**0.745**	0.414	− 0.524	**0.725**	0.498	1				
CI	0.491	− 0.833	**− 0.865**	**− 0.860**	**0.847**	− 0.326	− 0.410	**0.810**	**− 0.962**	**− 0.810**	**− 0.786**	1			
OMC	− 0.677	0.356	0.289	0.299	− 0.298	**− 0.843**	**− 0.820**	− 0.402	0.008	0.438	− 0.481	0.146	1		
MDD	**0.817**	− 0.666	− 0.667	**− 0.732**	**0.728**	− 0.257	− 0.197	0.681	− 0.657	− 0.748	− 0.572	**0.759**	− 0.173	1	
CBR	0.683	− 0.694	**− 0.714**	**− 0.756**	**0.746**	− 0.388	− 0.406	0.692	**− 0.778**	**− 0.740**	**− 0.705**	**0.892**	0.047	**0.958**	1

LL liquidity limit, *PI* plasticity index, *CI* Consistency index, *C2mm* size fractions less than 2 mm, *C400µm* size fractions less than 400 µm, *C80µm* size fractions less than 80 µm (fines), *gravel* gravel content, *Gm* the grading modulus, *Pm* plasticity modulus, *Pp* plasticity product, $\mathcal{E}_s$ swelling potential, *OMC* optimum moisture content, *MDD* maximum dry density and *CBR* California bearing ratio, *bold values* designate highly correlated geotechnical parameters in humid tropics by Ndzié Mvindi et al. (2017) and Ngo'o Ze et *al*. (2019). Similarly, Issiakou Souley (2016) has noticed that granulometry parameters and plasticity are geotechnical properties that differentiate lateritic soils based on the bearing capacity criterion.

5.3 Correlation Matrix

The Pearson correlation matrix presented in Table 3 shows that the geotechnical properties of LGM are all linearly interconnected. In this table, three categories of relationships were distinguished based on their correlation coefficient values:

- One variable is highly correlated with another when the correlation coefficient value is greater than 0.70. Thus, we have a high and strong positive correlation of SG with MDD; C2mm with C400µm, Pm, C80µm and Pp; C400µm with Pm, C80µm and Pp; C80µm with Pm and Pp; gravel content with Gm, MDD, CI and CBR; LL with Ɛs; Gm with CI; Pm with Pp and Ɛs; CI with MDD and CBR; MDD and CBR on the one hand. On the other hand, we also have high and strong negative correlations. This is the case of SG with P_P; C2mm with Gm, CI and gravel content; C400µm with Gm, CI, gravel content and CBR; C80µm with gravel content, Gm, OMC, and CBR; gravel content with Pp and Pm; LL with OMC; PI with OMC; Gm with Pp and Pm; Pm with CI and CBR; P_P with CI, MDD, and CBR; Ɛs with CI and CBR (Table 3).

- Furthermore, a variable is moderately correlated with another when the value of the correlation coefficient is between 0.50 and 0.70. Thus, a moderate positive correlation of SG with Gm, gravel content, and CBR; C2mm with Ɛs; C400µm with Ɛs; C80µm with Ɛs; LL with PI; Gm with MDD and CBR; Ɛs with MDD were noted and a moderate negative correlation of SG with C2mm, C400µm, C80µm, and OMC; C400µm with MDD; gravel content with Ɛs; Gm with Ɛs; Pm with MDD were also noted (Table 3).

- Nevertheless, variables with correlation values less than 0.50, are considered weakly correlated variables (Table 3).

It is, therefore, observed that the correlation coefficients are highly variable. This confirms the strong dispersion of geotechnical properties. A high and strong positive correlation between CBR and CI, gravel content, and MDD was observed. While,

Table 4 Relations between geotechnical parameters of the studied materials lateritic gravels

Relations	Type of régression	R^2	Model	Equations
CBR–MDD	Linear	**0.9185**	Model 1	CBR = 49.109*MDD − 62.115
CBR–gravel	Linear	**0.5566**	Model 2	CBR = 0.2537*gravel + 10.729
CBR–CI	Linear	**0.7963**	Model 3	CBR = 14.914*CI + 0.7414
CBR–SG	Linear	0.4665	Model 4	CBR = 36.508*SG − 73.81
CBR–C2mm	Linear	0.4810	Model 5	CBR = − 0.1968*C2mm + 31.887
CBR–C400µm	Linear	**0.5093**	Model 6	CBR = − 0.1995*C400µm + 31.097
CBR–C80µm	Linear	**0.5711**	Model 7	CBR = − 0.2325*C80µm + 31.523
CBR–LL	Linear	0.1508	Model 8	CBR = − 1.0096*LL + 84.645
CBR–PI	Linear	0.1651	Model 9	CBR = − 0.6227*PI + 39.199
CBR–Gm	Linear	0.4784	Model 10	CBR = 7.0041*Gm + 10.393
CBR–Pm	Linear	**0.6052**	Model 11	CBR = − 0.0095*Pm + 31.532
CBR–Pp	Linear	**0.5481**	Model 12	CBR = − 0.0134*Pp + 32.479
CBR–Ɛs	Linear	0.4973	Model 13	CBR = − 335.66*Ɛs + 55.41
CBR–OMC	Linear	0.0022	Model 14	CBR = 0.1053*OMC + 23.742

C2mm Size fractions less than 2 mm, *C400µm* size fractions less than 400 µm, *C80µm* size fractions less than 80 µm (fines), *gravel* gravel content, *Gm* grading modulus, *Pm* plasticity modulus, *Pp* plasticity product, *SG* specify gravity, *LL* liquid limit, *PI* plasticity index, *CI* Consistency index, ε_s swelling potential, *OMC* optimum moisture content, *MDD* maximum dry density and *CBR* California bearing ratio

The gas characters are the values of the coefficient of determination (R^2) of the CBR parameters. These coefficient of determination values measure the quality of the precision of a linear regression. The closer the R^2 value is to 1, the better the regression quality a strong negative correlation between CBR and C400µm, C80µm, Pm, PP, and Ɛs were identified from the correlation matrix. This confirms the correlation of some geotechnical parameters to CBR and the high variability of some geotechnical parameters concerning CBR also noticed by Fall et al. (1994); Fall (1997); Bohi, (2008); Issiakou Souley (2016), and Ngo'o Ze et *al.* (2019). Geotechnical parameters strongly correlated with CBR (CI, gravel content, MDD, C400µm, C80µm, Pm, Pp, and Ɛs) show the dependence of this latter with some intrinsic soil characteristics.

Table 5 Eigenvalues

	Eigenvalue	% of variance	Cumul Val Propre	Cumul % of the variance
Fact. 1	9.83	65.50	9.83	65.50
Fact. 2	3.62	24.11	13.44	89.61
Fact. 3	1.06	7.08	14.50	96.69
Fact. 4	0.50	3.31	15.00	100

5.4 Regression Analysis of LGM Geotechnical Parameters

The values of MDD, gravel content, and CI are related to those of CBR according to a positive linear relationship observed. The values of C400µm, C80µm, Pm, Pp are related to those of CBR according to a negative linear relationship as can be seen in Table 4. The following coefficient of determination values: 0.9185, 0.5566, 0.7963, 0.5093, 0.5711, 0.6052 and 0.5481 are noted for CBR vs. MDD; CBR vs. gravel content; CBR vs. CI; CBR vs. C400µm; CBR vs. C80µm; CBR vs. Pm and CBR vs. Pp relationships, respectively. The statistical results indicate that the values of C400µm, C80µm, Pm, and Pp negatively influence the CBR, and their high contents in LGM may lower the CBR values. On the other hand, MDD, gravel content, and CI values positively influence CBR and their high contents would increase LGM CBR values. The relationship developed between MDD and CI value as a function of CBR was statistically significant ($R^2 > 0.7963$). The Pearson correlation coefficient of model 1 ($R^2 = 0.9185$) indicates that the equation of CBR vs. MDD is a very good predictor of CBR (Eq. 6).

$$CBR = 49.109 \times MDD - 62.115 \tag{6}$$

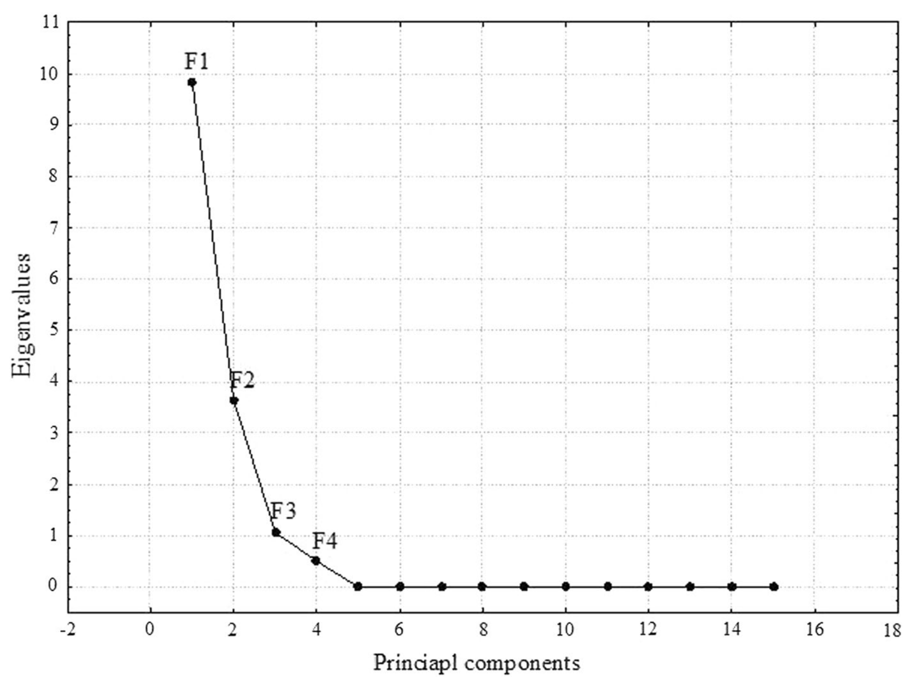

Fig. 6 Eigenvalues of principal components

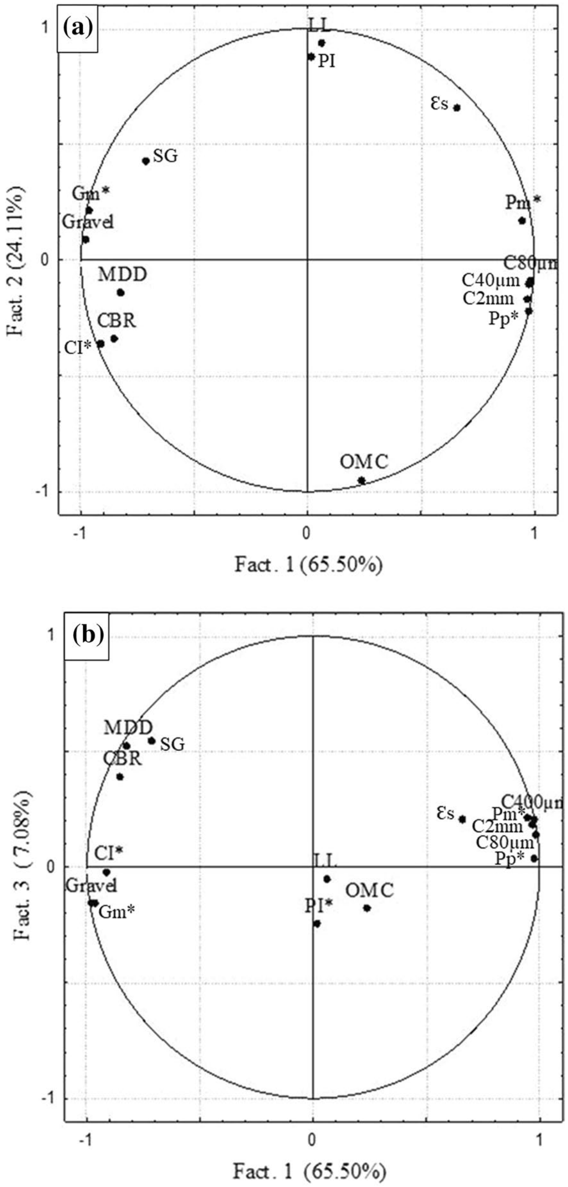

Fig. 7 Geotechnical variables plotted on the **A** F1 × F2 and **B** F1 × F3 axis

This observation is coherent with the investigation of Katte et al. (2018) on subgrade soil of the south region of Cameroon. Nevertheless, the values of SG, C2mm, LL, PI, Gm, Ɛs and OMC of the BPLGM, have coefficients of determination less than 0.5000 and are weakly correlated with CBR. This shows that the SG, C2mm, LL, PI, Gm, Ɛs, and OMC; might weakly influence CBR. This trend was also shown by the correlation matrix. The weak correlation of some geotechnical parameters concerning CBR is due to the dispersion of these geotechnical parameters. This dispersion of some geotechnical parameters was also noted in the Niger LGM by Issiakou Souley (2016); similarly, in LGM from gneiss in a humid tropical savannah zone of Central Cameroon as noted by Mvindi Ndzié et *al*. (2017) and also in LGM overlying contrasting metamorphic rocks of the humid tropical zone of Cameroon by Ngo'o Ze et *al*. (2019).

5.5 Influence of Some Geotechnical Parameters on CBR

The analysis of the influence of some geotechnical parameters on the CBR was performed by applying the Principal Component Analysis (PCA) of a data set of 20 observations and 15 variables. According to the Kaiser criterion, three principal components were extracted with an eigenvalue greater than 1, as can be seen in Table 5 and Fig. 6, accounting for 96.69% of the total variance in the data set.

Factor axis 1 (Fact. 1) explains 65.50% of the total variance (Fig. 7). Fact. 1 is characterized by a high positive loading on six variables (C80µm, Pm*, C400µm, Pp*, εs, and C2mm) and a negative loading on six variables (Gm*, gravel content, MDD, CBR, CI* and εs). This shows that Gm*, gravel content, MDD, CI*, and SG are the variables that strongly control LGM CBR which increase or decrease in the same direction. There is an association of MDD, gravel content, CI, and CBR at this Fact. 1; and a strong correlation between them, as shown by Table 5. This suggests a strong influence of MDD, gravel content, CI on CBR. Since Pm*, C80µm, C400µm, Pp*, εs, C2mm, and OMC; oppose CBR on the factorial axis Fact. 1. This also suggests a negative influence on CBR and an antagonistic increase or decrease in their values. Thus, a high proportion of Pm*, C80µm, C400µm, Pp*, εs, C2mm, and OMC would decrease the CBR values. This is the case for the LGM of SEK and CHE sites. The opposition of these geotechnical parameters to the clouds formed by CBR, Gm*, Gravel, MDD, CI*, and SG; is similar to those of LGM developed on metamorphic rocks as also concluded by Ndzié Mvindi et al. (2017); Ngo'o Ze et *al*. (2019). Based on their position on the factorial plane, there is a relatively positive correlation between MDD and CBR ($R^2 = 0.958$). C80µm is

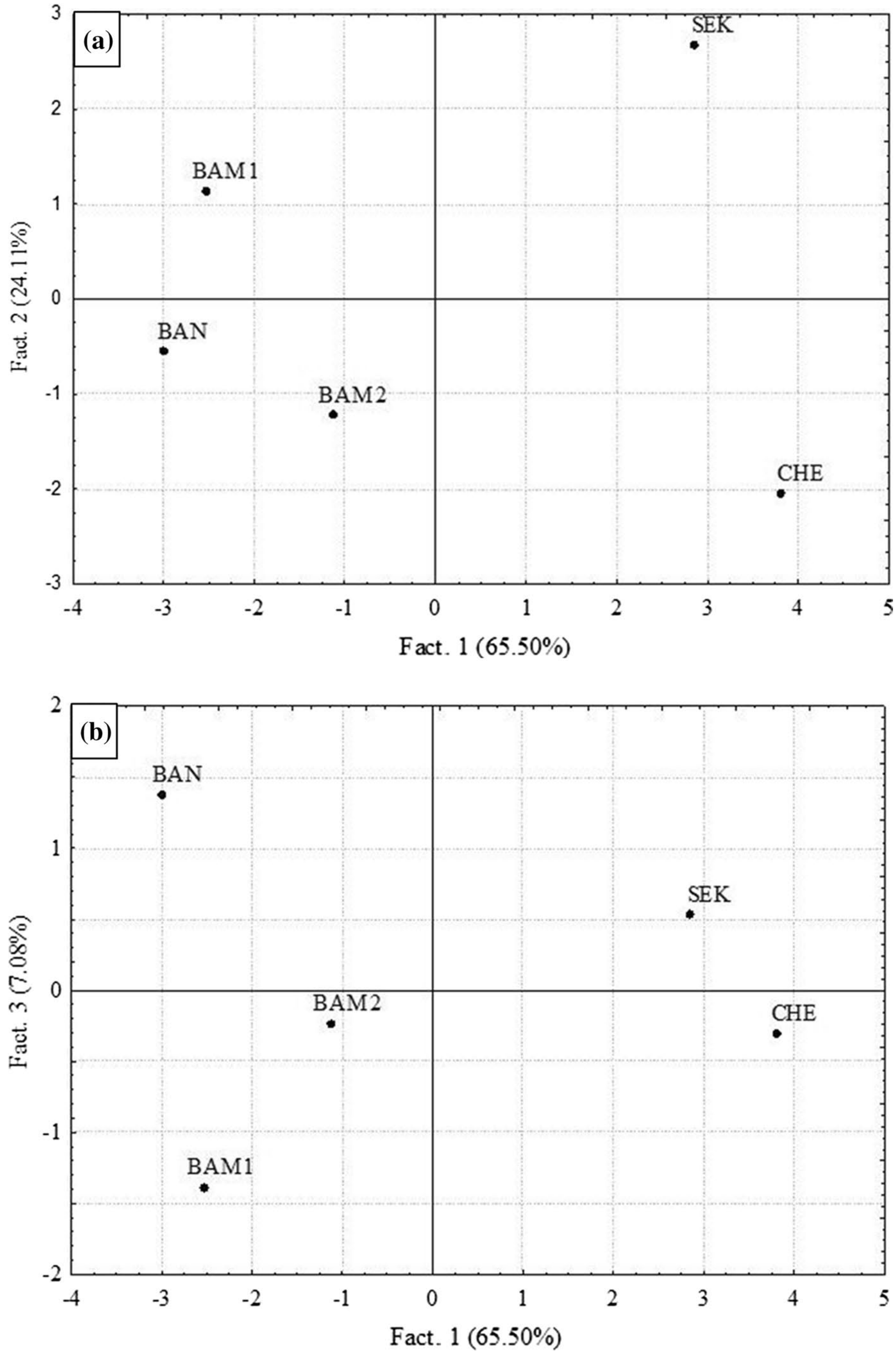

Fig. 8 Map of individual factors on the axis **a** F1 × F2 and **b** F1 × F3

also correlated with MDD in Fact. 1, and are closer to the correlation circle. Thus, the role of these two variables in the classification of lateritic gravels has also been investigated by Fall et al. (1994); Bohi (2008); Ndzié Mvindi et al. (2017), and Ngo'o Ze et *al*. (2019); who preconized their consideration in the geotechnical classification of these materials.

Factor axis 2 (Fact. 2) describes 24.11% of the total variance. Fact. 2 axis is characterized by a positive loading of PI* and LL; and a negative loading of OMC. This confirms that LL, PI, and OMC might not directly influence CBR. The correlation matrix also revealed low correlation coefficients ($R^2 > 0.5000$) between LL, Ip, OMC, and CBR.

Factor axis 3 (Fact. 3) explained 7.08% of the total variance. Fact. 3 has a negative loading with LL, PI, and OMC. This implies that OMC might be influenced by soil plasticity. This correlation explains the independence of CBR from plasticity characteristics and moisture content.

Two groups of LGM are distinguished in the study sites, as well as along the Fact. 1 axis of these individual factorial maps. The first group concerns LGM of the SEK, BAM1, and BAM2 sites, mainly influenced by Gm*, Gravel, MDD, CI*, SG, and CBR. The second group corresponds to the low bearing capacity LGM, characterized by granularity characteristics such as C80µm, Pm*, C400µm, Pp*, PI, εs, and C2mm.

Factor 2 and 3 allow us to distinguish three groups of materials. The first group represented by the LGM from the BAN site is characterized by CBR. The second group is represented by the BAM1 and BAM2 site LGM characterized by CBR, CI*, gravel content, and MDD. The LGM of BAM1 and BAM2 belong to the same geographical location and have different CBR (CBR = 25% and CBR = 27%, respectively). This can be attributed to the influence of MDD on their CBR. This situation can be justified by the high proportion of goethite (17.7%) and ilmenite (15.0%) present in the LGM BAM2 site. The third and last group represented by the SEK and CHE LGM, corresponds to materials enriched in fines (C80µm > 35%), and characterized by C80µm, Pm*, C400µm, Pp*, PI, εs and C2mm (Fig. 8).

Overall, the analysis of the influence of some geotechnical parameters on CBR showed that LGM CBR is positively correlated with Gm*, gravel content, MDD, CI*, and SG. This improves when their proportions are high in these materials. In contrast, CBR is negatively correlated with Pm*, C80µm, C400µm, Pp*, εs, C2mm, and OMC. Thus, improves when their proportions are high in these materials. This suggests that LGM with high values of Gm*, gravel content, MDD, CI* and SG; and low proportions of Pm*, C80µm, C400µm, Pp*, εs, C2mm, and OMC; are of good quality for their valorization in road construction. Furthermore, the values of CBR within these sites are scattered and have low to high variation. This variability and dispersion of CBR would

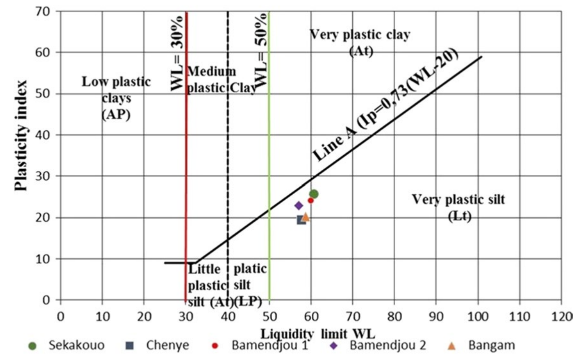

Fig. 9 Position of studied materials in Casagrande diagram

be attributed to the disproportionate distribution of constituents strongly influencing CBR (Gm*, gravel content, MDD, CI*, SG, Pm*, C80µm, C400µm, Pp*, εs, C2mm). This could be related to the heterogeneity of LGM. Owoyemi and Adeyemi, (2017) also noted the high heterogeneity of lateritic gravels in Mokwa derived from sandstones. Dispersion of geotechnical parameters has also been noted in the humid savanna LGM of central Cameroon as concluded by Ndzié Mvindi et al. (2017). This was also observed by Ngo'o Ze et *al*. (2019) regarding chlorite schists derived lateritic gravels of east Cameroon. This variability and geotechnical parameters dispersion do not allow an effective assessment of CBR for non-representative sampling.

5.6 Implications of LGM in Road Construction

The BPLGM have a specific gravity greater than 2.58 and have acceptable road construction performance (Nwaiwu et al. 2006). The average values obtained (<2.58) are plus or minus similar to those of lateritic soils of Bafang in western Cameroon; and those of Mfou in central Cameroon, according to Kamtchueng et al. (2015) and Hyoumbi Tchungulieu et *al*. (2018), respectively. These specific gravity values are lower than those observed on the southern and eastern Cameroon LGM by Nzabakurikiza et al. (2016) and Onana et al. (2017), except the Bangam LGM site. However, these values are higher than those obtained in Senegal (2.2 to 2.3) by Fall et al. (2008). The presence of hematite, ilmenite, maghemite, gibbsite, and goethite may justify the high specific gravity values of the BPLGM compared to those of Senegal. The average granulometric curves of these materials, partially lie between the lower and higher limits of grains percentages admitted for the sub-base layers (CEBTP 1984), except that of the Bamendjou 2 site.

The average values of the LL of the BPLGM (57.1 to 60.8%) are higher than the 50%, values prescribed for the sub-base layer by CEBTP (1984). These LL values are higher than those obtained in West Africa (23–55%) by Fall et al. (1995); Frempong (1995); Millogo et al. (2008), and Oyelami and Van Rooy (2016b). These high LL values might be attributed to the high absorption capacity of these materials. This high absorption capacity could be related to the great proportions of fine particles and kaolinite contents (21.6–36.6%). The average value of the PI is between 19.5 and 25.8%. This is approximately equal to the maximum value of 25% for the sub-base layer as prescribed by CEBTP (1984). These average PI values (19.5 to 25.8%), which are close to 25%, suggest the use of these materials as a sub-base and possibly as a subgrade layer. Furthermore, these PI values are lower than those obtained on Central Cameroon LGM developed on mica-schists (26%) by Kamtchueng et al. (2015), and the Eastern Cameroon LGM developed on chlorite schists (27%) by Ngo'o Ze et al. (2019). They are higher than those obtained in Nigeria (20%) by Chuka et al. (2011). The swelling potential (ε_S), is an important characteristic for material used in road construction (Millogo et al. 2008). The ε_S values of BPLGM (0.080- 0.103) indicate that they have low swelling potential. This low swelling potential was also supported by the XRD analysis and methylene blue values. The BPLGM are classified as highly plastic silts in the Casagrande plasticity diagram (Fig. 9).

The LGM grain sizes are mainly characterized by C2mm, C425µm, C80µm, and C2µm as described by Bagarre (1990). The BPLGM gravel contents vary between 41.4 and 68.8%; C2mm contents between 17.5 and 52.0; 400 µm contents between 15.2 and 49.8%; and fine particle contents vary between 18.0 and 44.0%. This particle size distribution is consistent with the work of Bagarre (1990), who revealed that lateritic gravels were characterized by a high proportion of gravels (20–60%) and low to moderate proportions of fines (10–35%). The average fine particle size of the BPLGM (18.0 to 44.0%), is higher than that obtained in Burkina Faso (10.5%), by Millogo et al. (2008) in the dry tropical savanna. Nevertheless, the SEK and CHE sites have the highest fine particle contents (> 35%), with clay content between (8 and 7% respectively), C400µm (42.0 and 49.8% respectively), and size fraction values less than 2 mm (44.6 and 52.0% respectively), but the lowest gravel contents (47.4 and 41.6% respectively). This might be justified by the poor drainage and intensive weathering of the SEK and CHE sites. Plasticity product (Pp) values of lateritic gravels from the BPLGM, range from 327 to 859. These average Pp values are much higher than those obtained in Nigeria (133–197), by Nwaiwu et al. (2006) and east Cameroon (161–755) by Ngo'o Ze et *al*. (2019). These Pp values show that the BPLGM can be used as a sub-base for any type of traffic, except those of the SEK site. Since they have a Pp value greater than 600. The SEK and CHE sites grading modulus values are above the required value (2.09) for use as a sub-base as recommended by Charman (1988) and Nwaiwu et al. (2006). Their Pm is below 500, which is the maximum required for use as a sub-base for any traffic suggested by Charman (1988). Nevertheless, materials from the BAM1, BAM2, and BAN sites have acceptable Gm* and Pm* values for sub-base use.

According to CEBTP (1984), and Sikali and Mir-emirati (1986), materials suitable for use as sub-base and the base course must have an MDD greater than or equal to 1.80 and 2.00 g/cm^3, respectively. The BAN and BAM2 sites have MDD values greater than 1.80 g/cm^3 and mean CBR values of 27 and 31%, respectively. Moreover, the MDD values of the SEK, CHE, and BAM1 sites are lower than 1.80 g/cm^3. They have an average CBR value of 21%, 22%, and 25%, respectively. The average CBR values are lower than those obtained on lateritic gravels from Central Cameroon (39%) by Kamtchueng et al. (2015), Burkina Faso (42%) by Millogo et al. (2008), Southern Cameroon (31–68%) by Onana et al. (2017) and Senegal (60–84%) by Fall et al. (2008). These average CBR values are greater than or equal to 25% for the BAM1, BAM2, and BAN sites, the minimum value for use as a sub-base layer for low-traffic pavements, as recommended by CEBTP (1984), and Sikali and Mir-emirati (1986). However, materials from the SEK and CHE sites have CBR below 25%. Thus, the BPLGM are silty or clayey gravels and sands, and silty soils of subgroups A-2-7 and A-4, respectively, according to the US *Highway Research Board* (HRB) classification (AASHTO 1998). They are also well-graded gravels (BAM1, BAM2, and BAN sites) and clayey sands (SEK and CHE sites), according to the Unified Soil Classification (ASTM 2006); and silty gravels (GL) according to the *Laboratoire Central des Ponts et Chaussées* classification (LCPC–SETRA 2000). However, the US HRB classification classifies the SEK and CHE sites as silty soils. They can be used as subgrade for any type of traffic, and as a sub-base for low-volume traffic T1 and T3.

6 Conclusion

We present here the assessment of lateritic gravelled materials for use in road pavements in Cameroon. Geotechnical identification, X-ray diffractometry, and statistical methods were used in this study. This study aimed to optimize the durability of LGM pavements.

These investigations show that the LGM du plateau de Bamileke were formed under humid climatic conditions and have high degrees of weathering. They are contained in the B-nodular horizon and are composed of kaolinite, gibbsite, goethite, hematite, quartz, maghemite, ilmenite, rutile, and anatase.

The geotechnical parameters of fines particle content (C80µm), gravel content, size fractions less than 2 mm (C2mm), and CBR are the most variable and scattered. Coefficient of determination values show a significant correlation between: CBR vs. MDD ($R^2=0.9185$); CBR vs. Gravel content ($R^2=0.5566$); CBR vs. consistency index ($R^2=0.7963$); CBR vs. size fractions less than 400 µm (C400µm) ($R^2=0.5093$); CBR vs. fines (C80µm) ($R^2=0.5711$); CBR vs. plasticity modulus ($R^2=0.6052$); and CBR vs. plasticity products ($R^2=0.5481$), respectively. Thus, the low correlation of some geotechnical parameters with the CBR might be due to the dispersion of these parameters.

The CBR values of LGM are positively correlated with the grading modulus (Gm), gravel content, MDD, CI, and specific gravity (SG). This improves when their proportions are high in these materials. In contrast, CBR is negatively correlated with Pm*, C80µm, C400µm, Pp, εs, C2mm, and OMC. Meanwhile, this decreases when their proportions are high in these materials.

The CBR values show a low to high variation. Their dispersion might be due to unequal constituents' distribution, which strongly influences the CBR values. This could be related to the heterogeneity of LGM. Therefore, BPLGM can be used as a subgrade layer for any type of traffic and as a subbase layer for low-volume traffic. However, the SEK and CHE sites are not usable, due to their poor characteristics. The exploration of LGM deposits should be directed towards LGM with high proportions of Gm, gravel, MDD, CI, SG and low proportions of Pm, C80µm, C400µm, Pp, εs, and C2mm.

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