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Statistical modeling of meiganga soils mechanical parameters: regression and correlation approach

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Abstract

In Meiganga, as in many tropical areas, lateritic soils are both an abundant resource and a source of uncertainty for engineers. Their behavior, inherited from a long history of weathering in a humid climate, often defies conventional normative frameworks, while heavy investigative equipment remains difficult to access. Based on this observation, this study aims to characterize the physical and mechanical properties of Meiganga soils and, on this basis, to develop empirical models for predicting their shear strength parameters from simple physical measurements. Seventy-two samples, taken from nine sites during the dry and rainy seasons, were subjected to physical tests and direct shear tests under unconsolidated, undrained conditions. The results reveal a strong dominance of the fine fraction (<0.08 mm: 28.8–82.9%), high plasticity (mean $I_p \approx 28\%$) and marked water variability. Apparent cohesion ranged from 18.9 to 32.1 kPa and internal friction angle from 19.5° to 31.2° . Statistical analyses (Pearson correlations, polynomial regressions) show that the friction angle is mainly controlled by the water content and fine grain size (w , $d_{0.08}$, S_r), while cohesion depends mainly on the plasticity index and the fine fraction (I_p , $d_{0.08}$). The models developed offer good predictive performance (R^2 up to 0.97; $RMSE < 4$ kPa for cohesion and $< 3^\circ$ for ϕ). These tools provide a reliable solution for the preliminary and rapid estimation of shear parameters for lateritic soils in tropical contexts where data is limited.

Keywords Meiganga, Lateritic soils, Physical properties, Shear strength, Modeling

1 Introduction

Lateritic soils, produced by intense weathering in tropical climates, are an essential construction material for infrastructure in hot and humid regions. However, their widespread use in civil engineering for roads, platforms, and foundations is likely challenging due to the complexity of their geotechnical behavior, characterized by high heterogeneity, high plasticity, and strong sensitivity to water content variations [1]. Among the key mechanical properties, shear strength is fundamental, as it directly determines the stability of structures. This strength comes from the interaction of several mechanisms:



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intergranular friction, cohesion linked to fines and natural cements (iron and aluminum oxides), and pore pressures [2, 3].

Scientific literature confirms the major influence of physical and state properties on shear parameters (c' , ϕ'), in particular water content, fine fraction, and plasticity index [1, 4]. However, direct determination of these parameters through laboratory testing (direct shear, triaxial) remains costly, time-consuming, and difficult to implement systematically. This constraint is particularly acute in many African contexts, where laboratory capacity and financial resources for in-depth geotechnical investigations are often limited [5, 6].

Faced with these challenges, establishing robust empirical correlations between simple-to-measure physical parameters (such as water content, Atterberg limits, or density) and strength characteristics is a pragmatic and economically viable alternative for reliable preliminary estimation. Although several models have been proposed internationally [1, 4, 7, 8], their applicability remains highly dependent on the local geological, mineralogical, and climatic context. This natural variability in laterites underscores the need to develop and validate region-specific correlations [5, 6, 9, 10].

The present study focuses on the town of Meiganga, in the Adamawa region of Cameroon, which is built on lateritic formations that are widely used but insufficiently characterized from a geotechnical point of view. This work aims to fill this gap by establishing, based on a field and experimental campaign, statistical prediction models adapted to the laterites of Meiganga. Based on physical characterization and direct shear tests, correlation and regression analyses (simple and multiple) are conducted. The performance of the empirical models developed is rigorously evaluated using recognized statistical indicators (adjusted coefficient of determination R^2 , root mean square error (RMSE), and mean absolute error MAE). The ultimate goal is to provide practicing engineers with simple, reliable, and directly applicable prediction tools for realistic estimation of shear strength in tropical contexts where data are limited.

2 Experimental methods

2.1 Study site locations and sampling

The lateritic soils studied were sampled in nine representative neighborhoods of the city of Meiganga (Adamawa, Cameroon): Doukouloukou, Gbakoungué, Ngoa-Ekellé, Pitoa, Zandaba, Rue 24, Sabongarie, Yelwa, and Ngassiri. This selection aims to cover the pedological and geotechnical variability of lateritic formations at the urban scale. A total of 45 samples of reworked soil (five per neighborhood) and 27 samples of intact soil were collected. The samples were taken manually using an auger, at an average depth of approximately 1.2 m, according to a staggered grid with a pitch of approximately 100 m. This strategy ensures a homogeneous distribution of sampling points and good spatial representativeness. This depth corresponds to the loose, uncemented surface horizon of the lateritic profile, which is most relevant for shallow foundations and earthworks. The location of the study area and the distribution of sampling sites are shown in Figs. 1 and 2. Physical tests (water content, Atterberg limits, grain size, density) were performed on reworked samples ($n = 45$). Direct shear tests (UU) were performed on undisturbed samples ($n = 27$). These were collected using a thin-walled Shelby tube and trimmed directly into the shear box.

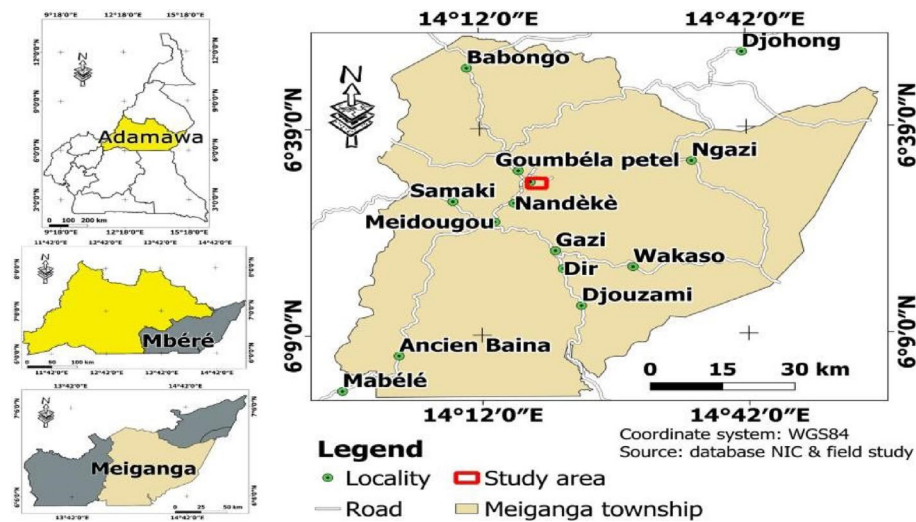


Fig. 1 Location of the study area (source: field data) (a) map of Cameroon, (b) maps of Mbéré division, (c) study area

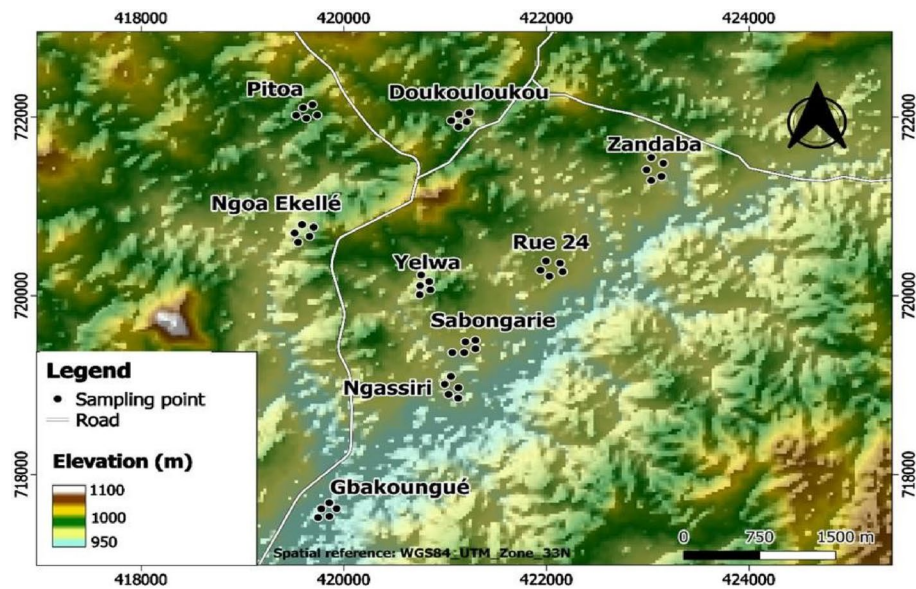


Fig. 2 Well sampling map. (source: field data).

2.2 Experimentation

The natural water content was determined in accordance with NF P 94 – 050 standard [11]. The granulometric analysis was carried out by dry sieving on the fraction greater than 0.08 mm according to NF P 94 – 056 standard [12], while the Atterberg limits were measured on the fraction less than 400 μm in accordance with NF P 94 – 051 standard [13]. The plasticity limit was obtained using the roller method and the liquidity limit using the Casagrande apparatus, a method equivalent to that of Vasilev. The plasticity, liquidity, and consistency indices were calculated from these measurements. The density of the solid grains was determined using a pycnometer in accordance with NF P 94 – 054 [14] standard, and the bulk density (ρ) was measured using the cutting kit method following NF P 94 – 053 standard [15]. Derived parameters such as dry density (ρ_d), degree

of saturation, void ratio, and porosity were calculated using standard soil mechanics relationships in order to characterize the compactness and structure of the materials.

Mineralogical analyses (XRD, SEM) were not performed in this study; references to clay mineralogy are based on regional literature [6, 8, 9].

Shear strength was evaluated by direct shear tests carried out under unconsolidated and undrained (UU) conditions, in accordance with NF P 94 – 074 standard [16], allowing the determination of apparent cohesion (c) and internal friction angle (ϕ). The direct shear tests were performed using a square shear box of 60 mm $\times$ 60 mm, under normal stresses of 100, 200, and 300 kPa. A constant shear rate of 0.5 mm/min was applied. For each of the 72 samples, three specimens were tested at each normal stress, giving a total of 216 shear tests. The tests were carried out under unconsolidated, undrained (UU) conditions with no back pressure.

The relationships between physical parameters and shear strength were analyzed using Pearson correlations and linear and polynomial regression models. This approach makes it possible to identify the dominant parameters while maintaining a robust physical interpretation, adapted to lateritic soils characterized by high variability. The use of second-order polynomial models is justified by the nonlinear nature of the interactions between water content, particle size distribution, and the mechanical behavior of partially saturated soils. The full dataset of 72 samples was split into training (80%, $n = 57$) and validation (20%, $n = 15$) subsets. A stratified random split was used, with stratification based on sampling site to ensure that each neighbourhood contributes proportionally to both subsets. The seed was set to 123 for reproducibility. The validation set was kept completely untouched during model development. It was used only once after the final model was selected, to evaluate generalisation performance. While 72 samples are modest for complex models, model complexity is low (5–6 predictors, no hidden layers) and the 10-fold cross-validation performed on the training set confirmed that the selected models are stable (coefficient of variation of CV-RMSE < 5%).

3 Results and discussions

The physical characteristics of soils in the town of Meiganga were studied using 45 samples of reworked soil and 27 samples of undisturbed soil. The percentage of particles passing through a 0.080 mm sieve and the soil consistency parameters are presented in the Table. 1

3.1 Water content and fine particles smaller than 0.080 mm

The physical characteristics of the samples, presented in Table 1, reveal significant water variability directly related to environmental conditions and the nature of the material. The natural water content ranges from 6.47% to 30.10% (average of 17.21%), with a high coefficient of variation (54.91%). This significant dispersion is an intentional consequence of the sampling methodology, designed to capture the critical seasonal influence in tropical climates: 20 samples were taken during the rainy season (May-June) and 25 during the dry season (September-October). This approach is essential because the geotechnical properties of laterites are strongly controlled by water content, a factor that directly influences their mechanical behavior and durability in structures, as confirmed by recent studies on the variability of soil parameters derived from gneiss in humid tropical areas [17].

Table 1 Fine particle content and consistency characteristics of soils

Statistical indices	Natural water content ω	Degree of saturation S_r	Liquidity limit ω_L	Plasticity limit ω_n	Plasticity index p_I	Liquidity index I_L	Consistency index I_c	d0.08 mm particle content
Maximum value $X_{\max}$ (%)	30.10	57.28	66.00	37.60	42.00	0.35	2.50	82.90
Minimum value $X_{\min}$ (%)	6.47	12.23	28.80	4.40	16.90	-1.50	0.70	28.80
Average value X_{avg} (%)	17.21	33.33	50.93	22.79	28.02	-0.23	1.24	52.05
Standard deviation	9.45	17.99	8.67	6.64	6.47	0.38	0.38	14.17
Coefficient of variation (%)	54.91	53.96	17.02	29.13	23.08	-167.08	30.62	27.22

The impact of this water variability is also visible in the degree of saturation, which varies from 12.23% to 57.28% (average of 33.33%). These values are consistent with the ranges observed by [18] on the ferrallitic soils of Bafoussam, although the averages in Meiganga are lower. This divergence can be explained by local pedoclimatic and topographic factors (rainfall, evapotranspiration, drainage) that modulate the intensity of weathering and water retention, a fundamental principle in the genesis of laterites highlighted by [1]. The dominant clay texture, which promotes high water retention [19], amplifies this sensitivity to climatic conditions.

The granulometric characterization confirms the predominance of the fine fraction in these soils. The proportion of particles smaller than 80 μm ranges from 28.80% to 82.90%, with an average of 52.05%, classifying these materials as “fine.” This composition is comparable to that observed in the lateritic soils of the Adamawa region used for the manufacture of CEB, where clay and silt fractions play a decisive role [8]. From a geotechnical point of view, this predominance of fines, coupled with water sensitivity, implies potentially problematic behavior for structures. As noted by [3, 20], and as recently demonstrated by [9] in their study on soil property modeling, a high fine content and variations in saturation generally lead to increased compressibility and slow consolidation settlement due to reduced permeability.

Consequently, the high proportion of fine particles ($< 80 \mu\text{m}$) and the wide range of natural water content identified in Meiganga indicate the imperative need to consider these parameters as key control variables in the development of predictive models for shear strength. They are key indicators of deformation potential and sensitivity to environmental conditions, directly related to the mineralogy of clays (kaolinite, illite) and their activity, as identified by systematic mineralogical and chemical analyses [21, 22]. Ignoring this variability would mean underestimating the risks of differential settlement and instability for shallow foundations, whose design in tropical areas requires a rigorous estimation of long-term deformation.

3.2 Atterberg limits and mechanical behavior

The Atterberg properties presented in Table 1 reveal characteristics that are essential for understanding the mechanical behavior of the lateritic soils of Meiganga. These

parameters, which are closely linked to mineralogy and grain size, are key indicators of the suitability of soils for use in earthen construction and as foundation support.

The liquidity limit (ω_L) shows a wide range of variation, from 28.80% to 66.00% (average = 50.93%). This variability reflects the heterogeneity of lateritic weathering profiles. These values are comparable to those reported for other Cameroonian laterites that can be used in ceramics or compressed earth blocks (CEB), as shown by [23] for the Yaoundé region and [8] for Garoua-Boulai (ω_L from 29.2% to 51.63%). However, they are significantly higher than those observed by [24] on other lateritic profiles. This divergence, which is common in the study of laterites [10], highlights the decisive influence of the intensity of pedogenic weathering and local mineralogical composition. Based on regional mineralogical studies on similar lateritic soils from the Adamawa and North regions [8, 22], the clay fraction is expected to be dominated by kaolinite with minor illite. Thus, the fine fraction of these soils is predisposed to have a clay activity that results in high Atterberg limits.

The plasticity index (PI) varies between 16.90% and 42.00% (average = 28.02%). These values classify Meiganga soils as plastic to very plastic clays (Class A3 according to the GTR [25]). Such plasticity is a hallmark of mature, fine-grained laterites, implying increased geotechnical risks: extreme sensitivity to water variations, a tendency to shrinkage-swelling, and potentially high compressibility that can lead to significant settlement under load [3]. This contrasts sharply with the low plasticity indices (< 16.5%) measured on hardened and gravelly lateritic horizons in Cameroon, which are used as road construction materials [26, 27]. This radical difference confirms that geotechnical behavior is intrinsically linked to the horizon of the weathering profile under consideration, with loose surface horizons being much more plastic and sensitive to water than deep cemented horizons.

The state indices (Liquidity Index LI and Consistency Index CI) quantify this water sensitivity. The LI ranges from – 1.50 (solid state) to 0.35 (plastic state), and the CI from 0.70 to 2.50. These wide ranges of values, similar to those observed on other ferrallitic soils in Cameroon [18], illustrate the extreme behavioral transition that these soils undergo between the dry and wet seasons. A soil can thus change from a firm and load-bearing state (CI > 1.25) to a plastic, even soft state, with drastically reduced bearing capacity. This critical transition is at the heart of the stability problems of earth structures and justifies the need for predictive models adapted to the local context, as recommended by [9] for regions with limited geotechnical data.

The in-depth statistical analysis conducted by [8] on similar soils demonstrates the close link between these Atterberg parameters and the mechanical characteristics of soils and CEB. It reinforces the importance of the characterization approach adopted in Meiganga, which integrates these fundamental parameters to develop robust engineering tools adapted to the practical constraints of construction sites in tropical areas.

3.3 Soil density parameter

Table 2 shows the experimental results for soil density parameters in the city of Meiganga.

Table 2 shows that the density of solid grains varies between 2.43 g/cm³ and 2.72 g/cm³, with an arithmetic mean of 2.59 g/cm³, a standard deviation of 0.07, and a coefficient of variation of 2.78%. These values are consistent with those reported by [8] on the

Table 2 Density parameters

Statistical indices	Density of solid grains $\rho_s \text{ g/cm}^3$	Soil density $\rho \text{ g/cm}^3$	Dry density of soil $\rho_d \text{ g/cm}^3$	Void ratio e	n porosity (%)
Minimum value $X_{\min}$	2.43	1.06	0.83	0.35	24.40
Maximum value $X_{\max}$	2.72	2.51	1.99	1.98	67.87
Average value X_{avg}	2.59	1.88	1.61	0.68	39.01
Standard deviation	0.07	0.35	0.30	0.40	11.14
Coefficient of variation (%)	2.78	18.40	18.35	59.10	28.55

lateritic soils of Mbé (Adamawa, Cameroon) and by [28] on the lateritic soils of Yaoundé (Center, Cameroon), where the density of solid grains varies between 2.15 g/cm³ and 2.72 g/cm³, with an average of 2.55 g/cm³. Similarly, for the lateritic soils of Yaoundé, this density ranges from 2.60 g/cm³ to 2.81 g/cm³, with an average of 2.69 g/cm³. However, these values differ from those obtained by [29] for aluminosilicate-rich soils in Puerto Rico, where the density of solid grains is less than or equal to 3.05 g/cm³. Overall, the densities measured are relatively high, which can be explained by the presence of iron oxide and silicate in the soils, contributing to their specific geochemical composition, typical of clayey and lateritic soils.

The bulk density (ρ) of the soils varies between 1.06 g/cm³ and 2.51 g/cm³ with an arithmetic mean of 1.88 g/cm³, a standard deviation of 0.35, and a coefficient of variation of 18.40%. These values are relatively higher than those obtained by [18] for the ferrallitic soils of Bafoussam (ranging from 1.30 g/cm³ to 1.89 g/cm³ with an arithmetic mean of 1.58 g/cm³, a standard deviation of 0.11, and a coefficient of variation of 6.89%). This difference in value can be explained by the percentage of particles smaller than 0.080 mm obtained for each soil: for Meiganga soils, we have an arithmetic mean of 52.05%, and for Bafoussam soils, a higher arithmetic mean of 88.01%. These values fall within the range of 1.00 g/cm³ to 1.98 g/cm³, according to [30].

The dry density varies from 0.83 g/cm³ to 1.99 g/cm³, with an arithmetic mean of 1.61 g/cm³, a standard deviation of 0.30, and a coefficient of variation of 18.35%. This variation can be explained by the strong influence of water content on soil density. Porosity values vary between 24.40% and 67.87%, with an arithmetic mean of 39.01%, a standard deviation of 11.14, and a coefficient of variation of 28.55%. These values are in the same proportions as those obtained by [31] (35.06% – 65.27%) on the soils of the city of Amti-man (Chad).

The relatively high values for solid grain density and the low values for porosity and void ratio give the soils of Meiganga their microporous character.

3.4 Shear strength properties and geotechnical variability

The shear strength parameters of Meiganga lateritic soils, determined by direct shear tests under unconsolidated and undrained (UU) conditions, reveal marked spatial heterogeneity, characteristic of tropical weathering profiles. The apparent cohesion (c) and internal friction angle (ϕ) values presented in Table 3 vary from 18.93 kPa to 32.05 kPa and from 19.47° to 31.24°, respectively.

This dispersion reflects the complexity of the combined resistance mechanisms specific to laterites: intergranular friction, cohesion linked to the fine plastic matrix, and

Table 3 Shear strength values of Meiganga soils

ZONE	Cohesion c (kPa)	Angle of internal friction ϕ (°)
DOUKOULOUKOU	22.53	21.33
GBAKOUNGUE	18.93	20.60
NGASSIRI	28.74	20.47
NGOA-EKELLE	26.15	23.75
PITOA	32.05	31.24
RUE 24	30.26	29.12
SABONGARIE	27.34	29.42
YELWA	19.8	19.47
ZANDABA	25.25	24.55

Table 4 Statistical analysis of shear strength parameters of meiganga soils

Parameter	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Cohesion c (kPa)	18.93	32.05	≈ 25.9	≈ 4.6	$\approx 17-18$
Friction angle ϕ (°)	19.47	31.24	≈ 24.9	≈ 4.6	$\approx 18-19$

cementation by iron and aluminum oxides, as described in mineralogical and geochemical studies on similar materials in the region [22, 23].

Analysis of the results distinguishes two main mechanical behaviors. On the one hand, the Pitoa and Rue 24 sites exhibit high resistances ($c > 30$ kPa, $\phi \approx 30^\circ$). These values are consistent with soils with a better-developed granular skeleton and more pronounced lateritic cementation, favoring both friction and cohesion. Similar characteristics were observed in the upper horizons of Garoua-Boulai, where friction angles between 29.2° and 34.8° were measured, associated with good bearing capacity for shallow foundations [8]. On the other hand, the Yelwa and Gbakoungué sites show weaker parameters ($\phi \approx 20^\circ$, $c \approx 20$ kPa). This behavior is typical of soils where a fine, plastic matrix dominates, with strength being governed more by cohesive forces than by friction. This negative correlation between fine content/plasticity and friction angle has been widely documented [3, 7] and is reflected in the high plasticity index values measured at Meiganga.

The average values obtained ($c \approx 25.9$ kPa; $\phi \approx 24.9^\circ$) fall within the range's characteristic of tropical lateritic and clay-loam soils, as reported by [20]. They are also comparable to the results of regional studies. For example, studies on soils of Bafoussam [18] and laterites in Garoua-Boulai [8] report cohesion and friction angles of the same order of magnitude for loose surface horizons. It is crucial to note that these parameters, measured under UU conditions, represent apparent cohesion including the effects of undrained suction. Their value can therefore decrease significantly under prolonged saturated conditions, a critical factor for the long-term stability of structures, as highlighted by [2] and, more recently, studies on the durability of stabilized soils [32]. Apparent cohesion in UU tests of unsaturated lateritic soils is not a true cohesive intercept but is partly due to matric suction [19, 32]. The UU test is relevant for short-term stability problems in tropical climates because of rapid loading during rainfall events.

Statistical analysis of the data (Table 4) confirms this variability, with coefficients of variation of around 17–19% for both parameters. Similar moderate variability has been observed in the geotechnical properties of lateritic gravels derived from gneiss in Cameroon, attributed to local hydromorphic conditions [17].

This heterogeneity fully justifies the development of a correlative and predictive approach. The Garoua-Boulai study demonstrated the power of multivariate analyses

to link the mechanical properties of soils and compressed earth blocks (CEBs) to simple physical parameters [8, 9]. Their models for predicting the strength of earth blocks, based on sand content, plastic limit, and cement, achieved an R^2 of.

96.65%. Applying a similar methodology to the Meiganga data, seeking correlations between (c , ϕ) and parameters such as fines content ($< 80 \mu\text{m}$), Atterberg limits (P_L , ω_L), or methylene blue value (VBS), would make it possible to generate reliable and economical estimation tools. These models would be particularly valuable in a context where access to direct mechanical testing is limited, thus meeting the need for practical engineering in resource-constrained tropical areas, as identified by [9].

3.5 Correlations between shear strength characteristics and physical parameters

This section analyzes the quantitative relationships between the shear strength parameters of Meiganga lateritic soils (internal friction angle ϕ and apparent cohesion C) and their physical characteristics. The approach adopted is part of a recognized method for characterizing local materials in resource-constrained contexts [9]. It combines (i) the analysis of Pearson's correlation coefficients, (ii) the development of empirical regression models, and (iii) the evaluation of their statistical performance using validation indicators (R^2 , RMSE, MAE). This approach aims to identify the dominant physical parameters and propose reliable predictive equations adapted to tropical geotechnical contexts, a methodology that has been successfully applied to similar soils in the Garoua-Boulai region [8].

3.5.1 Correlations between the angle of internal friction and physical parameters

Analysis of the relationships between the angle of internal friction (ϕ) and the physical parameters of Meiganga lateritic soils reveals the predominant influence of water content and particle size distribution, confirming the trends observed in regional studies. Pearson's correlation coefficients (Table 5) indicate that natural water content (ω , $R=0.625$), percentage of fines $< 0.08 \text{ mm}$ ($d_{0.08}$, $R=0.611$), and degree of saturation (S_r , $R=0.610$) are the parameters most correlated with ϕ .

This triad of influences (water content, fines, saturation) is logical from a mechanical point of view. An increase in water and fines tends to lubricate the contacts between coarser grains and increase the proportion of fine matrix, thereby reducing effective friction. This phenomenon is well documented for tropical soils [1, 3]. The positive correlations observed here suggest that in Meiganga, higher water and fine content is associated with higher friction angles. This could be explained by the structuring role of a partially cemented fine matrix (by iron and aluminum oxides), which, at a certain degree of saturation, contributes to cohesion and strength without completely canceling out friction. This hypothesis is supported by the mineralogy of these soils, which are rich in kaolinite and iron oxides, giving them a certain apparent cohesion even in the presence of fines [22, 23]. Other physical parameters, such as the plasticity index, liquidity limit, or porosity, have lower correlation coefficients ($R < 0.45$), indicating a secondary influence on ϕ when considered in isolation. This finding is consistent with the work of [3], who emphasize that the shear strength of soils is mainly controlled by water content and effective granular structure rather than by a single parameter.

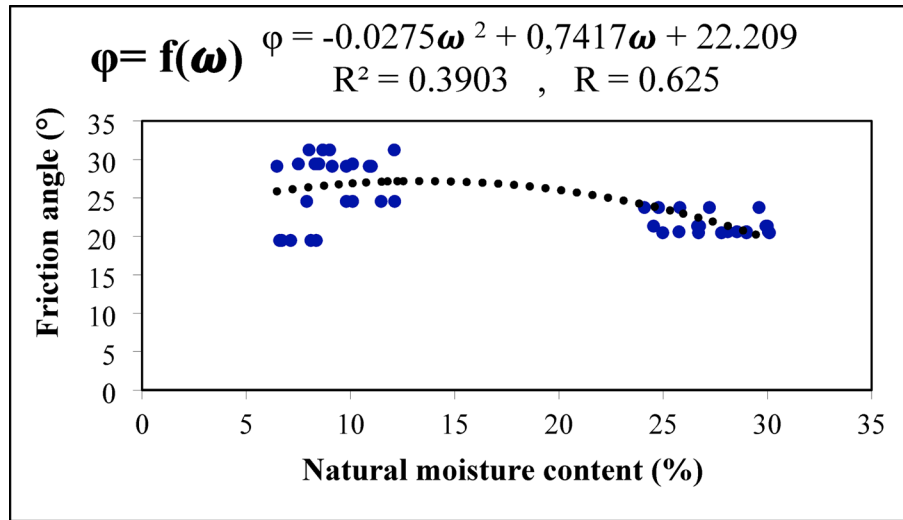
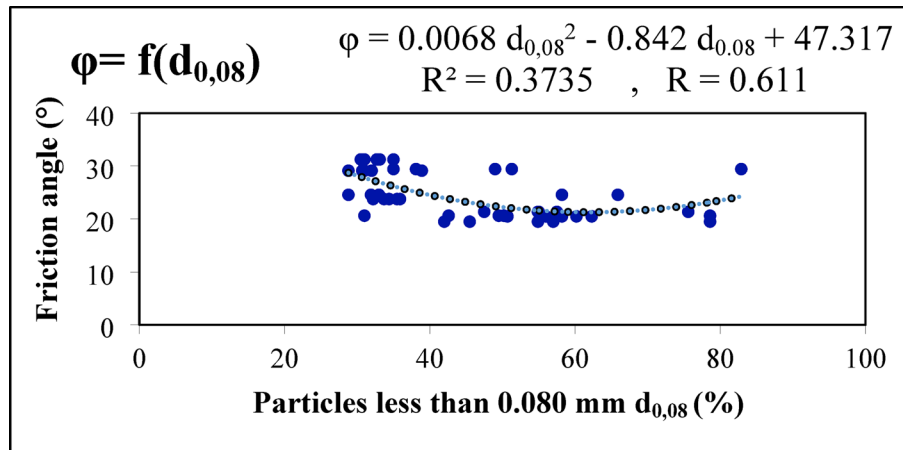
The regression models developed (Table 6) to predict ϕ from ω , $d_{0.08}$, and S_r have coefficients of determination (R^2) between 0.37 and 0.39, explaining approximately 37 to 39%

Table 5 Correlation coefficients between internal friction angle (φ) and physical characteristics of Meiganaga soils

Physical characteristic	ω	d00.08	s_r	I_i	I_c	p_s	P_I	ω_L	p	e	ω_p	p	n
Correlation coefficient R between φ and X	0.625	0.611	0.610	0.448	0.448	0.431	0.377	0.302	0.233	0.215	0.114	0.107	0.042

Table 6 Statistical indicators of internal friction angle prediction models

Model	Explanatory parameter	R	R ²	RMSE (°)	Model type
$\phi = f(\omega)$	Water content ω	0.625	0.391	$\approx 2.8\text{--}3.2$	Quadratic
$\phi = f(d_{0.08})$	Fines < 0.08 mm	0.611	0.373	$\approx 3.0\text{--}3.5$	Quadratic
$\phi = f(S_r)$	Degree of saturation	0.610	0.372	$\approx 3.1\text{--}3.6$	Linear

**Fig. 3** Correlation between internal friction angle and natural water content**Fig. 4** Correlation between internal friction angle and particles smaller than 0.080 mm

of the total variability. Although moderate, these values are comparable and even slightly higher than those often obtained for simple correlations on heterogeneous residual soils. They demonstrate the relevance of these easily measurable parameters for a robust preliminary estimate. The errors (RMSE of around 3°) are acceptable in the context of a preliminary study or on-site verification, given the range of variation of ϕ ($\approx 19^\circ$ to 31°).

The relationships between the angle of internal friction (ϕ) and the main physical parameters identified (water content ω , fines < 0.08 mm $d_{0.08}$, degree of saturation S_r) were modeled using empirical regressions (Figs. 3, 4 and 5), providing quantitative prediction tools.

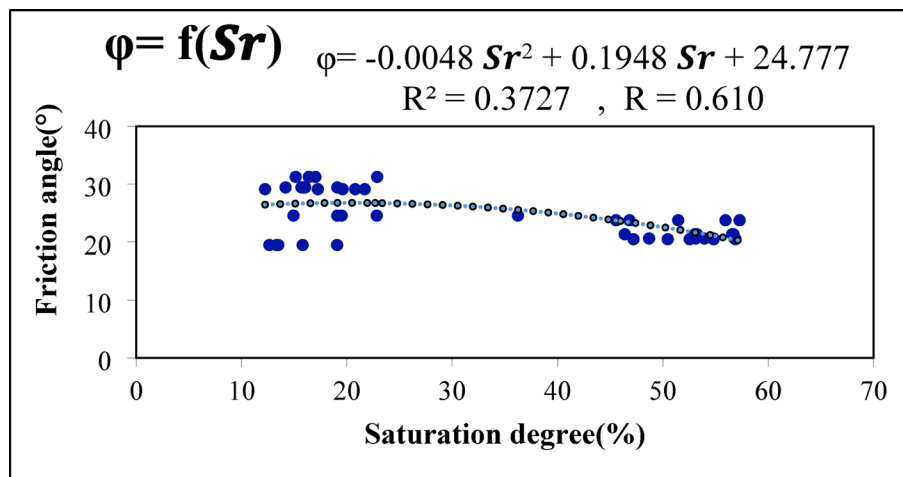


Fig. 5 Correlation between internal friction angle and degree of saturation

The relationship between ϕ and natural water content (ω) is illustrated in Fig. 3. It shows a clear trend toward a decrease in ϕ with an increase in ω , modeled by the quadratic equation: $\phi = -0.0275\omega^2 + 0.7417\omega + 22.209$. This behavior is classic and can be explained by the lubricating effect of water, which reduces friction at intergranular contacts [2]. The quadratic shape of the curve suggests that this effect is more pronounced above a certain water content, probably when the transition to a more plastic state occurs, saturating the fine matrix and drastically reducing the strength of the granular skeleton. This phenomenon is consistent with the high-water sensitivity of lateritic soils, as evidenced by their highly variable state indices (IL, IC).

The correlation between ϕ and the percentage of fines $d_{0.08}$ (Fig. 4) follows a decreasing trend modeled by:

$$\phi = 0.0068d_{0.08}^2 - 0.842d_{0.08} + 47.317.$$

This relationship reflects the decrease in granular interlock: an increasing proportion of fines fills the voids between larger grains and creates a matrix where direct contacts between angular particles (source of friction) are reduced, in favor of contacts mediated by the fine plastic phase [33]. The quadratic equation indicates that the negative impact of fines increases beyond a certain threshold. This observation is consistent with regional studies: comparison with data from Garoua-Boulai [8] shows that an excess of fines, in the absence of sufficient cementation, is often associated with lower friction angle values.

Finally, Fig. 5 confirms that an increase in the degree of saturation (S_r) leads to a decrease in ϕ . This expected relationship can be explained by the mechanics of unsaturated soils: an increase in S_r reduces matrix suction (unsaturated effective stress) and increases pore pressure under undrained loading, thereby reducing effective stresses and mobilizable frictional resistance [34]. In the context of laterites, this sensitivity to saturation reinforces the need to consider seasonal water conditions in the design of structures, as highlighted by [17] for gneiss-derived soils in Cameroon.

micro- and meso-structure of laterites (cemented domains, iron oxide coatings, micro-aggregates) to the observed shear response. The negative partial correlation between $d_{0.08}$ and ϕ is interpreted in terms of the “coating effect” of fines on coarse grains, which

reduces friction. The positive effect of S_r on cohesion is explained by the increase in capillary cohesion up to a certain saturation threshold, beyond which suction collapses.

All of these results corroborate that the angle of internal friction in Meiganga is mainly governed by a water-granular triptych (ω , $d_{0.08}$, S_r). The quadratic form of the best relationships suggests threshold or interaction effects between these variables. These simple models, although useful for an initial estimate, have moderate explanatory power ($R^2 \approx 0.37\text{--}0.39$, see Sects. 6–1), which is logical for univariate correlations on complex materials.

When the effect of fines content is accounted for, the partial correlation between ω and ϕ becomes negative ($r_{\text{partial}} = -0.68$). The original positive simple correlation arose because samples with higher water content also tended to have a better-developed granular skeleton (higher $d_{0.08}$), which obscures the direct lubricating effect of water.

3.5.2 Correlations between cohesion and physical parameters

Analysis of the correlations between apparent cohesion (C) and the physical parameters of Meiganga lateritic soils reveal a dominant dependence on plasticity and fine fraction. The correlation coefficients presented in Table 7 show a clear hierarchy in the influence of the parameters studied.

The plasticity index (P_I) appears to be the most decisive parameter ($R = 0.669$). This robust result confirms that the apparent cohesion measured under undrained conditions is largely governed by the activity of the clay minerals present. A high P_I value indicates a high proportion of fine particles capable of developing attractive electrochemical forces and interparticle bonds. This direct correlation between plasticity and cohesion is a fundamental characteristic of fine cohesive soils [3, 4]. It is corroborated by regional mineralogical analyses [8, 22] identifying kaolinite as the dominant clay mineral in Adamawa and North regions laterites, with illite added in some areas, contributing to plastic activity.

The percentage of fine particles smaller than 0.080 mm ($d_{0.08}$) is the second major explanatory factor ($R = 0.536$). This positive correlation, although more moderate, highlights the structuring role of the fine fraction: an increase in total specific surface area and capillary forces (suction) contributes to apparent cohesion, especially in the unsaturated state of the samples tested. The fact that the P_I is a better predictor than the simple fine content suggests that the mineralogical nature (activity) of clays is more decisive than their absolute quantity in generating cohesion. This finding is consistent with the observations of [2] on the importance of interparticle forces in cohesive soils.

Hydric parameters, such as the liquidity limit (ω_L) and natural water content (ω), show intermediate correlations ($R \approx 0.40\text{--}0.43$), indicating a secondary, essentially modulating role.

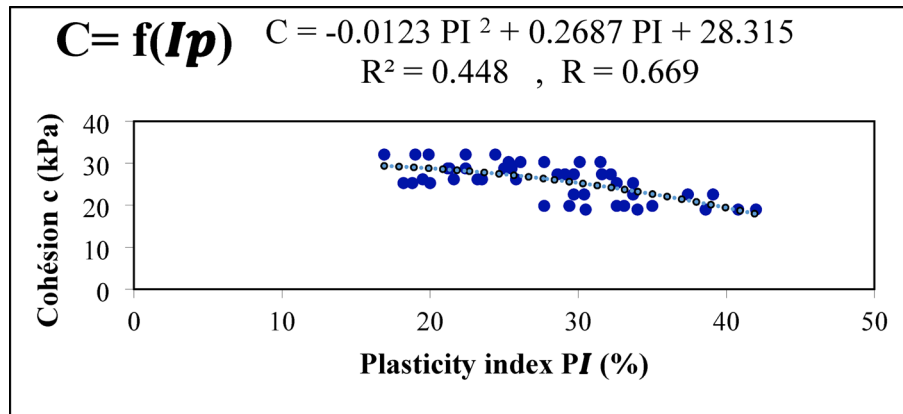
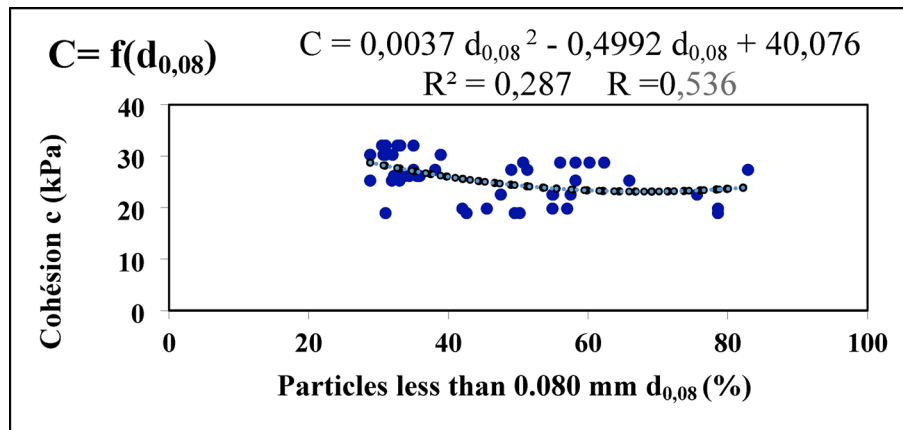
In contrast, parameters related to the overall structure and density of the soil (S_r , e , p_d , I_l , ρ , I_c , ρ_s , n , and ω_p) show low correlation coefficients ($R < 0.40$), suggesting that they do not significantly explain the variability in cohesion when considered in isolation. These observations are consistent with the conventional conclusions that the cohesion of fine soils is mainly governed by plasticity and clay content. Based on these results, two empirical models were developed (Table 8). The quadratic model linking cohesion to the plasticity index ($C = f(P_I)$) performs best, with $R^2 \approx 0.45$ and an RMSE of less than 5 kPa, indicating that approximately 45% of the variability in cohesion is explained by P_I . The

Table 7 Correlation coefficients between cohesion (kPa) and the physical characteristics of Meiganaga soils

Physical character	P_I	$d_{0.08}$	ω_L	ω	S_r	γ	p_d	I_L	p	I_c	p_s	n	ω_p
Correlation coefficient R between C and X	0.669	0.536	0.432	0.408	0.374	0.343	0.254	0.235	0.231	0.223	0.215	0.166	0.161

Table 8 Statistical indicators of cohesion prediction models

Model	Explanatory parameter	R	R	RMSE (kPa)	Type
$C = f(P_i)$	Plasticity index	0.669	0.448	$\approx 3.5\text{--}4.2$	Quadratic
$C = f(d_{0.08})$	Fines < 0.08 mm	0.536	0.287	$\approx 4.5\text{--}5.0$	Linear

**Fig. 6** Correlation between cohesion and plasticity index**Fig. 7** Correlation between cohesion and particles smaller than 0.080 mm $d_{0.08}$

linear model based on the fine fraction ($C = f(d_{0.08})$) shows a more limited explanatory power ($R^2 \approx 0.29$), but remains relevant in the preliminary phase when available data are limited. This finding is consistent with the conclusions of [2] and [20], according to which the cohesion of fine soils depends mainly on plasticity and clay fraction.

Based on these results, the plasticity index P_i and the percentage of fines of 0.08 were selected as the dominant physical parameters for graphical analysis (Figs. 6 and 7) and for developing empirical models for determining cohesion.

The empirical models developed (Fig. 6) quantify this relationship. The quadratic model $C = f(P_i)$ performs best ($R^2 \approx 0.45$, $RMSE < 5$ kPa). This moderate but significant explanatory power for a simple correlation is comparable to, or even superior to, that reported in many studies on residual soils.

Direct comparison with global empirical equations (Table 9) is limited by different geological contexts. Nevertheless, on the present dataset, the reference formulas yield lower R^2 and 3–4 times higher RMSE than the present multivariate models. This confirms the

Table 9 Performance comparison with reference empirical models

Reference model	Predicted parameter	R^2 (on our dataset)	RMSE
Skempton (1953) – $c = f(PI)$	undrained cohesion c	0.64	5.1 kPa
Gidigas (1976) – $\phi = f(d_{0.08})$	friction angle ϕ	0.52	4.8°
multivariate model of the present study	cohesion c	0.98	1.1 kPa
multivariate model of the present study	friction angle ϕ	0.93	1.1°

The quadratic equation is given by: $C = -0.0123 P_1^2 + 0.2687 P_1 + 28.315$

need for local calibration, as emphasized by regional studies [6, 9]. Proposed models, although site-specific, provide a substantial improvement over generic correlation.

It suggests that the increase in cohesion with P_1 reaches an optimum before potentially decreasing. This shape could be explained by the appearance, beyond a certain plasticity threshold, of more ductile and less resistant behavior, or by interactions with the natural water content. Physically, the increase in P_1 reflects a higher proportion of active clay particles capable of developing electrochemical forces and interparticle bonds, as shown by [4, 35].

Figure 7 shows an overall increase in apparent cohesion C with an increase in the percentage of fines $d_{0.08}$, confirming the structuring role of the fine fraction in the development of cohesive forces. This evolution can be explained by the increase in specific surface area and interparticle attraction forces, mainly of electrochemical and capillary origin. The correlation coefficient obtained ($R = 0.536$) reflects a moderate correlation, indicating that the influence of $d_{0.08}$ on cohesion remains partially conditioned by other parameters, notably the plasticity index and the water content of the soil. These results are consistent with the observations of [2, 35] and confirm that the pair (P_1 , $d_{0.08}$) constitutes a relevant basis for the empirical modeling of the cohesion of Meiganga lateritic soils.

3.5.3 Overall validation of empirical models

Figure 8 and Table 9 show the comparison between experimental values and predicted values for cohesion and internal friction angle, in the training and validation phases.

The robustness and reliability of the empirical models developed to predict cohesion (c) and internal friction angle (ϕ) were rigorously evaluated by statistical validation, comparing predicted values with measured experimental values (Figure 8).

The validation results, summarized by statistical indicators (Table 10), confirm the satisfactory performance and generalization ability of the models. The coefficients of determination (R^2) are remarkably high, approaching 0.98 for the training set and 0.97 for the validation set in the case of cohesion, and around 0.93 for the friction angle. These values, which are much higher than those obtained with simple univariate models ($R^2 \approx 0.37$ – 0.45), demonstrate the decisive benefit of the multivariate approach and model calibration. They indicate that the models capture between 93% and 98% of the variability in shear parameters, an exceptional performance for heterogeneous natural soils. Cohesion is effectively described by the parameters of plasticity and fine fraction, while the internal friction angle is mainly controlled by water content and particle size distribution.

This performance is corroborated by the low prediction error values. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) are minimal, in the range of 1.1 to 1.4 kPa for cohesion and approximately 1.0 to 1.1° for the friction angle. These errors, which are well below the natural ranges of variation of the parameters (c : ~13 kPa; ϕ :

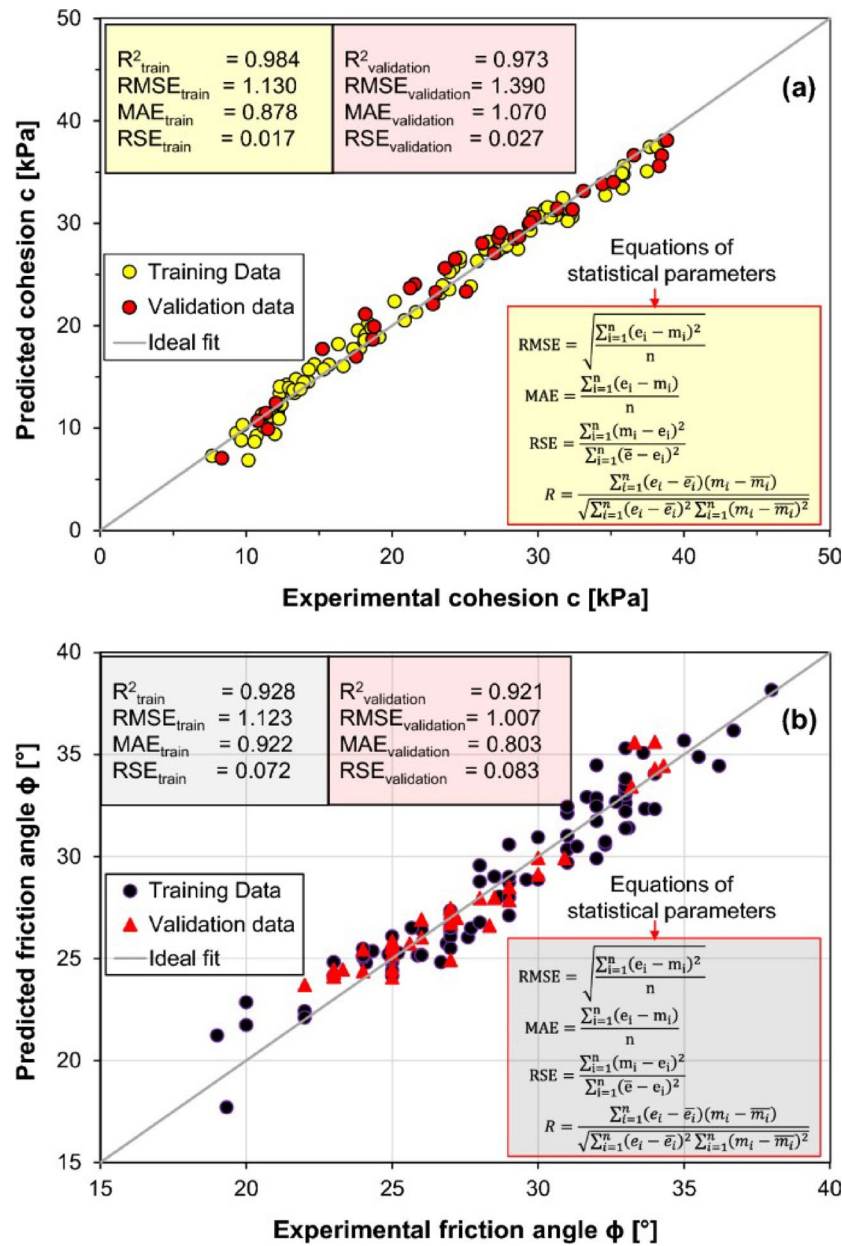


Fig. 8 Validation of models for predicting the shear strength of Meiganga lateritic soils: (a) cohesion c and (b) internal friction angle ϕ , comparison between experimental values and predicted values for the training and validation datasets

Table 10 Validation of empirical models for predicting the shear strength of lateritic soils in Meiganga

Predicted parameter	Data set	R^2	RMSE	MAE	RSE
Cohesion c (kPa)	Training	0.984	1.130	0.878	0.017
	Validation	0.973	1.390	1.070	0.027
Friction angle ϕ (°)	Training	0.928	1.123	0.922	0.072
	Validation	0.921	1.007	0.803	0.083

R^2 = coefficient of determination; RMSE = root mean square error; MAE = mean absolute error; RSE = standardized relative error

$\sim 12^\circ$), confirm the practical accuracy of the models for on-site estimation. The similarity in performance between the training and validation sets, as well as the low Root Mean Square Error (RMSE), attests to the absence of overfitting and the robustness of the models in predicting the behavior of new samples.

This successful validation fully confirms the choice of explanatory variables identified in the previous correlative analyses. Cohesion is effectively and accurately described by parameters related to the activity and quantity of the fine phase (plasticity index, fraction $< 80 \mu\text{m}$), reflecting the importance of interparticle forces in these lateritic soils with a clay matrix. The angle of internal friction is mainly controlled by water and granular state parameters, confirming the predominant role of water and skeleton structure in friction mobilization.

The increase in R^2 from univariate (0.29–0.45) to multivariate models (0.92–0.98) is not anomalous. Lateritic soil strength results from coupled mechanisms (water-fines-plasticity-cementation) that simple single-predictor models cannot capture. The final multivariate models include interaction terms (e.g., $\omega \times d_{0.08}$) and quadratic forms, which account for threshold effects and synergistic behavior. Similar improvements have been reported for tropical soils [6, 9]. The close agreement between training and validation R^2 and RMSE confirms that this performance is not due to overfitting.

4 Limitations of the study and scope of validity of the models

The empirical models developed are based on data collected exclusively in the town of Meiganga, in a geological and climatic context specific to tropical lateritic soils developed on basaltic bedrock. Their extrapolation to other environments must therefore be carried out with caution. The shear strength parameters were determined under unconsolidated and undrained conditions, representative of short-term stresses, and do not describe long-term drained behavior. Furthermore, although the samples covered both the dry and rainy seasons, the seasonal effect was not explicitly included in the modeling. Although samples were collected during both dry and wet seasons, the season itself was not introduced as a categorical predictor. This decision is deliberate: seasonal effects are primarily transmitted via changes in ω and S_r , which are already included as variables. Including 'season' would induce multicollinearity without improving model performance. Consequently, the proposed models are valid for lateritic soils with a fine fraction between 30% and 80% and a plasticity index between 15% and 45%, tested under UU conditions. Their application outside these ranges or under different drainage conditions requires prior recalibration.

5 Conclusion

This study has provided an in-depth characterization of the significant geotechnical heterogeneity of the lateritic soils of Meiganga, revealing the fundamental relationships between their composition, condition, and mechanical behavior. The results confirm that the properties of these soils are mainly governed by three interdependent factors: a grain size dominated by fines (average content $> 50\%$ of particles $< 80 \mu\text{m}$), high to very high plasticity.

(average $P_1 \approx 28\%$), and extreme water sensitivity marked by large seasonal variations in water content and degree of saturation.

Direct shear tests revealed contrasting mechanical performances between sites, reflecting variable balances between the different resistance mechanisms. This variability is systematically explained by distinct contributions from intergranular friction, cohesion linked to the fine plastic matrix, and cementation by iron and aluminum oxides.

Statistical analysis has made it possible to quantify and model these relationships with great precision. It has been shown that the internal friction angle (ϕ) is mainly driven by water content and grain size parameters (water content ω , degree of saturation S_r , percentage of fines $d_{0.08}$). The apparent cohesion (c) depends mainly on the activity and quantity of the fine phase, represented by the plasticity index (P_I) and the fine particle content. Based on these correlations, robust multivariate empirical models have been developed and validated. Their exceptional performance, as evidenced by coefficients of determination (R^2) approaching 0.97 to 0.98 and very low prediction errors (RMSE, MAE), demonstrates their reliability and generalizability.

These models therefore constitute a first-rate operational predictive tool for quickly and economically estimating shear parameters from simple physical tests, thus meeting a critical need identified in resource-limited contexts.

The results of this study represent a significant contribution to the regional geotechnical database and offer a reproducible methodology for the valorization of local materials. They provide engineers and practitioners with practical equations for the pre-design and verification phases, particularly for the design of shallow foundations and earthworks.

However, this practical advance comes with a crucial caveat: the success and safety of structures will depend on rigorous control of the water content of soils, both during design (considering the most unfavorable conditions) and during implementation (adapting construction methods and schedules). The proposed models, which are valid in a defined domain (UU conditions, specific ranges of P_I and fines), must be used in an informed manner, and their extrapolation to other contexts will require prior recalibration. By integrating these predictive tools into a responsible engineering approach adapted to the tropical context, it is possible to sustainably optimize infrastructure development in the Meiganga region and beyond.

5.1 Originality statement

The work titled “Statistical Modeling of Meiganga Soils Mechanical Parameters: Regression and Correlation Approach” has not been published elsewhere, in part, or another form.

Author contributions

BLN, JHKT, FN and GFNN: Conceived and designed the experiments; Performed field work and the experiments; Analyzed and interpreted the data; Wrote the paper. RPK and JTD: Performed field work, analyzed and interpreted the data; Wrote the paper, contributed reagents, materials, analysis tools, or data. JTD and BLN: Analyzed and interpreted the data; Wrote the paper, proofread the paper.

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Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

Declarations

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Consent for publication

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Competing interests

The authors declare no competing interests.

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References

1. Gidigas MD. Laterite soil engineering: Pedogenesis and engineering principles. Elsevier; 1976.
2. Terzaghi K, Peck RB. Soil mechanics in engineering practice (2e éd). Wiley; 1967.
3. Mitchell JK, Soga K. Fundamentals of soil behavior (3e éd). Wiley; 2005.
4. Skempton AW. (1953). The colloidal activity of clays. Dans *Proceedings of the 3rd International Conference on Soil Mechanics and Foundation Engineering* (Vol. 1, pp. 57–61). ICSMFE.
5. Daimary N, Sarmah A, Bhattacharjee A, Barman U, Saikia MJ. Geotechnical performance of lateritic soil subgrades stabilized with agro-industrial waste: An experimental assessment and ANN-based predictive modelling. *Geotechnics*. 2025;5(3):65.
6. Aboubakar A, Manefouet BI, Fotze A, Ngapgue QM, Baba F, A., Ahidjo S. Petrological and geotechnical studies of lateritic soils in the locality of Ngaoundal (Adamawa-Cameroon): Implication in road construction. *Arab J Geosci*. 2024;17(10):281.
7. Kulhawy FH, Mayne PW. Manual on estimating soil properties for foundation design. Rapport EL-6800. Electric Power Research Institute; 1990.
8. Taypondou DJ, Tchouta JHK, Langollo YT, Sam-Tunsa AA, Moudoh MB, Ngon GFN. Lateral Evolution and Modeling of Garoua-Boulai Soil Properties for Use in Earthen Constructions. *J Mater Eng Perform*. 2024;33(22):12573–92.
9. Taypondou DJ, Tchouta K, Ngon JHN, Ngapgue GF, Ngakoupain FL, B., Langollo T, Y. (2022). Evaluation of lateritic soils of Mbé for use as compressed earth bricks (CEB). *Heliyon*, 8(6), e10147. <https://doi.org/10.1016/j.heliyon.2022.e10147>
10. Maignien R. Review of research on laterites. UNESCO; 1966.
11. AFNOR. Sols: reconnaissance et essais – Détermination de la teneur en eau. Norme NF P 94–050). Association Française de Normalisation; 1993.
12. AFNOR. Sols: reconnaissance et essais – Analyse granulométrique par tamisage. Norme NF P 94–056). Association Française de Normalisation; 1993.
13. AFNOR. Sols: reconnaissance et essais – Détermination des limites d'Atterberg. Norme NF P 94–051). Association Française de Normalisation; 1996.
14. AFNOR. Sols: reconnaissance et essais – Détermination de la masse volumique des grains. Norme NF P 94–054). Association Française de Normalisation; 1993.
15. AFNOR. Sols: reconnaissance et essais – Détermination de la masse volumique apparente. Norme NF P 94–053). Association Française de Normalisation; 1993.
16. AFNOR. Sols: reconnaissance et essais – Essai de cisaillement direct. Norme NF P 94–074). Association Française de Normalisation; 1993.
17. Ndzié Mvindi AT, Onana VL, Ze N, Ohandja AO, H. N., Ekodeck GE. Influence of hydromorphic conditions in the variability of geotechnical parameters of gneiss-derived lateritic gravels in a savannah tropical humid area (Centre Cameroon), for road construction purposes. *Transp Geotechnics*. 2017;12:70–84.
18. Ngapgue F, Madjadoumbaye J, Nouanga P, Tejani A, Tatiéte T, T. Modeling of frictional and cohesive resistances of Bafoussam (Cameroon) soils. *Electron J Geotech Eng*. 2012;17:3463–74.
19. Jin P, Zhen W, Chen B, Sun DA, Gao Y, Xiong Y. Effect of microstructure on water retention behavior of lateritic clay over a wide suction range. *Geomech Eng*. 2021;25(5):417–28.
20. Das BM. Principles of geotechnical engineering. 7e éd. ed. Cengage Learning; 2010.
21. Ngon Ngon GF, Fouateu RY, Bitom DL, Bilong P. A geological study of clayey laterite and clayey hydromorphic material of the region of Yaoundé (Cameroon): A prerequisite for local material promotion. *J Afr Earth Sc*. 2009;55(1–2):69–78. <https://doi.org/10.1016/j.jafrearsci.2008.12.008>.
22. Nzeukou Nzeugang A, Tsozué D, Pagna BK, Madi AB, Deumeni AF, Ngos S, Nkoumbou C, Fagel N. Clayey soils from Boulgou (North Cameroon): Geotechnical, mineralogical, chemical characteristics and properties of their fired products. *SN Appl Sci*. 2021;3(4):551. <https://doi.org/10.1007/s42452-021-04541-4>.
23. Ngon Ngon GF, Fouateu Y, Lecomte Nana R, Bitom GL, Bilong DL, P., Lecomte G. Study of physical and mechanical applications on ceramics of the lateritic and alluvial clayey mixtures of the Yaoundé region (Cameroon). *Constr Build Mater*. 2012;31:294–9.
24. Remillon A. Étude géotechnique des sols latéritiques tropicaux et application aux terrassements routiers. *Bull de Liaison des Laboratoires des Ponts et Chaussées*. 1988;155:23–34.
25. AFNOR. Exécution des terrassements – Classification des matériaux (Norme NF P 11–300). Association Française de Normalisation; 1992.
26. Keyangue Tchouta JH, Yato CG, François KV, Cédric N, Grégoire DT, Mathurin K. Characterization of lateritic Banka gravelous (West Cameroon) for their use in road geotechnical. *Am Sci Res J Eng Technol Sci*. 2019;55(1):92–103.
27. Tsozué D, Nzeugang AN, Mache JR, Loweh S, Fagel N. Mineralogical, physico-chemical and technological characterization of clays from Maroua (Far-North, Cameroon) for use in ceramic bricks production. *J Building Eng*. 2017;11:17–24.
28. Ngapgue F. Études géotechniques des sols latéritiques de la ville de Yaoundé (Cameroon) comme sols de fondation des bâtiments et des ouvrages. [Thèse de doctorat, Université de Kiev]; 1997.
29. Lohnes RA, Demirel T. Strength and compressibility characteristics of tropical residual soils. *Eng Geol*. 1975;9(4):279–96.
30. Goudari A. Caractérisation géotechnique des sols latéritiques de l'île Maurice et implications pour les ouvrages de génie civil. *Revue Africaine des Sci et de la Technologie*. 2012;7(2):45–58.

31. Zagalo P. Propriétés géotechniques des sols argilo-latéritiques de la ville d'Amtiman (Tchad). [Mémoire de master, Université de N'Djamena]; 2016.
32. Caro S, Agudelo JP, Caicedo B, Orozco LF, Patiño F, Rodado N. Advanced characterisation of cement-stabilised lateritic soils to be used as road materials. *Int J Pavement Eng*. 2019;20(12):1425–34.
33. Sanglerat G. The penetrometer and soil exploration: Interpretation of penetrometer tests. Elsevier; 1972.
34. Fredlund DG, Rahardjo H. Soil mechanics for unsaturated soils. Wiley; 1993.
35. Mitchell JK. Fundamentals of soil behavior (2e éd). Wiley; 1993.

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