

Research Article

Mineralogical and Geotechnical Properties of Clayey Vertisols from Northern Cameroon: To Provide a Scientific Basis for Future Stabilization and Engineering Applications

Jabin Pagouo^{1,*}, Bertin Pagna Kagonbe², Etienne Yanne¹, Raïdandi Danwe¹

¹Department of Civil Engineering and Architecture, National Advanced School of Engineering, University of Maroua, Cameroon

²Local Materials Authority Promotion (MIPROMALO), Yaounde, Cameroon

Abstract

This study presents an integrated geotechnical, mineralogical and geochemical characterization of clayey Vertisols developed under Sudano-Sahelian climatic conditions in northern Cameroon, with the aim to provide a scientific basis for future stabilization and engineering applications. Representative Vertisol samples were collected from the North and Far North regions and investigated using standard geotechnical tests, chemical analyses, and mineralogical identification by X-ray diffraction. The results reveal clay-rich materials dominated by fine fractions, with textures ranging from sandy clay to sandy heavy clay, and displaying low to high plasticity indices, reflecting strong smectitic influence. Geochemically, the Vertisols are characterized by high SiO₂ and Al₂O₃ contents, moderate to high Fe₂O₃ levels, elevated CIA values (57–83%), and significant cation exchange capacities, indicating advanced chemical weathering under seasonally contrasted tropical conditions. Mineralogical assemblages are composed by smectite, kaolinite, illite, quartz and K-feldspars, confirming both pedogenetic clay formation and inheritance from parent materials. These combined characteristics explain the pronounced shrink–swell behavior and vertic features observed in the field. Overall, the studied Vertisols exhibit physicochemical properties that make them promising raw materials for sustainable construction applications and environmental uses, if appropriate stabilization strategies are implemented to mitigate their expansive behavior.

Keywords

Cameroon, Clay Material, Mineralogy, Geotechnical Properties

1. Introduction

The term Vertisols was introduced in the American soil classification system to designate soils exhibiting distinctive physicochemical and structural properties associated with high clay contents and pronounced shrink–swell behavior [1,

2]. According to Murray [2], Vertisols are defined by a minimum clay content of $\geq 35\%$, a cation exchange capacity (CEC) of at least 30 meq/100 g, and the presence of characteristic structural features such as micro-relief called gilgai, deep desiccation cracks, and slickensides. These diagnostic properties

*Correspondence: Jabin Pagouo (Jpagouo69@gmail.com)

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are mainly related to the dominance of expansive clay minerals, particularly smectites, which impart a strong sensitivity to seasonal soil moisture variations [3-7]. As a result, Vertisols undergo significant volumetric changes during wetting and drying cycles, strongly influencing their mechanical, hydraulic, and engineering behavior [4, 6].

Globally, Vertisols occupy approximately 2.5% of the Earth's land surface and are predominantly distributed in regions characterized by marked seasonal contrasts in rainfall and temperature [4]. Large Vertisol landscapes are found in India [8], northern Australia [9] and tropical Africa [3, 5-7], where alternating wet and dry seasons promote the development of shrink-swell processes. In Africa, extensive Vertisol areas occur in northern Cameroon, Nigeria, Chad, Sudan, Ethiopia, and Somalia [3, 5-7, 10-17]. Due to their high natural fertility and water-holding capacity, Vertisols represent important agricultural resources [10, 16]. In addition, their mineralogical composition and fine-grained texture make them attractive as raw materials for various engineering and construction applications, particularly in the context of sustainable and low-cost building materials [7, 11-16].

From a morphological viewpoint, Vertisols typically exhibit dark olive-grey to blackish colors, occasionally grading to reddish hues depending on the concentration of iron oxides and the nature of secondary minerals [4, 10, 15, 17]. Although their total organic matter content is generally low, especially in terms of humic substances, the dark coloration observed in many Vertisol profiles is primarily attributed to the formation of stable clay-humus complexes rather than to organic matter accumulation [10, 14, 18-20]. Structurally, the ubiquitous presence of slickensides, polygonal cracking patterns, and micro-relief constitutes a key diagnostic feature of Vertisols worldwide, reflecting the dynamic interaction between clay mineralogy and hydrological cycles [21]. These structural features have important implications for land management, foundation stability, and material performance in civil engineering applications.

Several studies have reported that Vertisols are commonly dominated by smectitic clay minerals, accompanied by varying proportions of kaolinite, illite, quartz, feldspars, and iron oxides [7, 11, 12, 14, 17, 22]. The relative abundance of expansive smectites largely controls key physicochemical properties such as plasticity, cation exchange capacity, water retention, and shrink-swell potential. Consequently, detailed mineralogical and chemical characterization is essential for assessing the suitability of Vertisols for agricultural management and engineering use [29].

In Cameroon, Vertisols are mainly confined to the Sudano-Sahelian area, extending between latitudes 8° and 13° N and longitudes 12° and 16° E [23, 24]. These clay-rich soils are particularly widespread in the plains of the North and Far North and cover an estimated area of approximately 1.2 million hectares [3, 6, 10, 17, 22, 23; 26, 27]. Their accessibility and spatial extent represent a significant opportunity for re-

gional development. In these areas, two main types of Vertisols have been identified. Lithomorphic Vertisols develop on basic parent rocks and are mainly located south of Maroua and northwest of Mora, whereas topomorphic Vertisols occur in low-lying areas and floodplains, where seasonal water-logging strongly influences soil evolution [3, 11, 16, 23]. The geomorphological position and hydrological regime of these Vertisols control their physical behavior, fertility status, and suitability for technical applications.

Despite their considerable potential, the exploitation and utilization of Vertisols are constrained by intrinsic properties related to the presence of expansive clays, including high plasticity indices, pronounced shrink-swell behavior, and strong sensitivity to moisture variations [7, 11, 23, 28, 29]. These characteristics may limit their direct use in construction and civil engineering unless appropriate stabilization or treatment techniques are applied [29, 30]. Consequently, a comprehensive characterization of Vertisols, encompassing geotechnical, mineralogical, and chemical properties is required prior to any valorization strategy.

In this context, the present study aims to characterize clayey materials from northern Cameroon through an integrated physicochemical and mineralogical approach, with particular emphasis on Vertisols developed in the Far North Region. The objective is to evaluate their potential for valorization in agriculture and, more specifically, in the production of sustainable building materials if stabilized with lime or fiber based on analogous clays. The outcomes of this work are expected to contribute to a better understanding of local Vertisol resources and to support the development of context-adapted valorization strategies that are compatible with the climatic and geological conditions of northern Cameroon.

2. Material and Methods

2.1. Location and Physiography of the Study Area

Figure 1 shows the location of the study sites. The study area, situated in Cameroon's Far North and North regions, has a tropical climate with an extended dry season lasting about eight months (October-May). Average annual rainfall is 800 mm, and the mean temperature is 29 °C [31], with April being the hottest month and January the coolest. Vegetation consists of scattered trees and shrubs within grasslands, including *Acacia seyal*, *Balanites aegyptiaca*, *Faidherbia albida*, *Combretum* spp., *Bombax costatum*, and *Ziziphus mauritiana* [32, 49]. In Far North, the study area has a gentle slope from West to East, marked respectively by Mount Mandara, the Maroua plain, and the floodplain [33, 49]. Mount Mandara and Makabai constitute the high peaks of the area [49]. Their lithology is composed of pre- to syntectonic calc-alkaline/granitoids; greenstones made up of low- to medium-grade

Neoproterozoic volcano-sedimentary gabbros; Neoproterozoic metabasites associated with schists; and alluvium composed mainly of sand, clayey sand, and silty sand [7, 11, 34, 35, 49]. Due to their geological and topographical context and climatic conditions, these areas are favorable deposition zones for alluvial clay materials.

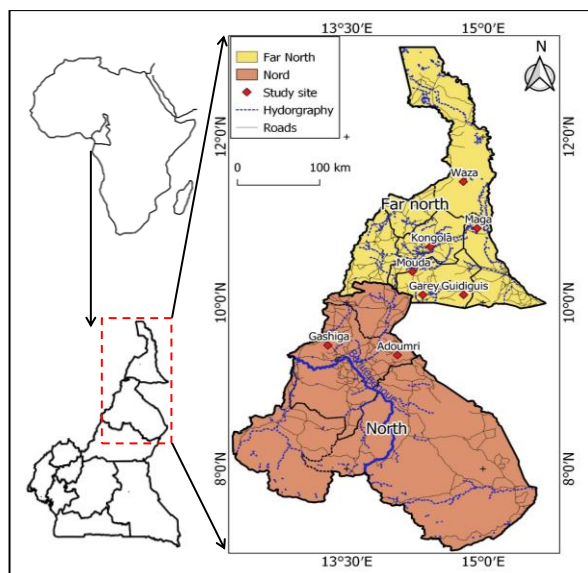


Figure 1. Location of the study sites.

2.2. Sample Strategy and Preparation

To achieve the study objectives, several field campaigns were carried out. Initial site investigations were performed to collect practical information on parameters such as clay layer thickness and spatial homogeneity. Soil color was assessed using the Munsell Soil Color Chart [36]. Collected samples were carefully packaged in plastic bags, labeled with an indelible marker, and transported to the laboratory for further analyses. In the North region, sampling was conducted at Gaschiga and Adoumri, while in the Far North region, the localities of Guidiguis, Garey, Mouda, Maroua, Maga, and Waza were selected for sample collection.

2.3. Laboratory Work

In the laboratory, clay samples were prepared according to the requirements of each analysis, including air-drying, crushing with a mortar and pestle, and sieving to remove coarse fragments. The samples were then analyzed for their geotechnical, chemical, and mineralogical properties. Geotechnical characterization included particle size distribution, Atterberg limits and methylene blue. These analyses were carried out at the National Laboratory for Civil Engineering of Cameroon (LABOGENIE). Both chemical and mineralogical compositions analysis were performed at the geochemistry unit of “Ci-

menteries du Cameroun” and the Laboratory of Clays, (Geochemistry and sedimentary Environment, University of Liège, Belgium) respectively.

Granulometric characterization was performed through a dual approach integrating dry sieving and sedimentation analysis to ensure full coverage of the clay particle size spectrum. As described in [37], the coarse fraction ($>80 \mu\text{m}$) was determined after oven drying the samples, followed by mechanical separation using a calibrated series of standard sieves. The particle size distribution indices were then calculated according to the mathematical expressions provided in Equations (1) and (2).

$$\% \text{ passing} = \frac{\text{weight retained}}{\text{Initial weight}} \times 100 \quad (1)$$

$$\% \text{ passing} = 100 - \% \text{ weight retained} \quad (2)$$

Particles smaller than $80 \mu\text{m}$ were analyzed through hydrometer sedimentation, applying Stokes' law to relate settling velocity in an aqueous medium to equivalent particle diameter. The soil suspensions were treated with sodium hexametaphosphate as a dispersing agent to ensure complete deflocculating. Density measurements were collected at specified time intervals between 15 s and 24 h. The resulting dataset enabled comprehensive particle size distribution assessment, supporting soil classification and evaluation of geotechnical parameters associated with adsorption processes.

Consistency parameters were evaluated through determination of the Atterberg limits, namely the liquid limit (WL), plastic limit (WP), and plasticity index (PI) on the fine fraction ($<400 \mu\text{m}$). Following the procedure described in [38], the liquid limit corresponds to the moisture content at which the soil paste merges after 25 blows in the Casagrande cup apparatus. The calculation of WL was performed according to Equation (3).

$$WL = WN \cdot (N/25)^{0.121} \quad (3)$$

WL = liquidity limit; W = water content; N = number of shocks

The plastic limit (WP) was established as the moisture content at which the soil, shaped into a cylindrical thread of 3 mm diameter, loses its plasticity and breaks apart. Its determination was carried out according to the relationship presented below.

$$Wp = 100 \left(\frac{Ph - Ps}{Ps - tare} \right) \quad (4)$$

Ph: weight of the wet sample; Ps: weight of the dry sample.

Computed from Equation (5), the plasticity index (PI) defines the moisture range over which the material exhibits plastic deformation. Beyond its use in classification systems, PI is commonly interpreted as a proxy for clay mineralogical characteristics and surface activity, thereby contributing to the assessment of the soil's engineering performance.

$$PI = WL - WP \quad (5)$$

The natural moisture content, expressed as the ratio of water mass to the mass of solid particles, was measured to provide a reference for subsequent analyses. Following the procedure described by [39], samples were carefully managed to maintain their in-situ characteristics during collection and transport. In the laboratory, the fresh mass of each sample (M_{wet}) was recorded prior to oven-drying at 105 °C until a constant dry mass (M_{dry}) was obtained. The moisture content was calculated following equation (6). Exchangeable cations were dosed by ammonium acetate extraction method at pH 7 and Cation Exchange Capacity (CEC) was determined using the sodium saturation method.

$$NMC = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100 \quad (6)$$

Chemical Composition, LOI, and CIA: Major element concentrations in clay samples were determined by X-ray fluorescence (XRF) on powdered specimens using a Philips XRF-SPW1404k at the geochemistry unit of Cimenteries du Cameroun. Fused glass beads were prepared to reduce matrix effects and ensure sample homogeneity. Results are reported as oxide weight percentages using fundamental parameter calculations. Loss on ignition (LOI) was measured as the weight loss after heating at 1000 °C for 2 h. The Chemical Index of Alteration (CIA), indicating the degree of chemical weathering [40], was calculated from molecular proportions (Equation (7)), with CaO^* corrected for contributions from carbonate and apatite [41].

$$CIA = Al_2O_3 / (Al_2O_3 + CaO^* + Na_2O + K_2O) \times 100 \quad (7)$$

Mineralogical Analysis: The mineralogical composition of the soils was determined using X-ray powder diffraction following the method of Moore and Reynolds [42]. To conduct this analysis, eight representative samples were selected for

preparation. The prepared powder vertisol samples (2g of each raw sample) were analyzed. After the analysis of the diffractograms generated by the Shimadzu model XRD-7000 X-ray diffractometer, the entire mineralogy of the selected sample of vertisol was conducted. The diffractometer was equipped with a Cu-K α radiation source ($\lambda = 1.5406 \text{ \AA}$), and operated between 5° and 80° of 2θ (2Theta) for around one hour per sample at 40 kV and 40 mA. Using “match! 3” data processing software, the major mineralogical phases were identified. Semi-quantitative mineralogy was estimated using Rietveld refinement (Bruker TOPAS).

3. Results and Discussions

3.1. Vertisols Morphology

Based on the morphological data summarized in the Table 1, all profiles display diagnostic features typical of Vertisols developed under Sudano-Sahelian environments in northern Cameroon. Overall, pronounced microrelief features called gilgai and well-developed desiccation cracks are systematically observed at the soil surface across all study sites, reflecting the strong shrink-swell behavior typical of Vertisols. The studied materials are uniformly classified as Vertisols and are characterized by dark colors, ranging from dark gray (2.5Y 6/1) to black (10YR 2/1), reflecting high clay contents and intense pedoturbation processes [3]. According to the literature review [7, 11, 12, 22, 25], the dark gray color of these Vertisols is mainly attributed to the high silica content of the clay fraction, which limits the stabilization and accumulation of organic matter throughout the soil profiles. In contrast, the occurrence of very dark to black colors (10YR 2/1) is commonly linked to the formation of stable organo-mineral complexes resulting from strong interactions between clay minerals and organic matter, as re-reported by Azinwi et al. [22] and Basga et al. [10].

Table 1. Morphology of the clay samples.

Soil provenance	Sample code	Color (dry)	Textural Class/ Structure	Boundary	Special feature
Gaschiga	J1	Dark gray (2.5Y 6/1)	Sandy heavy clay/Massive	Progressive Limit	Presence of quartz fragments
Adoumri	JII	Dark gray (2.5Y 6/1)	Sandy heavy clay/Massive	Progressive Limit	Presence of quartz fragments
Guidiguais	JIII	Dark gray (2.5Y 6/1)	Sandy clay/Massive	Progressive Limit	Presence of quartz fragments Some desiccations cracks
Garey	JVI	Black (10YR 2/1)	Sandy heavy clay/Massive	Progressive Limit	Presence of quartz fragments
Mouda	JV	Dark gray to black (5	Sandy heavy clay/Massive	Progressive Limit	Presence of quartz

Soil provenance	Sample code	Color (dry)	Textural Class/ Structure	Boundary	Special feature
		YR 2.5/1)			fragments
Congola	JVI	Dark gray (2.5Y 6/1)	Sandy heavy clay/Massive	Progressive Limit	Presence of quartz fragments Some desiccations cracks
Maga	JVII	Dark gray (2.5Y 6/1)	Sandy heavy clay/Massive	Gradual	Some desiccations cracks
Waza	JVIII	Dark gray (2.5Y 6/1)	Sandy heavy clay/Massive	Progressive Limit	Some desiccations cracks

These chromatic variations therefore reflect both mineralogical composition and organic matter dynamics, which jointly control the pedogenetic evolution and surface expression of Vertisols in the study area [21, 22, 25, 43]. The texture is dominated by sandy clay to sandy heavy clay classes, associated with a massive structure, indicating a low degree of structural differentiation resulting from repeated shrink–swell cycles [7, 21–23]. Horizon boundaries are predominantly progressive to gradual, attesting to vertical homogenization of the soil profiles driven by vertic movements [4, 10, 22, 25]. The recurrent presence of quartz grains and fragments, locally forming sandy deposits, suggests an inheritance from alluvial or colluvial parent materials and highlights the contribution of poorly weathered coarse fractions [7, 25]. Moreover, the frequent occurrence of desiccation cracks observed at several sites confirms the typical hydromechanical behavior of Vertisols, controlled by the dominance of expansive clay minerals [22, 43]. Overall, these morphological attributes indicate weakly differentiated soils, strongly affected by pedoturbation,

and are consistent with classical descriptions of Cameroonian Vertisols reported in the scientific literature [5–7, 10, 11, 22–24, 27].

3.2. Basic Physical Properties of the Clay Samples

Table 2 presents the key physical properties of the studied clay samples, including natural moisture content, particle size distribution, Atterberg limits, and pH. The combined analysis of the particle size distribution curves are illustrated in Figure 2 and the ternary diagram of the World Reference Base for Soil Resources in Figure 3 confirm the classification of the studied materials as Vertisols. The granulometric curves indicate a marked predominance of fine fractions, with high cumulative passing percentages at small sieve openings, which is fully corroborated by the positioning of the samples within the clay-dominated domains of the

Table 2. Physicals characteristics of the studied vertisols.

Samples								
	JI	JII	JIII	JIV	JV	JVI	JVII	JVIII
Particle size distribution (%)								
Clay: (<0.002 mm)	44.2	30.8	47.2	52.4	45.9	63.9	62.1	37.7
Silt: (0.002–0.02 mm)	21.2	15.3	12.0	13.3	24.9	16.2	15.8	11.7
Sand: (0.02–2 mm)	30.4	53.3	38.9	29.7	28.5	19.9	21.4	50.6
Gravel: (>2mm)	3.2	0.6	1.9	3.3	0.7	0.0	0.7	0.0
Atterberg Limits and CBR								
Liquid limit (%)	38.7	38.1	26.5	38.7	27.6	34.2	52.0	26.4
Plastic limit (%)	19.1	17.9	13.3	22.9	14.9	18.4	20.8	12.4
Plastic index	19.6	20.1	13.2	15.9	12.7	15.8	31.1	14.0
CBR	3.50	8.00	4.00	6.00	6.00	6.00	2.50	6.00

	Samples							
	JI	JII	JIII	JIV	JV	JVI	JVII	JVIII
pH and Organic Matter								
M.O (%)	3.3	1.2	2.9	5.5	9.5	4.1	5.5	2.7
pH	6.60	7.03	6.64	7.31	7.83	7.61	7.85	7.84

Most studied samples plot in the sandy heavy clay textural classes (JI, JIII, JIV, JV, JVI, JVII, JVIII) while a one extend toward sandy clay (JII), reflecting moderate variations in sand content without altering the overall fine-textured nature of the studied materials. This textural distribution confirms that the study materials constitutes the dominant fraction, consistent with the high proportions of fine particles inferred from the granulometric curves. Samples located closer to the very heavy clay domain likely exhibit higher smectitic clay contents, which explains the pronounced shrink-swell behavior observed in the field, including deep desiccation cracks, prismatic macrostructures and microrelief called gilgai. The slight dispersion of points within the clayey domain suggests local heterogeneities in parent material or depositional conditions, as well as the influence of pedoturbation processes typical of Vertisols [3, 22, 44]. Overall, the strong convergence between the granulometric curves and the textural triangle reinforces the reliability of the textural classification and highlights the dominant control of fine particles on the hydromechanical behavior and land-use constraints of these black clay soils. These characteristics are similar to those from Benue Valley clays in North region of Cameroon [3, 12-14, 22, 25] and Logon valley clays in Far North region of Cameroon [6, 7, 10, 11, 34, 17, 44].

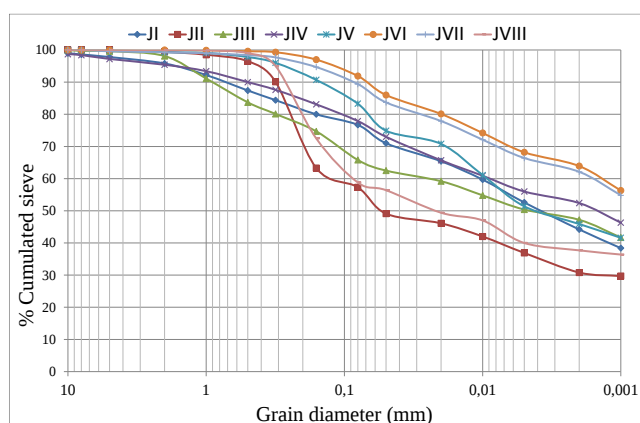


Figure 2. Grains size distribution of the clay samples.

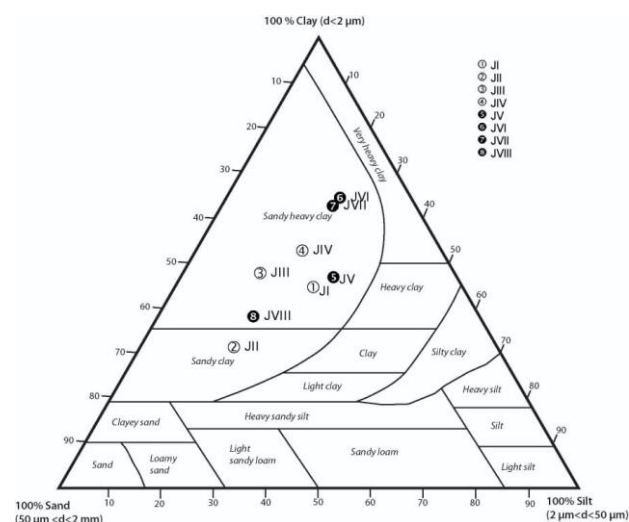


Figure 3. Ternary diagram from the Belgian classification of the clay samples.

The results of Atterberg Limits indicate a broad range of plasticity behaviors, which can be interpreted using the standard plasticity chart in relation to clay mineral content illustrated in Figure 4. The samples exhibit plasticity levels ranging from low (JIII, JV, JVI, JVIII) to medium (JI, JII, JIV) and high (JVII). Overall, samples plotting above the A-Line form a distinct cluster, with the majority of plastic clays positioned in the upper domain between smectite-rich and illite-rich compositions. The elevated liquid and plastic limits are attributable to the substantial surface area and elevated cation exchange capacity of smectite minerals [14, 22, 25, 44]. The corresponding CBR values (2.5-8%) reveal low bearing capacity, particularly for the sample exhibiting the highest PI (31.1%), which recorded the lowest CBR (2.5%). This inverse relationship reflects the typical mechanical response of clay-rich soils, where increased plasticity and clay activity reduce shear strength and load-bearing capacity. Consequently, the studied Vertisols are unsuitable for direct use as subgrade or construction material without prior stabilization.

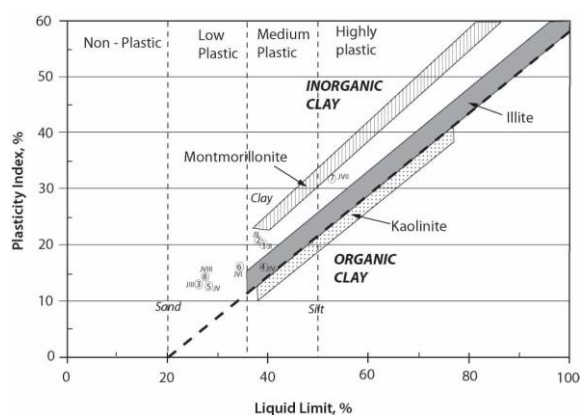


Figure 4. Casagrande's plasticity chart of the clay samples.

The pH values, ranging from 6.60 to 7.85, indicate generally acidic (6.60-6.64) to slightly alkaline (7.03-7.85) conditions, characteristic of Vertisols rich in swelling clays for

structural stability as well as the availability of major nutrients. The observed pH range is a direct result of the samples' mineralogical composition and geochemical weathering history. A pH below 7.0 indicates highly weathered clays saturated with H^+ , in which leaching has depleted most base cations. The exchange complex is therefore dominated by H^+ and Al^{3+} ions, which hydrolyze water to generate H_3O^+ [14, 45].

Organic matter contents vary widely from 1.2% to 9.5%, reflecting significant differences in organic inputs and the intensity of mineralization processes, strongly influenced by wetting-drying cycles. Low organic matter contents suggest rapid mineralization, whereas higher values indicate local conditions conducive to organic matter accumulation. This combined variability of pH and organic matter directly controls the physicochemical and geotechnical properties of Vertisols, particularly cation exchange capacity and shrink-swell behavior.

3.3. Chemical Characteristics

Table 3. Chemical Composition, LOI and Weathering Indices Analysis.

	Samples							
	J1	JII	JIII	JVI	JV	JVI	JVII	JVIII
SiO ₂	64.60	61.35	59.41	45.77	64.53	60.93	58.40	63.35
Al ₂ O ₃	12.05	14.69	14.85	15.34	13.64	13.68	13.12	11.94
Fe ₂ O ₃	7.50	6.90	5.15	10.74	6.94	4.92	7.62	8.92
K ₂ O	0.98	2.23	1.24	1.10	1.86	2.62	2.14	1.39
MgO	0.39	0.83	0.33	1.45	0.60	0.56	0.86	0.71
TiO ₂	0.43	0.51	0.56	0.77	0.55	0.23	0.55	0.26
P ₂ O ₅	0.08	0.10	0.00	0.28	0.08	0.00	0.00	0.10
CaO	1.05	1.59	9.75	8.13	0.39	0.96	2.47	1.87
NaO	0.40	0.92	0.08	2.44	0.79	1.57	0.60	0.37
MnO	0.16	1.10	0.05	0.39	0.31	0.27	1.27	0.38
LOI	9.31	9.78	8.59	13.51	10.08	15.42	12.99	10.71
SiO ₂ /Al ₂ O ₃	5.36	4.18	4.00	2.98	4.73	4.45	4.45	5.31
CIA	83.22	75.61	57.30	56.79	81.78	72.65	71.60	76.71
CEC	28.22	19.04	14.79	34.79	31.79	19.14	30.69	23.66
CaCO ₃ (%)	5.88	5.60	5.85	7.48	8.80	7.00	6.95	4.88

Based on the geochemical data summarized in the Table 3, these studied Vertisols exhibit a chemical signature typical of Vertisols developed under Sudano-Sahelian environments in

Cameroon. The major element composition is dominated by silica (SiO₂: 45.8-64.6%) and alumina (Al₂O₃: 11.9-15.3%), reflecting the abundance of aluminosilicate clay minerals, in

agreement with the high clay contents (up to 64%) and the elevated plasticity indices observed. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios, ranging from 3.0 to 5.4, suggest a predominance of smectite-type minerals [10, 34] with an illitic tendency, together with a variable contribution of inherited quartz phases, as commonly reported for Vertisols in Benue [14, 22, 25, 26] and Logone Valley [5, 6, 10, 15]. Moderate to high Fe_2O_3 (4.9-10.7%) and TiO_2 (0.23-0.77%) contents reflect the influence of mafic to intermediate parent materials and indicate an advanced degree of chemical weathering [7]. This interpretation is supported by the high values of the Chemical Index of Alteration (CIA: 57–83%), pointing to intense chemical weathering under climatic conditions favorable to desilication and relative enrichment in Al and Fe. The loss on ignition (LOI: 8.6-15.4%) and the high cation exchange capacity (CEC: 14.8-34.8 meq/100 g) attest to the high activity of expansive clay minerals and to a significant retention of basic cations, particularly Ca^{2+} and Mg^{2+} , consistent with the notable CaO contents and the measurable presence of CaCO_3 (4.9-8.8%). Finally, neutral to slightly alkaline pH values (6.6–7.9), combined with variable organic matter contents, confer a buffered geochemical functioning to these Vertisols, which favors structural stability but also explains the pronounced shrink–swell behavior characteristic of Cameroonian Vertisols described in the literature [3; 7, 10, 11, 14, 22, 25-27].

3.4. Mineralogical Composition of the Studied Vertisols

X-ray diffraction (XRD) analyses of the studied Vertisols presented in Figure 5 reveal the presence of a suite of clay and non-clay minerals, reflecting both pedogenetic transformation and inheritance from parent materials. The presence of smectite is inferred from basal reflections at ~ 14 Å; however, glycolation was not performed and therefore confirmation of expandable layers remains tentative, consistently identified by basal reflections at 14.71 Å and 4.48 Å. These reflections are diagnostic of expandable 2:1 layer silicates typical of vertic soils undergoing frequent shrink–swell cycles [3, 6, 7, 11, 14].

Associated clay minerals include kaolinite, with a distinct reflection at 7.16 Å, and illite, with a characteristic peak at 10.01 Å, indicating the coexistence of both secondary and residual clay species developed under tropical weathering conditions [14, 42]. The co-occurrence of these clay minerals aligns with recent observations of mixed clay assemblages in Vertisols and weathering profiles developed in Soudano-sahelian areas of Cameroon, where smectite formation under pedogenic conditions has been documented [5-7, 11, 14, 22, 27, 46].

Non-clay minerals are represented by quartz and potassium feldspars (K-feldspars) identified at a series of reflections: quartz at 4.25 Å, 3.34 Å, and between 2.45 Å and 1.37 Å, and K-feldspars at 4.04 Å, 3.47 Å, 3.24 Å, and 3.18 Å. The presence of these primary silicates, also re-reported in regional soil studies of alluvial and granitic derived Vertisols in northern Cameroon, confirms the partial preservation of parent material mineralogy despite ongoing weathering processes [5-7, 11, 14, 22, 27, 46].

The combined occurrence of clay minerals (smectite, kaolinite, and illite) and resistant primary phases (quartz, feldspars) is consistent with mineralogical characterizations of Vertisols and other fine-textured tropical soils under seasonally contrasted climates [7, 22, 48]. Such assemblages are also in line with broader regional soil studies that highlight the coexistence of pedogenically formed clays with inherited detrital minerals in semiarid to sub humid contexts in Africa [22, 46, 47].

Overall, the mineralogical framework of these Vertisols highlights a balance between inherited detrital minerals and secondary clay minerals formed by in situ weathering processes. This balance is consistent with the pronounced vertic properties observed morphologically (high clay content, dark coloration, strong pedoturbation) and has important implications for soil behavior, including shrink–swell potential, hydraulic conductivity, and geotechnical properties. The preservation of quartz and feldspars alongside abundant smectite indicates that these soils retain memory of their parent sediments while dynamically evolving under tropical weathering regimes.

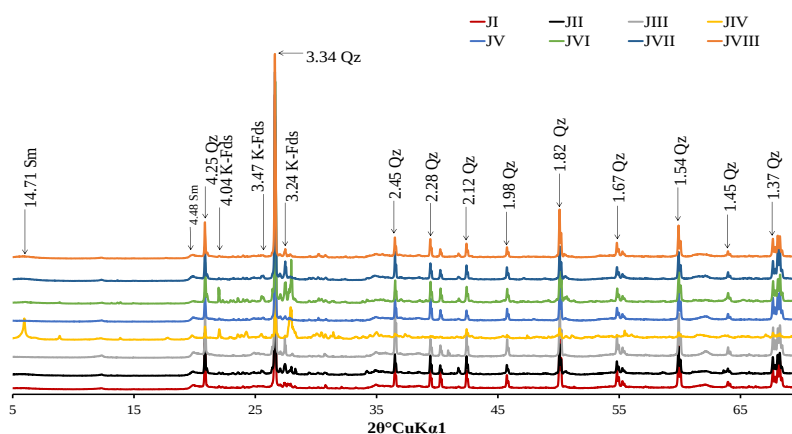


Figure 5. X-Ray Diffractograms of Studied Soil: Sm: Smectite, Ka: Kaolinite, Il: Illite, Go: Goethite Qz: Quartz, K-Felds: K-Feldspar.

4. Conclusions

This study provides a comprehensive characterization of clayey Vertisols from the Sudano-Sahelian zone of northern Cameroon through a combined morphological, geotechnical, mineralogical and geochemical approach. Field observations confirm the presence of typical vertic features, including gilgai micro-relief, deep desiccation cracks and massive, weakly differentiated profiles, reflecting intense pedoturbation driven by seasonal wetting-drying cycles. Granulometric analyses reveal a marked dominance of fine fractions, with most samples classified as sandy heavy clays to sandy clays, consistent with their Vertisol classification and their strong shrink-swell potential.

The geotechnical properties, particularly the wide range of Atterberg limits and plasticity indices, highlight the strong control exerted by clay mineralogy on soil behavior. Samples with medium to high plasticity are closely associated with smectite-rich assemblages, which confer high surface activity, elevated cation exchange capacity and significant water sensitivity. Geochemical data further indicate advanced chemical weathering, as evidenced by high CIA values and relative enrichment in Al_2O_3 and Fe_2O_3 , while the presence of quartz and feldspars reflects partial inheritance from alluvial and crystal-line parent materials.

Mineralogical analyses confirm that smectite is the dominant clay mineral, accompanied by kaolinite and illite, together with non-clay minerals such as quartz and K-feldspars. This mixed mineralogical assemblage explains both the favorable adsorption capacity and the problematic expansive behavior of these Vertisols. From an applied perspective, the physicochemical properties of the studied materials suggest a strong potential for valorization in agriculture, environmental remediation and, more specifically, in the production of sustainable construction materials such as fired bricks, compressed earth blocks or stabilized clay products. However, their high plasticity and swelling capacity require careful consideration and the implementation of suitable stabilization techniques to ensure long-term mechanical performance.

Overall, this work contributes to a better understanding of Vertisol resources in northern Cameroon and provides a scientific basis for their rational and context-adapted valorization in building material if stabilized with lime or fiber based on analogous clay. The results highlight the importance of integrating mineralogical and geochemical information into geotechnical assessments in order to optimize the use of local clay materials under tropical and semi-arid conditions.

Abbreviations

WL	Liquid Limit
WP	Plastic Limit
PI	Plasticity Index
Ph	Weight of the Wet Sample

Ps	Weight of the Dry Sample
pH	Hydrogen Potential
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CIA	Chemical Alteration Index
XRF	X-ray Fluorescence
LOI	Loss on Ignition
LABOGENIE	National Laboratory for Civil Engineering of Cameroon

Author Contributions

Jabin Pagouo: Conceptualization, Writing – original draft, Resources

Bertin Pagna Kagonbe: Formal Analysis, Methodology

Etienne Yanne: Writing – review

Raïdandi Danwe: Supervision

Data Availability Statement

Data used in this article are available upon request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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