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Geotechnical and Geochemical Assessment of Lateritic Soils for Road Pavement Layers in Semi-Arid Regions: Case of the Maroua-Mora Corridor (Cameroon)

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Abstract

This study investigates the geotechnical and geochemical characteristics of lateritic soils along the Maroua-Mora corridor in the semi-arid Far North region of Cameroon, with the aim of assessing their suitability for road construction applications. Eight representative soil samples were collected and analyzed through standardized laboratory tests, including particle size distribution, Atterberg limits, Modified Proctor compaction, California Bearing Ratio (CBR), and X-ray fluorescence (XRF). The results indicate that the soils are predominantly sandy to sandy-clayey, with coarse fractions ranging approximately from 58% to 77% and fines content between 23% and 42%, and varying from low to moderate plasticity (PI = 9 - 20). Compaction characteristics show maximum dry densities ranging from 2.060 to 2.157 g/cm^3 and optimum moisture contents between 6.8% and 12.3%. CBR values (15 - 40) classify most materials within S4-S5 categories, suitable for subgrade and foundation layers but marginal for base course applications without stabilization. Geochemical analysis reveals dominance of SiO_2, Al_2O_3, and Fe_2O_3, reflecting varying degrees of lateritization. Soils enriched in sesquioxides exhibit improved mechanical performance due to natural cementation, whereas silica-rich materials show lower cohesion and require stabilization. The $SiO_2/(Al_2O_3 + Fe_2O_3)$ ratio emerges as a key parameter controlling engineering behavior. The study highlights the strong interdependence between geotechnical properties and geochemical composition, demonstrating that the performance of lateritic soils in semi-arid environments is governed by both mineralogical and compaction factors. This integrated approach provides a reliable framework for optimizing the use of local materials in road construction and contributes to sustainable infrastructure development in Sahelian regions.

Keywords

Lateritic Soils, Geotechnical Characterization, Geochemical Analysis, Road Construction Materials, Far North Cameroon

1. Introduction

In developing countries, particularly in sub-Saharan Africa, the expansion and sustainability of road infrastructure remain critical drivers of economic growth, regional integration, and access to essential services [1]. Nevertheless, the performance and durability of road networks are often constrained by the inadequate characterization and inappropriate use of locally available construction materials [2]-[8]. This issue is especially pronounced in semi-arid environments, where climatic factors such as high temperatures, seasonal rainfall variability, and erosion processes significantly accelerate the degradation of pavement structures [9].

In Cameroon, the deficit in transport infrastructure constitutes a major constraint to socio-economic development [1] [4]. This challenge is particularly acute in the Far North Region, where rapid demographic growth and increasing commercial activities exert additional pressure on already fragile road networks [8]. The Maroua-Mora axis represents a strategic corridor for national and regional connectivity, notably facilitating trade with neighboring countries such as Chad and Nigeria. However, this road is frequently affected by structural distress, including rutting, cracking, and surface erosion, raising concerns regarding the engineering suitability of the materials used in pavement layers [9].

In the Sahelian context of northern Cameroon, road construction relies predominantly on locally available geomaterials, particularly lateritic soils and, to a lesser extent, granitic arenites. These materials are widely used due to their accessibility and economic advantages in tropical regions [10]. However, their geotechnical performance is highly variable and largely dependent on their mineralogical composition, granulometry, degree of weathering, and geochemical characteristics [11]-[15]. In many cases, the lack of rigorous characterization and quality control leads to suboptimal use, resulting in premature deterioration of road infrastructures.

Furthermore, the increasing demand for construction materials, combined with uncontrolled exploitation practices, has led to the progressive depletion of high-quality lateritic resources [13] [14]. This situation underscores the necessity of developing a comprehensive understanding of the geotechnical and geochemical behaviour of these materials in order to optimize their use in road engineering applications. Several studies have demonstrated the potential of lateritic soils for various civil engineering purposes, including road construction, embankments, earth dams, and compressed earth blocks [10]-[15]. However, region-specific data remain insufficient, particularly in semi-arid zones such as the Far North of Cameroon.

In this context, the present study aims to assess the geotechnical and geochemical properties of lateritic soils collected along the Maroua-Mora axis, with a view to evaluating their suitability for different pavement layers, including subgrade, subbase, and low-traffic base applications. The study seeks to contribute to the establishment of a reliable geotechnical database that can support infrastructure development in the region. Particular attention is given to the relationships between mineralogical composition, chemical indices, and engineering performance.

Beyond the local scale, this research also proposes an integrated methodological framework combining geotechnical, geochemical, and geological approaches. Such a framework could be extended to other Sahelian regions to improve the identification, mapping, and sustainable management of construction material resources. Ultimately, this approach aims to promote the rational and optimized use of locally available materials, thereby enhancing the durability and resilience of road infrastructures in semi-arid environments.

2. Localization and Experimental Methods

2.1. Localization of Study Area and Sample Collection

The study area is located in the Far North Region of Cameroon, between latitudes 10˚N - 13˚N and longitudes 14˚E - 16˚E, along the Mora-Maroua axis within the Diamaré Division (**Figure 1**). This area represents a key socio-economic corridor connecting Cameroon with Chad and Nigeria. Investigations were mainly carried out in Maroua I, II, and III subdivisions. The climate is Sudan-Sahelian, characterized by a long dry season (October-May) and a short rainy season (June-September) [16]. The average annual rainfall ranges between 700 and 900 mm, with a mean temperature of about 28˚C [16]. These climatic conditions significantly influence weathering processes and the geotechnical behaviour of soils [14]. Geomorphologically, the area consists of low-relief plains and discontinuous highlands (inselbergs). The hydrographic network is mainly seasonal, dominated by the Mayo Tsanaga, Mayo Kaliao, and Mayo Mizao rivers, which belong to the Lake Chad basin [17]. The soils are predominantly hydromorphic vertisols associated with ferruginous and alluvial soils. These materials are known for their high clay content and shrink-swell behaviour, which can affect road performance [17]-[19]. Geologically, the area belongs to the Precambrian basement and is composed mainly of gneisses, granites, and gabbros [20]. The weathering of these rocks leads to the formation of lateritic soils widely used in road construction. Their properties vary depending on mineralogical and geochemical composition, which justifies their detailed characterization in this study.

The eight sampling sites were selected in order to represent the main lateritic formations developed along the Maroua-Mora corridor under varying geomorphological and geological conditions. The selected sites cover materials derived from different parent rocks and weathering environments distributed across the Meri, Maroua, and Mora subdivisions. At each site, disturbed bulk samples were collected from representative lateritic horizons between 0.5 and 1.5 m depth. Each sample corresponds to a composite material obtained from several closely spaced points within the same borrow area to minimize local heterogeneity. In addition, these eight soil samples were collected along the Maroua-Mora axis in the Far North Region of Cameroon, covering the subdivisions of Meri (Mambang, Mogordom, Djoulgouf), Maroua I (Meskine, Pont Sava), and Mora (Doulo, Guédéré, Makalingai) as presented in **Table 1**. Samples were taken at depths between 0.5 and 1.5 m and coded (MAM, MOG, DJO, MES, PSA, DOU, GUE, MAK) for traceability. Field observations indicate predominantly reddish-brown lateritic soils (2.5YR 5/4), with sandy clayey texture and coarse-grained structure. This relative homogeneity suggests similar weathering conditions, with minor variations likely related to local mineralogical differences [14].

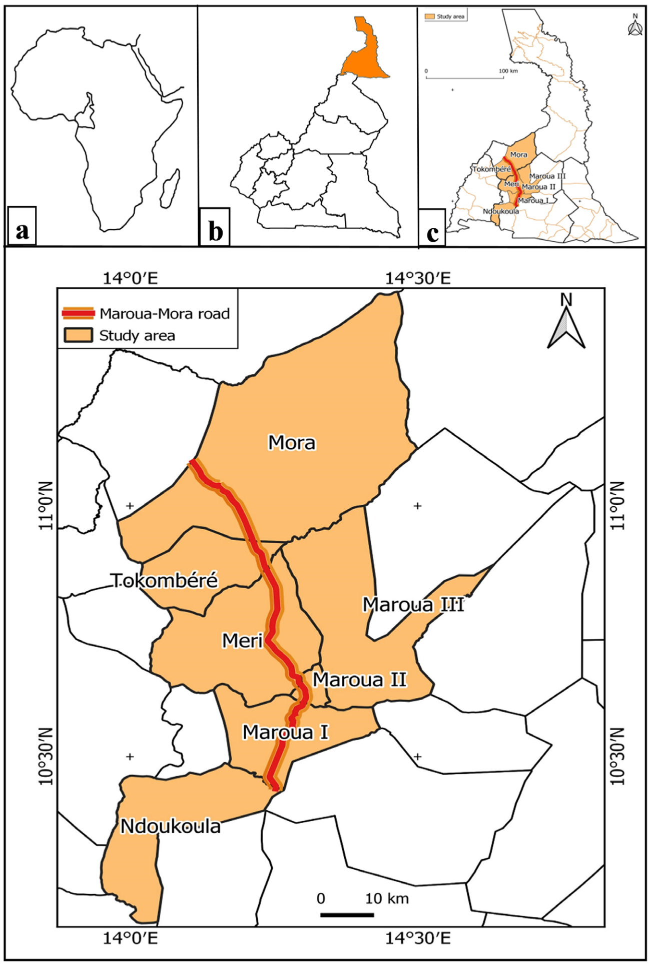

Figure 1. Location map of the case study area.

Table 1. Macroscopic characteristics of the studied soils.

Division	Subdivision	Place of Sampling	Sample Code	Coordinates	Color (Dry)	Textural Class	Structure
Diamaré	Meri	Mambang 1	MAM	10˚38'06" 14˚17'39"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
	Meri	Mogordom	MOG	10˚41'15" 14˚16'04"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
	Meri	Djoulgouf	DJO	10˚37'28" 14˚28'08"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
	Maroua I	Meskine	MES	10˚33'25" 14˚15'25"	Yellowish Brown (10YR5/6)	Sandy Clayey	Coarse-Grained Structure
Mayo Sava	Mora	Pont Sava	PSA	11˚01'03" 14˚10'32"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
		Doulo	DOU	11˚06'21" 14˚10'24"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
		Guédéro	GUE	11˚14'41" 14˚08'37"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure
		Makalingaï	MAK	10˚51'03" 14˚13'40"	Reddish Brown (2.5YR5/4)	Sandy Clayey	Coarse-Grained Structure

2.2. Experimental Study

2.2.1. Geotechnical and Mechanical Properties of Lateritic Soils

The experimental analysis consisted of a series of standard geotechnical, mineralogical, and geochemical tests aimed at comprehensively characterizing the physical, hydric, mechanical, and compositional properties of the studied soils. These analyses made it possible to evaluate their particle size distribution, plasticity, natural water content, as well as their compaction and bearing performance, while also integrating the study of their mineralogical composition and geochemical signature, in order to assess their suitability for civil engineering applications, particularly road construction.

Particle size distribution was determined using a combination of sieving and sedimentation techniques. Dry and wet sieving were applied to particles larger than 80 µm, depending on soil cohesiveness, while finer fractions were analyzed by sedimentation. This combined approach enabled the establishment of granulometric curves and the classification of soil particles into distinct size fractions [21] [22].

The Atterberg limits, including liquid and plastic limits, were determined on the fine fraction passing the 0.4 mm sieve, in accordance with [23]. These parameters are essential for assessing soil consistency and its sensitivity to moisture variations [24] [25].

The natural water content was measured by oven-drying samples at 105˚C - 110˚C until constant mass was achieved. The water content was calculated as the ratio of water mass to dry mass, expressed as a percentage [26].

The specific gravity of soil particles was determined using the pycnometer method, based on the displacement of a liquid of known density. This method allows accurate estimation of the density of solid particles [27].

Compaction characteristics were evaluated using the Modified Proctor test [28], which establishes the relationship between water content and dry density. This test allows the determination of the optimum moisture content and maximum dry density under conditions representative of road construction.

The bearing capacity of the soils was evaluated using the California Bearing Ratio (CBR) test [29]. This method determines the resistance of compacted soils to penetration under standardized conditions and yields key parameters for pavement design. CBR tests were performed on specimens compacted at 95% of the Modified Proctor optimum under unsoaked conditions, in accordance with NF P 94-078 [29]. For each sample, at least three replicate specimens were tested, and the average CBR value was retained. The penetration resistance was measured after standard compaction and curing procedures. The interpretation of the results was carried out in accordance with data reported in **Table 2**, which presents the CBR classification and corresponding recommendations for road construction [30].

Table 2. CBR classes and recommended use in road construction [30].

CBR Class	Use in Road Construction
S1: 0 < CBR < 5	Not suitable for road construction
S2: 5 < CBR < 10	Platform layer
S3: 10 < CBR < 15	Form layer and embankment
S4: 15 < CBR < 30	Foundation layer for Traffic T1
S5: 30 < CBR < 60	Foundation layer for Traffic T2/T3; Base layer for Traffic T1
S6: 60 < CBR < 120	Foundation layer for Traffic T3/T4; Base layer for Traffic T2
S7: CBR > 120	Base layer for Traffic T3

2.2.2. Geochemical Analyses

The chemical composition of the samples was determined by X-ray fluorescence spectrometry (XRF) at the Bureau Veritas Commodities Laboratory. This technique enables both qualitative and quantitative determination of major and trace elements based on the emission of characteristic radiation following atomic excitation. Geochemical data are essential for assessing the origin, weathering degree, and potential engineering applications of lateritic materials [31]-[33]. Prior to XRF analysis, samples were oven-dried, crushed, and finely ground to obtain homogeneous powders. Loss on ignition (LOI) was determined after heating at 1000˚C. Analytical quality control included duplicate analyses and calibration using certified reference materials at the Bureau Veritas Commodities Laboratory.

3. Results and Discussion

3.1. Geotechnical Parameters

3.1.1. Particle Size Analysis

Particle size distribution indicates a predominance of coarse fractions (65% - 97%), confirming a sandy-to-sandy-clayey texture, while the fine fraction (<0.080 mm), ranging from 23% to 42%, remains sufficiently significant to confer an intermediate behavior between granular and cohesive materials (**Figure 2**). The generally continuous grading curves fall within the CEBTP [30] envelopes for subbase and, locally, base layers, suggesting an overall acceptable particle size distribution for road applications.

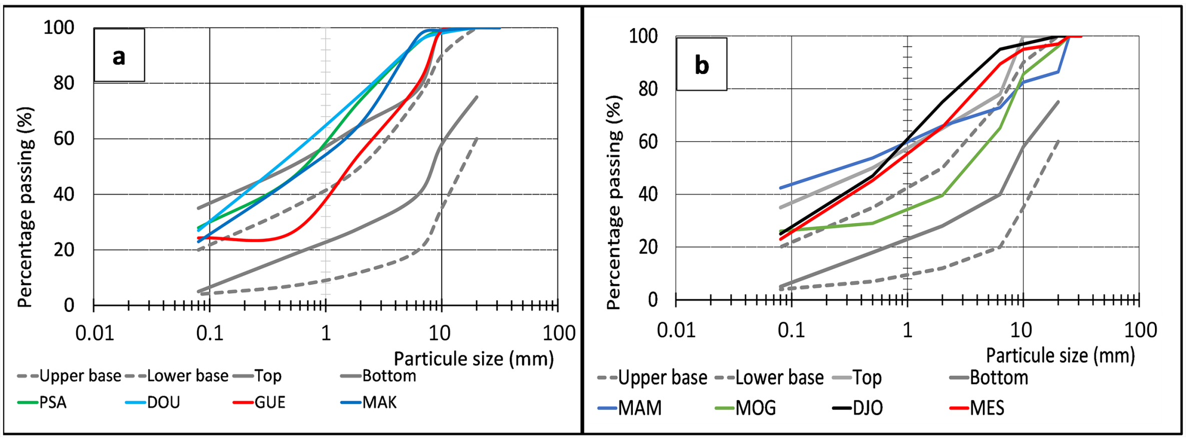

Figure 2. Position of granulometric curves on the CEBTP [30] spindles for base and subbase layers: (a) sample from Mayo Sava Division, (b) sample from Diamare Division.

These findings are consistent with the work of Kamtchueng *et al.* [12], who demonstrated that lateritic soils containing moderate fines (20% - 30%) exhibit improved compaction and higher CBR values. However, when the fine content exceeds this range, a progressive decline in bearing capacity is observed. Kagonbé *et al.* [13] [14] reported comparable trends on lateritic materials from Garoua, where fine contents between 20% and 40% were associated with increased plasticity and a reduction in mechanical performance. More broadly, the inverse relationship between fine fraction and bearing capacity, coupled with increased moisture sensitivity, is well established in lateritic soil mechanics [2]. This tendency is further supported by recent results obtained on Meiganga soils, where an average fine content of about 52% is associated with predominantly plastic behavior and reduced surface bearing capacity [34]. Therefore, despite a globally favorable grading, the relatively high proportion of fines (23% - 42%) may limit mechanical performance, indicating that stabilization remains necessary for optimal use in base layers.

3.1.2. Atterberg Limits and Swelling Potential

The Atterberg limits reported in **Table 3** indicate liquid limits ranging from 35% to 50% and plasticity indices between 9% and 20%, reflecting overall low to moderate plasticity. The MAM sample (PI = 20%) stands out with the highest plasticity, consistent with a greater proportion of active clay minerals, whereas MAK (PI = 9%) and GUE (PI = 10%) correspond to less plastic and more stable materials. Positioning on the Casagrande chart (**Figure 3**) confirms that all samples fall within the ML-CL domain, indicative of silty to clayey soils with moderate plasticity, in agreement with typical lateritic soils described by Gidigasu [10] and regional studies in northern Cameroon [13]-[15]. Compared to the highly plastic and swelling lateritic fine soils reported by Hyoumbi *et al.* [5], these materials exhibit significantly lower plasticity and very limited linear swelling (Ɛs = 0.001 - 0.008), indicating reduced shrink-swell potential and improved dimensional stability. The plasticity modulus (207 - 848) further highlights this variability: the high value for MAM (848) reflects marked water sensitivity and behavior approaching more plastic lateritic facies, whereas the lower values for MAK (207) and GUE (243) confirm more stable and less moisture-sensitive soils, consistent with the interpretation of Lérau [24].

Table 3. Summary of geotechnical for the studied soil.

Sample Code	Specific Weight (g/cm^3)	Granulometric Analysis					Limits of Atterberg			Module of Plasticity	Linear Swelling	Classification	
		31.5	20	**2.0**	**0.5**	**0.080**	**WL**	**PL**	**PI**	**f*PI**	ε_s	H.R.B	GTR
MAM	2.803	100	86	66	54	42	50.0	30.0	20.0	848	0.008	A-7-6	A2
MOG	2.650	100	96	40	29	26	35.0	23.0	12.0	313	0.003	A-2-6	B6
DJO	2.632	100	100	75	47	25	37.0	24.0	13.0	325	0.003	A-2-6	B5
MES	2.610	100	97	66	45	23	35.0	24.0	11.0	253	0.002	A-2-6	B6
PSA	2.455	100	100	74	46	28	40.0	26.0	14.0	391	0.004	A-2-6	B6
DOU	2.453	100	100	76	54	27	40.0	25.0	15.0	405	0.004	A-2-7	B6
GUE	2.589	100	100	55	26	24	37.0	27.0	10.0	243	0.002	A-2-7	B6
MAK	2.610	100	100	66	45	23	35.0	26.0	9.0	207	0.001	A-2-6	B6

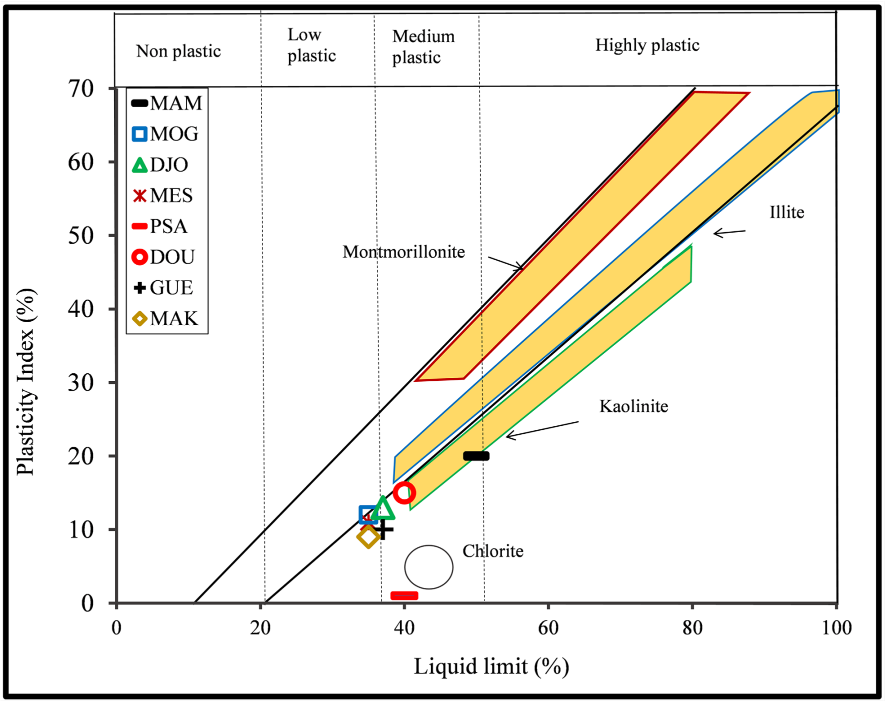

Figure 3. Position of the investigated materials on the Casagrande plasticity chart.

3.1.3. Mechanical Characteristics

The mechanical characteristics derived from **Table 4**, supported by the compaction and strength trends in **Figure 4** and **Figure 5**, indicate a heterogeneous but globally favorable behavior of the studied lateritic soils for road applications. Maximum dry densities (2.060 - 2.157 g/cm^3) and optimum moisture contents (6.8% - 12.3%) are consistent with sandy clay laterites and comparable to values reported in northern Cameroon [35]. The Proctor curves exhibit the classical bell-shaped pattern, confirming well-defined compaction optima and efficient particle rearrangement. The weak inverse relationship between MDD and OMC, together with local variability, reflects differences in granulometry and soil fabric, while lower fines content favors higher densities and reduced water demand [30] [36].

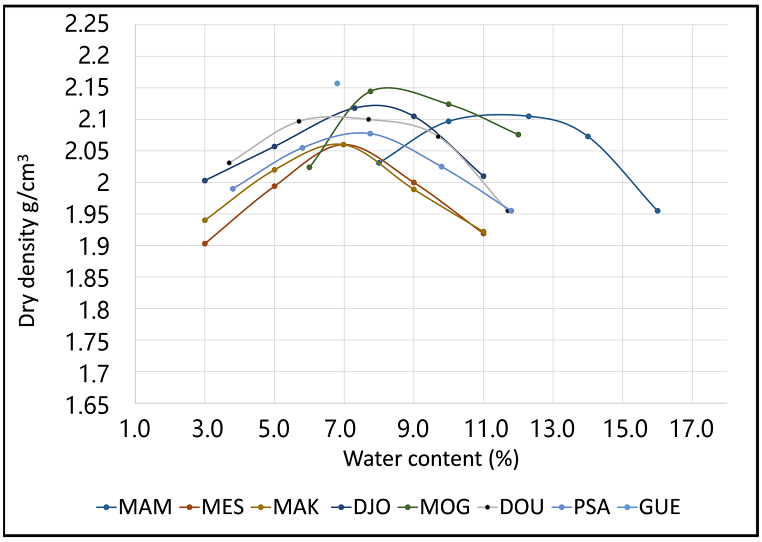

Figure 4. Variation of dry density with water content.

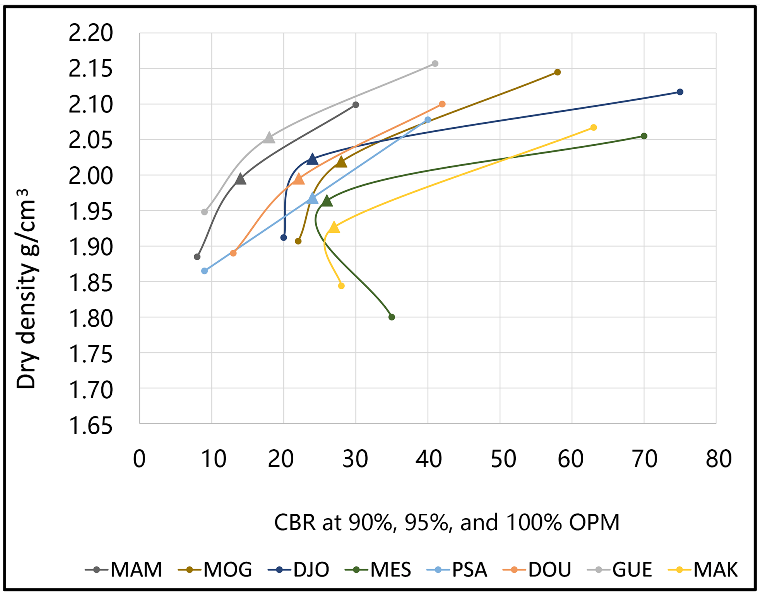

Figure 5. Variation of CBR index values (CBRi) with dry density.

Table 4. Mechanical parameters.

Sample Code	Specific Weight g/cm^3	Proctor (Compacity)		CBRi to 95% of OPM	Linear Swelling Ɛs	Lift Class
		g/cm^3	w %			
MAM	2.803	2.105	12.3	20	0.007	S4
MOG	2.650	2.145	7.8	38	0.004	S5
DJO	2.632	2.118	7.3	50	0.002	S5
MES	2.610	2.060	7.0	56	0.002	S5
PSA	2.455	2.078	7.8	24	0.005	S4
DOU	2.453	2.100	7.7	22	0.004	S4
GUE	2.589	2.157	6.8	24	0.019	S4
MAK	2.610	2.060	7.0	47	0.002	S5

CBRi values at 95% OPM range between 15 and 40, with an average around 30, placing most materials within S4-S5 classes according to CEBTP [30]. Based on standard specifications, S4 materials (15 - 30) are suitable as foundation layers for low traffic (T1), whereas S5 materials (30 - 60) can be used as foundation layers for moderate traffic (T2-T3) and even as base layers for low traffic roads (T1). This classification confirms that the studied soils are generally adequate for subgrade and foundation applications, but remain marginal for base layers under higher traffic without improvement. The positive, though weak, correlation between CBR and dry density (**Figure 5**) highlights the dominant role of compaction in strength development, consistent with observations by Kamtchueng [12]. Linear swelling remains low (0.002 - 0.019), confirming limited expansiveness and good dimensional stability. Overall, these soils, classified as sandy clays [37], exhibit mechanical performance controlled by moisture-density conditions and fines content; although suitable for form and foundation layers across traffic classes (T1-T3), stabilization is recommended to meet the requirements of higher traffic levels or base course applications.

3.1.4. Analysis of Relationships between Particle Size Distribution, Plasticity, Compaction Parameters, and Soil Bearing Capacity

The correlations presented in **Figure 6** highlight the interdependence between geotechnical parameters governing the mechanical performance of lateritic soils.

The inverse relationship observed between fines content and CBR values confirms that an increase in fine particles, particularly clay fractions, leads to a reduction in bearing capacity due to higher plasticity and moisture sensitivity. Similarly, the negative correlation between plasticity index and CBR further supports the detrimental effect of soil plasticity on strength characteristics. The swelling-CBR relationship emphasizes the influence of volumetric instability on load-bearing performance, particularly in clay-rich materials. In contrast, the relationship between maximum dry density and optimum moisture content reflects typical Proctor compaction behavior, controlled by particle arrangement and soil fabric. The positive correlation between plasticity index and liquid limit indicates a coherent evolution of consistency limits, reflecting mineralogical control, especially the presence of kaolinite and iron oxides in lateritic systems. Overall, these trends are consistent with previous studies on tropical and lateritic soils, which demonstrate that granulometry, plasticity, and compaction characteristics are key determinants of their suitability for road construction applications [2] [4] [10] [38]-[41].

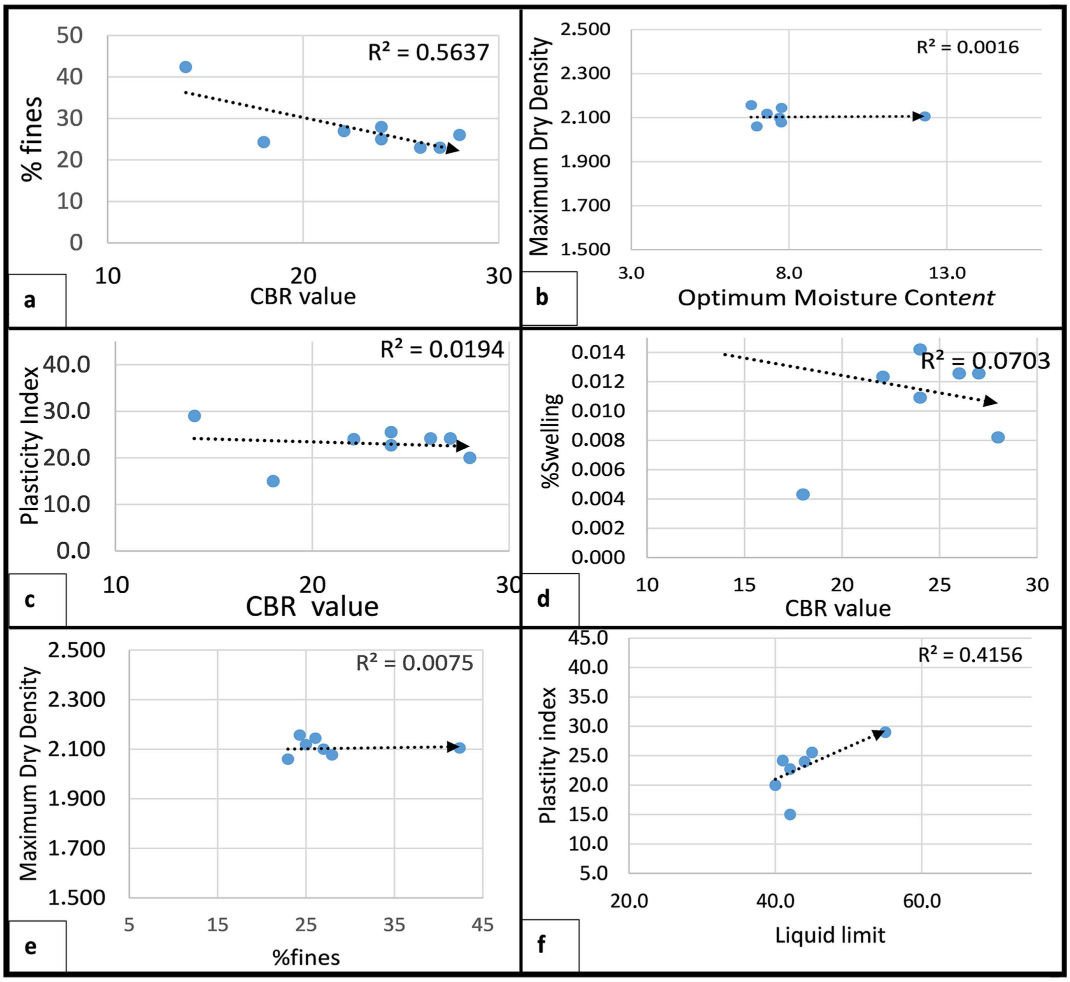

Figure 6. Correlations between: (a) fines content/CBR value, (b) maximum dry density/optimum moisture content, (c) plasticity index/CBR value, (d) swelling/CBR value, (e) maximum dry density/fines content (%), and (f) plasticity index/liquid limit.

3.2. Geochemical Composition

The geochemical composition of the studied lateritic soils (Table 5) is dominated by SiO_2 (44.43 wt.% - 89.77 wt.%), followed by Al_2O_3 (3.85 - 18.62 wt.%) and Fe_2O_3 (2.39 wt.% - 26.76 wt.%), confirming their typical lateritic nature under tropical weathering conditions. These ranges are consistent with those reported in the Far North Cameroon, where quartz, aluminosilicates, and iron oxides control soil composition [42]. High SiO_2 contents in DJO (89.77 wt.%), MAK (78.06 wt.%), and PSA (75.26 wt.%) indicate quartz-rich, weakly cohesive materials, as confirmed by their high $SiO_2/(Al_2O_3 + Fe_2O_3)$ ratios (4.5 - 13.2).

Table 5. Chemical composition of the studied soils.

	MAM	DJO	PSA	MAK	DOU	MES	MOG
SiO_2	49.03	90.59	76.62	79.30	71.17	54.11	69.08
Al_2O_3	20.55	3.88	12.68	8.74	12.82	13.36	13.00
Fe_2O_3	20.46	2.86	2.81	2.43	4.96	29.20	15.34
K_2O	0.22	1.63	5.34	6.15	7.44	0.96	0.71
MgO	0.86	0.25	0.25	0.35	0.43	0.31	0.19
TiO_2	2.03	0.58	0.39	0.30	0.48	0.70	0.88
P_2O_5	0.08	0.03	0.00	0.01	0.03	0.04	0.05
CaO	4.17	0.00	0.39	2.13	0.75	0.25	0.04
Na_2O	2.33	0.10	1.46	0.49	1.76	0.16	0.04
MnO	0.27	0.09	0.05	0.10	0.15	0.90	0.67
LOI	10.36	0.90	1.78	1.56	5.67	9.13	7.20
SiO_2/Al_2O_3	2.39	23.32	6.04	9.08	5.55	4.05	5.32
$SiO_2/(Al_2O_3 + Fe_2O_3)$	1.20	13.42	4.94	7.10	4.00	1.27	2.44

These materials are typically weakly laterized, with good compaction potential but limited interparticle bonding, leading to moderate to low bearing capacity (CBR) without stabilization [19]. This interpretation is further supported by their position in the SiO_2-Al_2O_3-Fe_2O_3 ternary diagram (**Figure 7**), where they cluster toward the silica apex, reflecting residual quartz enrichment and limited pedogenetic transformation. In contrast, MAM (SiO_2 = 44.43 wt.%; Al_2O_3 = 18.62 wt.%; Fe_2O_3 = 18.54 wt.%) and MES (SiO_2 = 49.59 wt.%; Fe_2O_3 = 26.76 wt.%) show enrichment in sesquioxides and low $SiO_2/(Al_2O_3 + Fe_2O_3)$ ratios (≈1.20 - 1.26), indicating advanced laterization. These compositions may indicate the probable presence of kaolinite and iron oxides (goethite/hematite), which promote natural cementation, enhancing cohesion and expected CBR values, as commonly observed in ferruginous laterites (5). Intermediate materials (DOU, MOG) present $SiO_2/(Al_2O_3 + Fe_2O_3)$ ratios between 2.4 and 3.6, reflecting moderately laterized soils with mixed granular and cohesive behavior, associated with intermediate compaction and bearing properties.

Al_2O_3 contents (up to 18.62 wt.% in MAM) indicate the development of clay minerals through hydrolysis, contributing to plasticity and moisture retention [42] [43]. Fe_2O_3, particularly in MES (26.76 wt.%) and MOG (14.30 wt.%), enhances mechanical strength through natural cementation and is often associated with goethite, as indicated by TiO_2 presence [44]. LOI values (0.89 wt.% - 9.39 wt.%) reflect variations in clay content and hydrated phases, with higher values in MAM and MES indicating greater weathering intensity and cohesion, but also increased moisture sensitivity [43] [45]. Overall, MAM and MES are the most suitable for road base applications due to strong sesquioxide content and cementation effects, while MOG and DOU show intermediate performance. PSA, MAK, and DJO, being silica-rich, require stabilization to achieve adequate mechanical performance. These results confirm that the balance between silica and sesquioxides, particularly Fe_2O_3 and Al_2O_3, is the main control factor of the geotechnical behavior of lateritic soils, in agreement with previous studies [19].

Correlation between Geochemical Indices and Engineering Properties:

The correlations between the geochemical ratio $SiO_2/(Al_2O_3 + Fe_2O_3)$ and the engineering properties highlight the influence of geochemical composition on the behavior of the studied lateritic soils (Figure 7). The Plasticity Index (PI) displays a moderate negative correlation ($R^2 = 0.3209$), indicating that increasing silica content is associated with lower plasticity (Figure 7(a)). This behavior reflects the reduced influence of clayey and ferruginous constituents in silica-enriched soils. Although the correlations remain moderate, the results confirm that geochemical composition contributes significantly to the geotechnical performance of lateritic materials. In contrast, the relationship with the California Bearing Ratio (CBR) shows a weak positive correlation ($R^2 = 0.129$), suggesting that silica-rich materials tend to exhibit slightly improved bearing capacity due to the predominance of sandy and quartz-rich fractions (Figure 7(b)). Figure 8 shows that the studied lateritic soils are mainly distributed within the kaolinisation and weak laterisation domains of the SiO_2-Al_2O_3-Fe_2O_3 ternary diagram, indicating a moderate degree of weathering and lateritic evolution.

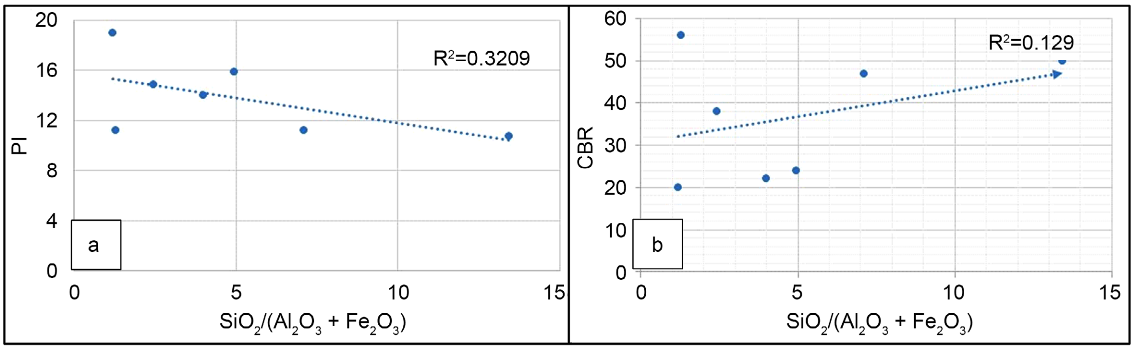

Figure 7. Correlation between geochemical indices and engineering properties of the lateritic soils: (a) correlation between the geochemical ratio $SiO_2/(Al_2O_3 + Fe_2O_3)$ and plasticity index (PI) values; (b) correlation between the geochemical ratio $SiO_2/(Al_2O_3 + Fe_2O_3)$ and California Bearing Ratio (CBR) values.

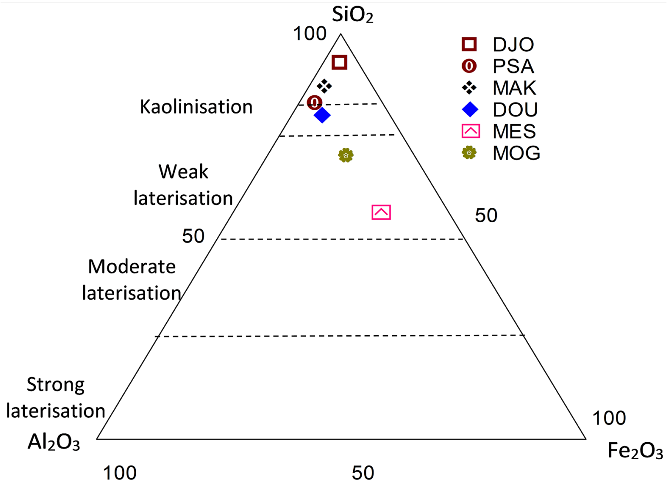

Figure 8. POSITION of studied lateritic soils in SiO_2-Al_2O_3-Fe_2O_3 (Wt. %) ternary diagram [46].

4. Conclusion

This study provides a comprehensive assessment of lateritic soils along the Maroua-Mora corridor through a coupled geotechnical and geochemical approach. The results reveal significant variability in engineering performance, primarily controlled by granulometric distribution, plasticity, and the balance between silica and sesquioxides. Geotechnically, the soils exhibit low to moderate plasticity and satisfactory compaction characteristics, with CBR values indicating suitability for subgrade and subbase applications under low to moderate traffic conditions. However, their performance as base course materials remains limited without mechanical or chemical stabilization, particularly for silica-rich soils. Geochemically, the enrichment in Fe_2O_3 and Al_2O_3 enhances natural cementation and improves strength, whereas high SiO_2 content is associated with reduced cohesion. The $SiO_2/(Al_2O_3 + Fe_2O_3)$ ratio is identified as a robust predictive indicator of mechanical behavior and material quality. The findings confirm that road performance in semi-arid environments is governed by a complex interaction between mineralogical composition, chemical indices, and compaction conditions. The study, therefore, emphasizes the necessity of integrating geochemical parameters into conventional geotechnical evaluation frameworks. Only selected ferruginous lateritic materials (e.g., MAM and MES) exhibit properties approaching the requirements for low-traffic base-course applications without stabilization. From an applied perspective, this work contributes to the development of a regional geotechnical database and supports the rational and sustainable use of local materials. Future research should focus on stabilization techniques and advanced statistical modeling to further optimize material selection and improve pavement durability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Owusu-Manu, D., Jehuri, A.B., Edwards, D.J., Boateng, F. and Asumadu, G. (2019) The Impact of Infrastructure Development on Economic Growth in Sub-Saharan Africa with Special Focus on Ghana. *Journal of Financial Management of Property and Construction*, **24**, 253-273. https://doi.org/10.1108/jfmpc-09-2018-0050

[2] Gidigasu, M.D. (1983) Development of Acceptance Specifications for Tropical Gravel Paving Materials. *Engineering Geology*, **19**, 213-240. https://doi.org/10.1016/0013-7952(83)90004-2

[3] Lemougna, P.N., Melo, U.F.C., Kamseu, E. and Tchamba, A.B. (2011) Laterite Based Stabilized Products for Sustainable Building Applications in Tropical Countries: Review and Prospects for the Case of Cameroon. *Sustainability*, **3**, 293-305. https://doi.org/10.3390/su3010293

[4] Nzabakurikiza, A, Onana, V.L, Ngo'o, ZA, Ndzie-Mvindi A.T., Ekodeck, G.E. (2017) Geological, Geotechnical, and Mechanical Characterization of Lateritic Gravels from Eastern Cameroon for Road Construction Purposes. *Bulletin of Engineering Geology and the Environment*, **76**, 1549-1562. https://doi.org/10.1007/s10064-016-0979-y

[5] Hyoumbi, W.T., Pizette, P., Wouatong, A.S.L. and Abriak, N. (2018) Mineralogical, Chemical, Geotechnical and Mechanical Investigations of Bafang Lateritic Fine Soils Formed on Basalts (West-Cameroon) for Road Embankment Purpose. *Earth Science Research*, **7**, 42-57. https://doi.org/10.5539/esr.v7n2p42

[6] Tamba, C. F., Kengni, L., and Tematio, P. (2023) Geotechnical Suitability of Soils in Road Construction for Sustainable Development in Tropical Africa: Case of Lateritic Graveled Soils of Bandjoun (West, Cameroon). *Advances in Civil Engineering*, **2023**, 1-14. https://doi.org/10.1155/2023/6662521

[7] Saurav, S. and Sinha, S. (2025) Evaluation of Cementitiously Stabilized Granular Materials for Low Volume Roads in India. *International Journal of Pavement Research and Technology*, **18**, 1065-1082. https://doi.org/10.1007/s42947-023-00399-4

[8] Fanta A.F. (2023) Amélioration des propriétés et caractéristiques mécaniques des sols argileux du type 2/1 par adjonction des liants dans la région de l'extrême-nord du cameroun. Master Thesis, University of Maroua.

[9] Ella, E.G. (2020) Caractérisation minéralogique, géochimique et géotechnique des formations altéritiques et leur implication dans la construction routière à l'extrême-nord du cameroun. Master Thesis, University of Maroua.

[10] Gidigasu, M.D and Kuma D.O.K. (1987) Engineering Significance of Lateralization and Profile Development Processes. *Proceedings of the 9th Regional Conf for Africa on Soil Mechanics and Foundation Engineering*, Dublin, 31 August-3 September 1987, 3-20.

[11] Logmo, E.O., Ngon, G.F.N., Samba, W., Mbog, M.B. and Etame, J. (2013) Geotechnical, Mineralogical and Chemical Characterization of the Missole II Clayey Materials of Douala Sub-Basin (Cameroon) for Construction Materials. *Open Journal of Civil Engineering*, **3**, 46-53. https://doi.org/10.4236/ojce.2013.32a006

[12] Kamtchueng, B.T., Onana, V.L., Fantong, W.Y., Ueda, A., Ntouala, R.F., Wongolo, M.H., *et al.* (2015) Geotechnical, Chemical and Mineralogical Evaluation of Lateritic Soils in Humid Tropical Area (Mfou, Central-Cameroon): Implications for Road Construction. *International Journal of Geo-Engineering*, **6**, Article No. 1. https://doi.org/10.1186/s40703-014-0001-0

[13] Kagonbé, B.P, Tsozué, D., Nzeukou, A.N., Basga, S.D., Belinga, R.E, Likiby, B. and Ngos III, S. (2020) Suitability of Lateritic Soils from Garoua (North Cameroon) in Compressed Stabilized Earth Blocks Production for Low-Cost Housing Construction. *Journal of Geosciences and Environmental Protection*, **11**, 658-669.

[14] Kagonbé, B.P., Souleymanou, B., Bakaïné, V.D., Belinga, R.E.B., Aziwo, B.T., Hamdja, A.N., *et al.* (2023) Assessment of Soils Developed on Various Formations in Maroua (Far North, Cameroon) for Production of Compressed Earth Bricks. *Open Journal of Applied Sciences*, **13**, 874-887. https://doi.org/10.4236/ojapps.2023.136070

[15] Japhet, T.D., Tchouata, K.J.H., Ngon Ngon, G.F., Ngapgue, F., Ngakoupain, B.L. and Tchedele, L.Y. (2022) Evaluation of Lateritic Soils of Mbé for Use as Compressed Earth Bricks (CEB). *Heliyon*, **8**, e10147. https://doi.org/10.1016/j.heliyon.2022.e10147

[16] Suchel, J.B. (1972) The Distribution of Rainfall and Rainfall Patterns in Cameroon, Contribution to the Study of the Climates of Tropical Africa. CEGET/CNRS, 287.

[17] Kagonbé, P.B., Klamadji, M.N., Özgür, C., Djoulaiyatou, D., Soureiyatou, Fadil-Djenabou, Bakaïné V.D., Yanné, E., Djoda, F.P. and Bandeya, D. (2025) Suitability of clays from Maroua (Far North Cameroon) and Physical Properties of Their Adobe Bricks Reinforced with Staff Waste Powder for Eco-Friendly Construction. *Journal of Ceramic Processing Research*, **26**, 547-558.

[18] Hervieu, J. (1970) Quaternary of North Cameroon. Diagram of Geomorphological

Evolution and Relations with Pedogenesis. *ORSTOM Notebook*, *Soil Science Serial*, **8**, 295-320.

[19] Tsozué, D., Nzeugang, A.N., Mache, J.R., Loweh, S. and Fagel, N. (2017) Mineralogical, Physico-Chemical and Technological Characterization of Clays from Maroua (Far-North, Cameroon) for Use in Ceramic Bricks Production. *Journal of Building Engineering*, **11**, 17-24. https://doi.org/10.1016/j.jobe.2017.03.008

[20] Gountie, D.M., Tsozue, D., Kpoumie, A. and Nzeukou, N.A. (2022) Identification of Major Sources Controlling Groundwater Geochemistry in Mount Makabaï in the Far-North of Cameroon (The Northernmost Part of the Pan-African Belt). *Acta Geochimica*, **42**, 266-289. https://doi.org/10.1007/s11631-022-00577-4

[21] Mailloux, A. and Chenard, J. (2011) Les essais qualitatifs réalisés sur les enrobés et leurs constituants. Presses de l'École des Ponts.

[22] AFNOR (1996) NF P 94-056: Analyse granulométrique. AFNOR.

[23] AFNOR (1993) NF P 94-051: Limites d'atterberg. AFNOR.

[24] Lérau, J. (2006) Mécanique des sols. INSA Editions.

[25] Djaani, M. and Benmansour, S.F. (2011) Stabilisation des sols gonflants de la ré-gion d'in-amenas par ajouts des liants hydrauliques. Master Thesis, Université Kasdi Merbah Ouargla.

[26] AFNOR (1995) NF P 94-050: Détermination de la teneur en eau. AFNOR.

[27] AFNOR (2001) NF EN 1097-6: Essais sur granulats. AFNOR.

[28] AFNOR (1999) NF P 94-093: Essais proctor. AFNOR.

[29] AFNOR (1997) NF P 94-078: Indice CBR. AFNOR.

[30] CEBTP (1984) Guide pratique de dimensionnement des chaussées pour les pays tropicaux. CEBTP.

[31] Thorez, J. (2003) L'argile, minéral pluriel. *Bulletin de la Société Royale des Sciences de Liège*, **72**, 19-70.

[32] Fabbri, B., and Fiori, C. (1985) Clays and Complementary Raw Materials for Stone Ware Tiles. *Mineralogica et Petrographica Acta*, **29A**, 535-545.

[33] Meseguer, S., Jordán, M.M., Pardo, F. and Sanfeliu, T. (2011) Geology and Application of Clays Used in Castellon Ceramic Cluster (NE, Spain). *Journal of Geography and Geology*, **3**, 132-140. https://doi.org/10.5539/jgg.v3n1p132

[34] Bachirou, L.N., Hermann, K.T.J., Emmanuel, F., Japhet, T.D., François, N.N.G., Kueda, R.P., *et al.* (2026) Physical Properties and Allowable Bearing Capacity of Lateritic Soils from Meiganga (Adamawa Region-Cameroon) for Their Use in the Dimensioning of Foundations. *Open Journal of Applied Sciences*, **16**, 32-47. https://doi.org/10.4236/ojapps.2026.161004

[35] Nanga Bineli, M.T. (2014) Caractérisation géologique et géotechnique des grav-eleux latéritiques d'ebolowa. Master Thesis, University of Yaoundé I.

[36] Autret, P. (1983) Latérites et graveleux Latéritiques. Institut des Sciences et Techniques de l'Équipement et de l'Environnement pour le Développement.

[37] O'Flaherty, C.A. (1988) Highway Engineering. Edward Arnold.

[38] Ola, S.A. (1975) Stabilization of Nigerian Lateritic Soils with Cement, Bitumen, and Lime. *Proceedings of the* 6*th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, Durban, 145-152.

[39] Osula, D.O.A. (1996) A Comparative Evaluation of Cement and Lime Modification of Laterite. *Engineering Geology*, **42**, 71-81. https://doi.org/10.1016/0013-7952(95)00067-4

[40] Bell, F.G. (2007) Engineering Geology. 2nd Edition, Butterworth-Heinemann.

[41] Amu O.O., Oluwole F.B. and Iyiola A.K. (2011) The Suitability and Lime Stabilization Requirement of Some Lateritic Soil Samples as Pavemen. *International Journal of Pure and Applied Sciences and Technology*, **2**, 29-46.

[42] Iyammi, B.M., Tchedele, L.Y., Alarba, S.T.A., Mache, J.R. and Mominou, N. (2023) Physico-Chemical, Mineralogical Characterization, and Ceramic Properties of Clay Materials from South Mindif (Far North, Cameroon). *JMST Advances*, **5**, 13-26. https://doi.org/10.1007/s42791-023-00047-9

[43] Murray, H.H. (2007) Chapter 8 Common Clays. In: *Developments in Clay Science*, Elsevier, 141-145. https://doi.org/10.1016/s1572-4352(06)02008-3

[44] Chahi, A., Petit, S. and Decarreau, A. (2002) Infrared Evidence of Dioctahedral-Trioctahedral Site Occupancy in Palygorskite. *Clays and Clay Minerals*, **50**, 306-313. https://doi.org/10.1346/000986002760358067

[45] Beuria, P.C., Biswal, S.K., Mishra, B.K. and Roy, G.G. (2017) Study on Kinetics of Thermal Decomposition of Low LOI Goethetic Hematite Iron Ore. *International Journal of Mining Science and Technology*, **27**, 1031-1036. https://doi.org/10.1016/j.ijmst.2017.06.018

[46] Schellmann, W. (1986) A New Definition of Laterite. *Geological Survey of India Memoirs*, **120**, 1-7.