

# Compositional Suitability Assessment and New Classification of Lateritic Soils for Road Construction: Case of Materials from the Thies Region in Senegal

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## Abstract

Lateritic soils are found over large areas in tropical countries where their suitability for road engineering is a real concern, both compositionally and mechanically. Mineralogical and geochemical characterization, and profile description were carried out on Pliocene gravel lateritic soils from the Thies region to assess their suitability for road construction. These soils were sampled in Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia borrow pits in that region. Minerals that make up these studied materials are quartz, kaolinite, hematite and goethite, identified by X-Ray Diffraction and confirmed with Infrared spectroscopy. This mineralogy is characteristic of lateritic soils which are concretionary structure and are formed in well-drained tropical regions like that of Thies. According to the chemical results, these gravel lateritic soils are poor in organic matter, OM < 3wt%. They also belong to the true laterites class,  $\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3) < 1.33$ . As part of this project, Gbaguidi and Diop have defined an oxide ratio and proposed the new *Diop ternary diagram* for classifying lateritic soils. Therefore, Thies materials are ferruginous lateritic soils,  $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3 < 1$ , containing non-swelling clay (kaolinite) and rich in gravelly nodules, S/CEC < 50wt%. As a result, these soils are compositionally suitable for road construction. These appreciated mineralogical, geochemical and pedological properties can now help overcome compositional challenges well before determining the bearing capacity of lateritic ma-

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terials. This mechanical strength, which largely depends on their composition, is decisive in defining the optimal conditions for using lateritic materials in road geotechnics.

## Keywords

Lateritic Gravel, Mineralogy, Geochemistry, Soil Profile, Thies

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## 1. Introduction

The mineralogical, geochemical and pedological characterization of gravel lateritic soils used as road materials in Senegal, often does not precede the determination of their geotechnical characteristics for optimal use (Diop et al., 2023). In road engineering, the current specifications for using these materials only consider their main geotechnical properties that are granularity, plasticity, compaction characteristics and bearing capacity (AGERROUTE, 2015; CEBTP, 1984; IDRRIM, 2023; LCPC-SETRA, 2000). Compositional characteristics are crucial in determining the evolution of geotechnical properties and the increasingly early deterioration of roads in Senegal, as in other tropical countries where laterites are used in road construction (Cissé & Ndoye, 2007; Diop et al., 2023; Foko Tamba et al., 2022). Therefore, before considering the use of laterite materials in road geotechnics, it would be necessary first to look at their mineral stability and chemical composition, which guide their classification (Foko Tamba et al., 2022; Kessoum Adamou et al., 2023; Schellmann, 1983). The unequivocal classification of laterites remains a challenge, although several attempts have been made by different authors. Some have used ratios of silicon, aluminum and iron oxides (Joachim & Kandiah, 1941; Martin & Doyne, 1927, 1930), while others have proposed diagrams (Bárdossy, 1982; Schellmann, 1983; Sinisi, 2018). All have been criticized or are likely to be criticized for failing to define classification limits or for not qualifying the materials (Autret, 1980; Bourman & Ollier, 2002; Florentin & Lhériveau, 1952), but only their formation process. To overcome these challenges, Gbaguidi and Diop proposed in this study a new ternary diagram and a ratio of classification. The materials used as objects of study come from the Thies region in western Senegal.

Numerous borrow pits of gravel lateritic soils, located in the Thies region, regularly supply the road construction sites of the country (AGERROUTE, 2015; Diop, 2015; Diop, 2016, 2017, 2022; Samb, 2014). The materials of five borrow pits of this region have been characterized in advance. The minerals constituting the gravel lateritic soils were firstly identified and these materials were secondly classified according to their chemical composition according to Joachim & Kandiah, (1941); Martin & Doyne (1927) and by Gbaguidi and Diop. Thirdly, the lateritic profiles of these materials were described.

## 2. Materials and Methods

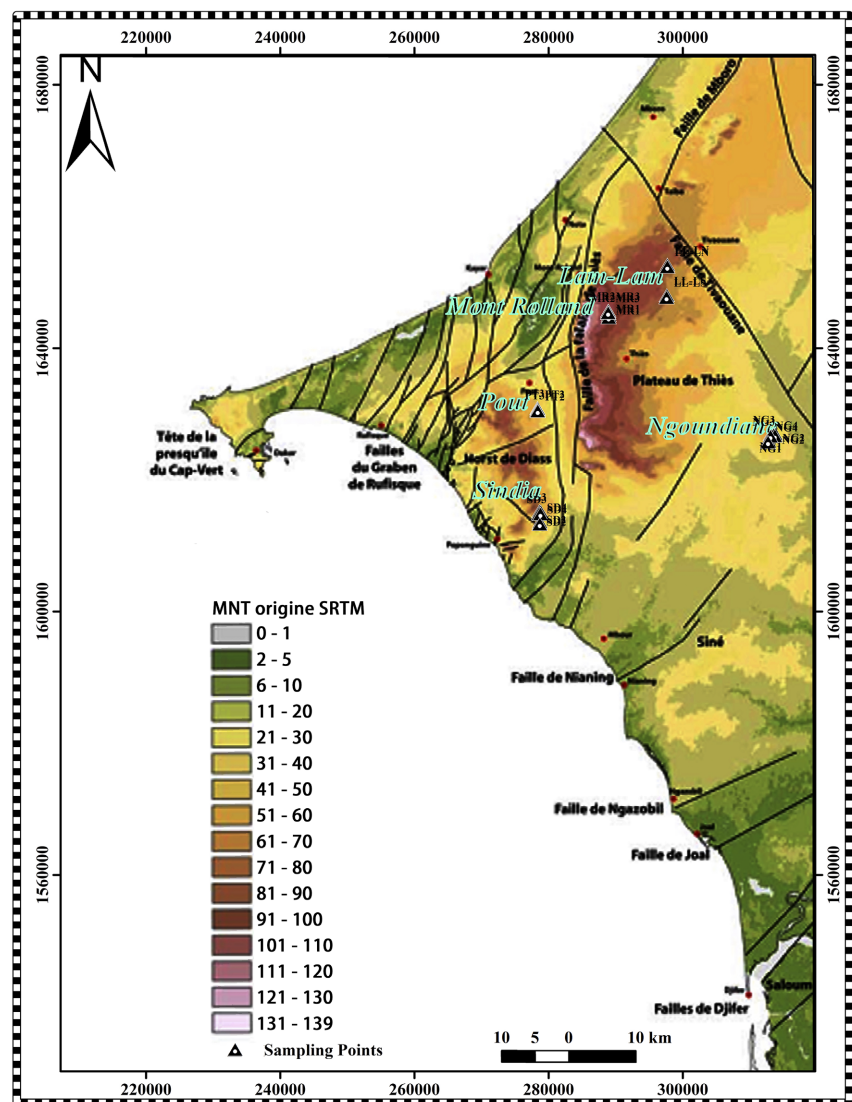
The samples used to characterize the materials were collected during the month

of July. Physical, geochemical and pedological methods were used for their characterization.

## 2.1. Geography of the Borrow Pits

The domain including the lateritic gravel formations studied is located in western Senegal and between 16°30' and 17°10' West longitude, and 14°30' and 15°30' North latitude.

The gravel lateritic soils studied come from the borrow pits of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia in the Thies region (Figure 1).



**Figure 1.** Digital terrain model and structural map of the borrow pits in Thies (Roger et al., 2009, modified).

Located east of Dakar, the Thies region covers 6,670 km<sup>2</sup> of the total 196,712 km<sup>2</sup> area of the country, and is made up of three (3) departments (ANSD, 2021): Mbour, Thies and Tivaouane.

This region has on the whole a flat relief except for the Thies plateau that culminates at 105 m altitude, the Diass massif which reaches 90 m and the Thies basin which extends over 65 km<sup>2</sup> area. The relief is then marked by horsts and grabens.

The borrow pits of gravel lateritic soils present variable altitudes due to the mode of pocket operation for the proper supply of road construction sites.

### 2.1.1. Climate

Thies has two Atlantic facades and the climate of the region is influenced by sea currents. It is of the Sudano-Sahelian type in the South and South-East, and more Sahelian in the North and North-East while in the West it is sub-Canarian. This climate is tropical and characterized by a dry season from November to mid-June and a rainy season from mid-June to October, with average annual rainfall varying between 400 and 600 mm as indicated by the ANSD (2021).

### 2.1.2. Vegetation

The vegetation of the Thies region is generally that of a tropical savannah with shrubs and little herbaceous plant species. In this region, especially in Pout, there are also fruit plants such as *Adansonia digitata*, *Carica papaya*, *Mangifera indica*, *Citrus sinensis* and *Citrus reticulata*. *Calotropis procera*, *Euphorbia obtusifolia*, *Guiera senegalensis*, *Cassia occidentalis*, *Combretum micranthum* and *Boscia senegalensis* are fairly well represented on the sites studied. However, the lateritic zones support very few fruit plants with the exception of *Adansonia digitata* and a few rare *Mangifera indica*.

## 2.2. Geological Setting

The main factors in lateritic weathering are climate and vegetation as supported by Nahon and Demoulin (1971) as well as the petrographic nature of the bedrock, drainage conditions and ecosystem influences as noticed by Tardy (1993).

### 2.2.1. Process and Products of Lateritic Weathering

The laterization process results, in accordance with Estéoule-Choux (1983), to:

- complete alteration of primary minerals (feldspars, micas, amphiboles, pyroxenes, etc.), with removal of bases as well as part of the silica;
- kaolinite formation;
- the formation of iron oxides and hydrated iron (hematite and goethite) and aluminum (gibbsite).

All the factors contributing to the rapid elimination of the bases, as the original poverty of the rock in minerals resistant to weathering and well-drained environment, are favorable to alteration. The more or less complete elimination of the bases determines the nature of the clay minerals formed (Estéoule-Choux, 1983).

According to Schellmann (1981), lateritic soils are products of intense weathering of rocks with a high content of iron and/or aluminum sesquioxide and a low silica content, as in a simply kaolinized rock. They consist mainly of quartz, kaolinite, hematite and goethite mineral aggregates.

As noted by Autret (1980, 1983); Bagarre (1990); Foko Tamba et al. (2022);

Kamtchueng et al. (2015); Millogo (2008), gravel lateritic soils are loose and located in tropical areas and consisting of a granular fraction of quartz gravels, pisolites or ferruginous nodules packed in a fine silty-clay matrix.

Many borrow pits of gravel lateritic soils are exploited in Thies where the geological setting has been favorable to their formation. According to Nahon & Demoulin (1971), these gravel lateritic soils are dated to the Pliocene. This dating is based on a correlation established from Dakar where the same laterite type is located between the volcanic formations of the Tertiary and those of the Quaternary (Roger et al., 2009).

Usually, a borrow pit of gravel lateritic soils presents pockets of different granular classes. The granularity of the best pockets is characterized by samples with more than 40wt% of particles greater than 2 mm and fines (mineral particles less than 0.080 mm in diameter) ranging from 12 to 25wt% (AFNOR, 2005).

Climatic conditions, in particular temperature and precipitation were determining factors in the genesis of lateritic soils in the Thies region. It is thus important to locate the gravel lateritic soils studied in their regional then local geological context.

### 2.2.2. Geology of the Thies Region

The geology of the Thies region is characterized by Meso-Cenozoic sedimentary formations with some outcrops of volcanic rocks of which the most important is that of Diack in the Miocene. Weathering has given gravel lateritic soils end-products which are sometimes covered by Quaternary sands.

Sedimentary deposits are present in this context, from the Triassic to the Paleocene, and include limestones, marls, clays and phosphates as substratum supporting sandstones and sands; these formations generally contain inclusions with varied morphologies. The chemical weathering is quite significant and produce gravel lateritic soils often covered by clayey sands or redden sands from the Ogozian ergs of the Pleistocene.

Tertiary volcanism occurred both in Dakar at Cap Manuel and in the Thies region. This volcanism is marked by basanite or dolerite basanite lava lakes at Diack (near Ngoundiane), a basanite sill at Lam-Lam (near Mont Rolland) and a basanite flow at Seune Sérère (near Pout).

The global tectonics of horst and graben is at the origin of the Senegalese-Mauritanian sedimentary basin in which most of the ferruginous soils of Senegal are found.

The structural scheme of the western part of the basin shows a dense network of submeridian faults east of Dakar (Rufisque Graben faults). To the east of this network, the Horst of Diass stands out. It is limited on its eastern edge by the fault of the Thies cliff (Figure 1). This part is organized in Horsts of Dakar and Diass, and in Graben of Rufisque with a system of benches in Bargny, Sébikhotane and Pout to the west of the Diass Horst. These benches are consecutive to a regime of normal faults-oriented NE-SW.

The structure of the Horst of Diass is greatly underestimated, due to the lateritic overlay which masks tectonic accidents (Roger et al., 2009).

Fine deposits characterize the Triassic stratigraphy in the western part of the Senegalese sedimentary basin. Medium to coarse sand deposits characterize the Maastrichtian (Figure 2) whose summit is composed of ferruginous sands and nodules forming the dismantling facies (Roger et al., 2009).

The Horst of Diass constitutes a high zone during the Cenozoic sedimentation, in the northern sector of the Tivaouane fault; the thicknesses are controlled by a set of synsedimentary faults.

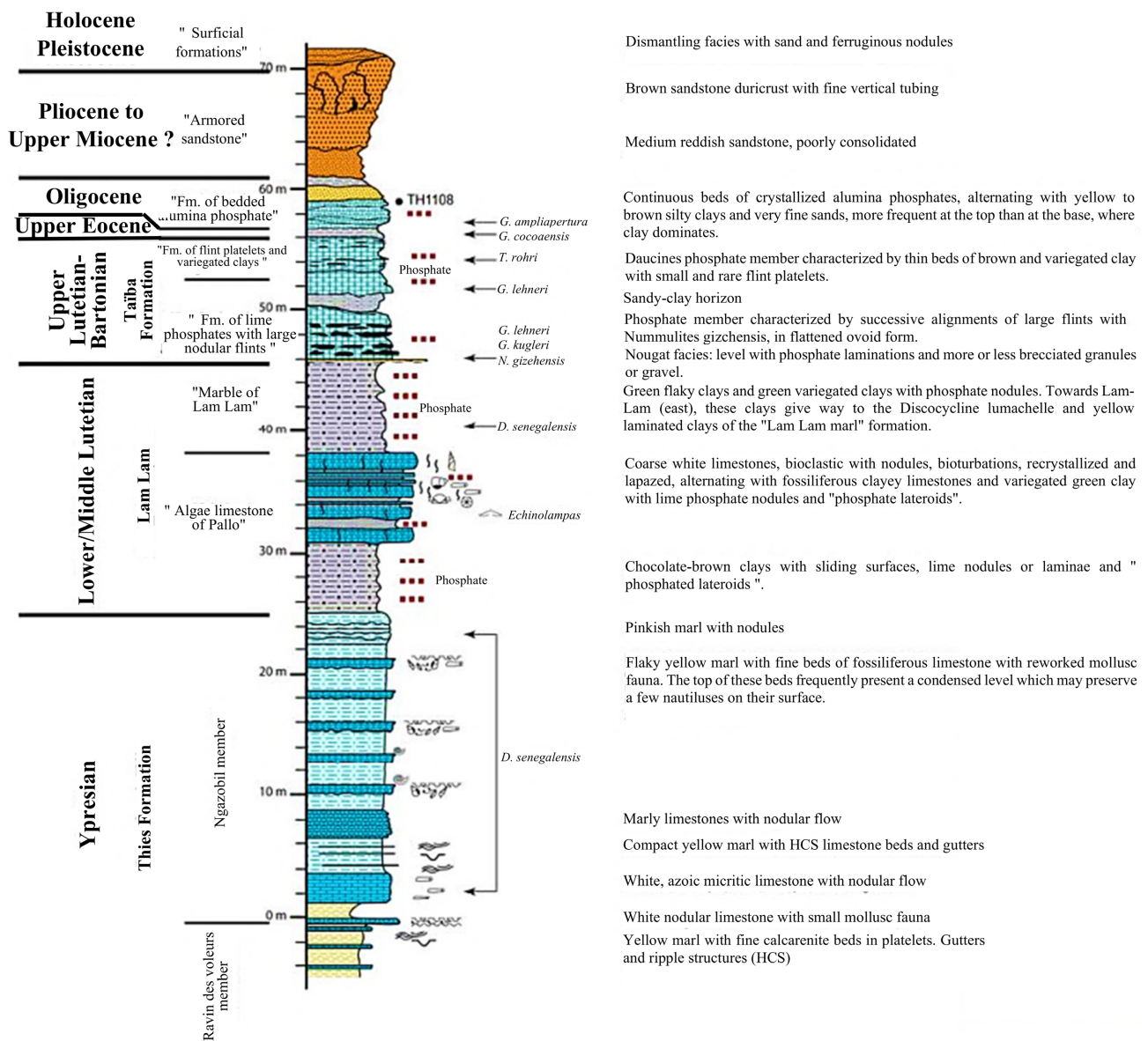


Figure 2. Lithostratigraphic section of Pallo and Lam-Lam borrow pits on the Thies plateau (Roger et al., 2009, modified).

### 2.2.3. Geological Context of Gravel Lateritic Soils in the Thies Region

The lateritic weathered soils of western Senegal are mainly located in the Thies region and particularly in Lam-Lam, Mont Rolland, Pout, Paki-Toglou, Bandia, Diass, Dougar, Kholpe, Ngoundiane and Sindia. There are also duricrust outcrops

with sub-horizontal topography overhanging the cliff of Thies.

In the region, from North to South and from East to West (**Figure 1**), the lateritic gravel samples come from five borrow pits, three on the Thies plateau (Lam-Lam, Mont Rolland and Ngoundiane) and two on the Horst of Diass (Pout and Sindia).

#### 2.2.4. Methods

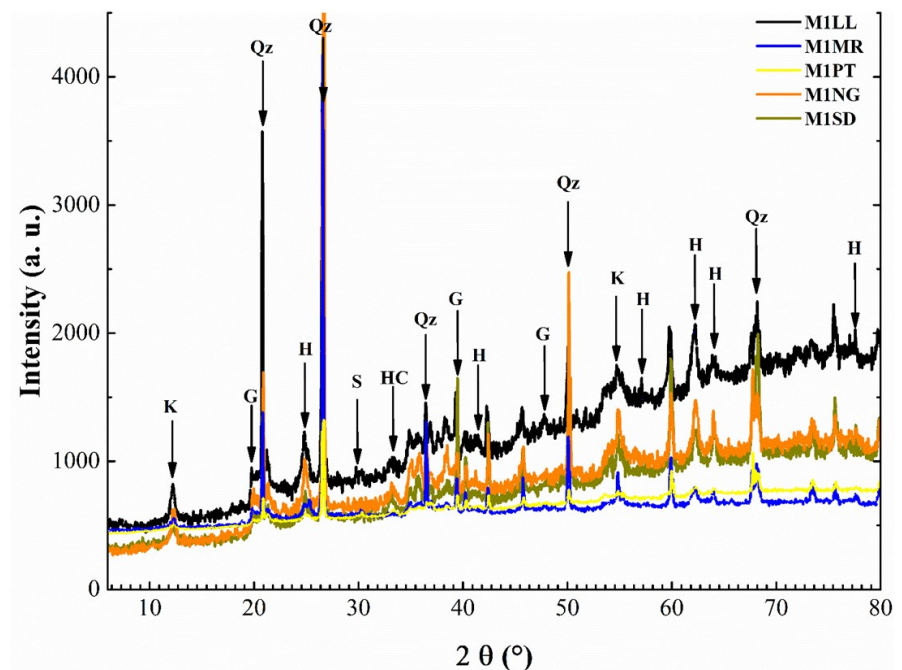
Mineralogical and geochemical characterization was carried out on pulverized samples of the 0/2 mm granular fraction taken from the Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia borrow pits.

The mineralogical characterization was performed by physical methods, namely: X-ray diffraction for mineral identification (Diop et al., 2023) and infrared spectroscopic analyzes for mineralogy confirmation, using Bruker Alpha platinumium-ATR Fourier transform infrared spectroscopy at 32 scans in the range of 400-4000 cm<sup>-1</sup>. Their chemical composition was determined by chemical analytical methods after drying and sifting the soil samples. A control sample was used for the various experiments. The methods used are semiquantitative emission spectrographic, EDTA titration, colorimetric, flame photometry, emission spectrographic and flame atomic absorption (Shacklette & Boerngen, 1984). The study is supplemented by a description of lateritic soil profiles (AFES, 2008; Baize et al., 1990).

### 3. Results and Discussion

#### 3.1. Mineralogical Characterization by X-Ray Diffraction

Six minerals forming gravel lateritic soils were identified by X-ray diffraction (**Figure 3**). They belong to three mineral classes according to Strunz and Nickel (2001).



**Figure 3.** Mineralogical identification of gravel lateritic samples from Lam-Lam (LL), Mont Rolland (MR), Pout (PT), Ngoundiane (NG), and Sindia (SD) in the Thies region.

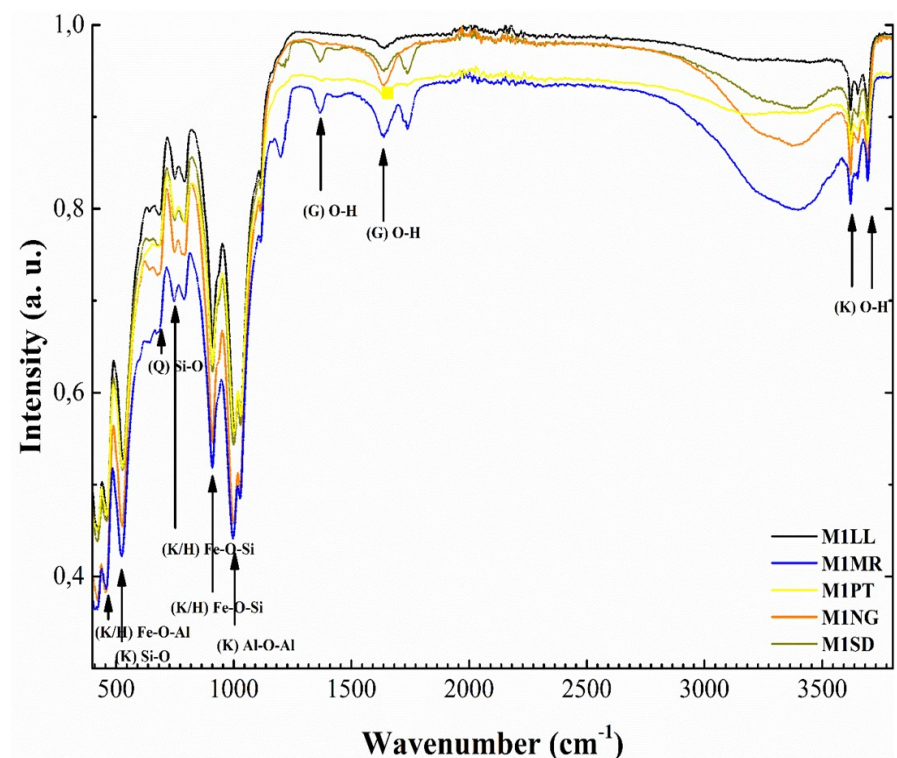
- silicates: quartz ( $\text{SiO}_2$ ), stishovite ( $\text{SiO}_2$ ) and kaolinite ( $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ );
- oxides and hydroxide: an iron oxide, hematite ( $\text{Fe}_2\text{O}_3$ ) and an iron oxide-hydroxide, goethite ( $\text{FeO}(\text{OH})$ );
- a carbonate mineral: calcite hydrocarbonate ( $\text{Ca}_3(\text{CO}_3)_2(\text{OH})_2$ ).

Hematite or goethite can be masked depending on the reducing or oxidizing state of the environment respectively, the two most often coexist in lateritic soils in dry and draining conditions (Diop et al., 2023).

X-ray diffraction is a crystallographic analysis, necessarily based on the geometry of minerals. Its results may therefore content a degree of error that can be avoided by infrared spectrometry. This method complements that of the X-ray diffraction and allow the detection of crystallochemical interatomic vibrations.

### 3.2. Infrared Spectroscopy Applied to the Gravel Lateritic Soils of Thies

This analysis allows to determine the mineralogical composition of geomaterials through inter-mineral bonds (Figure 4). Existing bonds with the elements of hydrocarbon calcite as well as the vibration of the bonds with stishovite are not detected. Raman spectrometer (Diop et al., 2023) like that of Fourier Transform Infrared (FTIR), corroborates the X-ray diffraction results concerning the presence of characteristic minerals (quartz, kaolinite, hematite and goethite) in the analyzed lateritic soils. Such minerals were detected by Foko Tamba et al. (2022); Kessoum Adamou et al. (2023); Hyoumbi et al. (2018) in lateritic soils.



**Figure 4.** Fourier transform infrared spectrogram of gravel lateritic samples from Lam-Lam (LL), Mont Rolland (MR), Pout (PT), Ngoundiane (NG), and Sindia (SD) in Thies.

### 3.3. Geochemical Characterization

Laterization is a geochemical alteration characterized by new-formation, crystallization, and inheritance of minerals if the weathering process is not complete. This alteration has an impact on the composition and classification of laterites.

#### 3.3.1. Lateritic Weathering

The two types of alterations affecting primary rock-forming minerals are biochemical and geochemical weathering. Quartz (inherited mineral), kaolinite (new-formed mineral), hematite and goethite (crystallized minerals) are all present in the gravel lateritic soils of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia.

Quartz, kaolinite, hematite and goethite are characteristic minerals of lateritic soils that form in tropical regions by geochemical weathering with good drainage (Schellmann, 1981).

#### 3.3.2. Chemical Results

The chemical results of the gravel lateritic samples studied are presented in **Table 1**.

The percentage of silica ( $\text{SiO}_2$ ) varies from 5.07 in Sindia to 35.78wt% in Pout. The proportions of silica are 9.20 and 10.50wt% respectively in Lam-Lam and Mont Rolland both located in the same geological context. In Ngoundiane, silica reached 16.37wt%.

The percentage of alumina ( $\text{Al}_2\text{O}_3$ ) is low in Ngoundiane with 2.77wt% and reaches 14.84wt% in Lam-Lam. The proportions of alumina are respectively 12.81, 8.87 and 11.64wt% in Mont Rolland, Pout and Sindia.

Ferric oxide ( $\text{Fe}_2\text{O}_3$ ) is abundant in all the studied samples, ranging from 30.15 in Mont Rolland to 51.91wt% in Ngoundiane sample. The ferric oxide proportions are 41.41, 35.59 and 41.27wt% respectively in Lam-Lam, Pout and Sindia.

Alkaline base oxides ( $\text{K}_2\text{O}$  and  $\text{Na}_2\text{O}$ ) are not abundant in the five borrow pits. They are contained in the soils in percentages ranging from 0.16 (Pout and Ngoudiane) to 0.31wt% (Mont Rolland) for  $\text{K}_2\text{O}$  and 0.59 (Mont Rolland) to 1.83wt% (Sindia) for  $\text{Na}_2\text{O}$  content.

Alkaline-earth base oxides ( $\text{CaO}$  and  $\text{MgO}$ ) are significant in the soils studied. They are varying from 2.03 (Pout) to 13.13 (Mont Rolland) for  $\text{MgO}$  and 2.55 (Ngoundiane) to 10.24 (Lam-Lam) for  $\text{CaO}$  content. These results could demonstrate that the weathering process which affects mainly the alkaline and the alkaline-earth base oxides is not complete.

The amounts of the other oxides in these soils seemed to be closely linked to their bedrock composition as for  $\text{P}_2\text{O}_5$  and  $\text{SO}_3$  or for their relative humidity as for  $\text{H}_2\text{O}$ . These oxides are not involved in the classification of this soils and are increasingly released during the laterization process.

#### 3.3.3. Previous Classification of Lateritic Soils

Some authors have classified laterites according to their chemical composition without taking into account their mineralogy.

Martin & Doyme (1927, 1930) propose a  $R_{MD}$  ratio-based classification (1):

$$R_{MD} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3} \quad (1)$$

$R_{MD} < 1.33$ : corresponds to true laterites;

$1.33 \leq R_{MD} < 2$ : corresponds to lateritic soils;

$R_{MD} \geq 2$ : corresponds to non-lateritic soils.

Joachim & Kandiah (1941) define the  $R_{JK}$  ratio of silica to aluminum and iron sesquioxides defined in Equation (2), using the same classification limit values as Martin & Doyne (1927, 1930).

$$R_{JK} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3} \quad (2)$$

These classifications are often used nowadays and are not unanimous of the fact that  $R_{MD}$  and  $R_{JK}$  ratios classify, in laterites, iron ores, bauxites and many ferruginous sandstones.

According to the values of the  $R_{MD}$  ratio defined by  $\text{SiO}_2/\text{Al}_2\text{O}_3$ , the gravel lateritic soils of Lam-Lam, Mont Rolland and Sindia are classified as true laterites, within the meaning of Martin & Doyne (1927, 1930),  $R_{MD}$  is less than 1.33. In contrast, the Pout and Ngoundiane gravel lateritic soils are classified as non-laterite soils,  $R_{MD}$  exceeds 2 (Table 1).

Considering the values of the  $R_{JK}$  ratio of Joachim & Kandiah (1941) defined by  $\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$ , the gravel lateritic soils of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia are all classified as true laterites,  $R_{JK}$  is less than 1.33. (Table 1).

### 3.3.4. New Classification and Diagram

As part of this work, Gbaguidi and Diop propose the  $R_{GD}$  ratio, in Equation (3), which is defined by the weight percentage of aluminum sesquioxides over that of iron oxides. This ratio could complete the classification of Joachim and Kandiah (1941) and allows to classify laterites, previously identified by mineralogical analysis, in two groups, based on their chemical composition. It is defined as follows:

$$R_{GD} = \frac{\text{Al}_2\text{O}_3}{\text{Fe}_2\text{O}_3} \quad (3)$$

$R_{GD} < 1$ : corresponds to ferruginous laterites;

$R_{GD} \geq 1$ : corresponds to aluminous laterites.

According to the values of the  $R_{GD}$  ratio defined within the framework of this study by  $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ , the gravel lateritic soils studied all correspond to ferruginous laterites, as the  $R_{GD}$  is less than 1 (Table 1).

These various classifications, and the contributions and breaches of the authors, as well as the work of Bárdossy (1982), Schellmann (1983), Sinisi (2018) and Hyoumbi et al. (2018) have served Diop, within the scope of this work, in proposing a new Classification of tropical residual soils (Figure 5). To avoid the drawbacks noted in the classifications of Martin & Doyne (1927, 1930) and Joachim and Kandiah (1941) by Florentin and Lh riteau (1952), Autret (1980), and Bourman and

Ollier (2002) while being inclusive towards bauxites; Diop proposes a use of this classification diagram after mineralogical analysis and detection of mineral oxides and hydroxides of residual tropical soils. This diagram is dedicated to lateritic resources and not to the classification of non-residual formation such as ferruginous sedimentary rocks and/or those with a ferruginous matrix or cement.

It is a ternary diagram based on the chemical results of major elements in lateritic soils, providing contents of iron, aluminum and silicon oxides. This diagram distinguishes, on the one hand, the class of non-lateritic soils and, on the other hand, four other classes of lateritic soils, with two ferruginous and two aluminous, when the silica content is relatively less than 50wt% compared with the sum of iron and aluminum oxide contents.

These four classes are divided into two sub-classes, one representing lateritic soils and the other representing true lateritic soils, depending on whether the silica content is between 25 and 50wt% or between 0 and 25wt%, respectively. The intensity of weathering is proportional to the richness of iron and aluminum oxides in tropical soils, but inversely proportional to silica content. For true lateritic soils, weathering is very intense, for lateritic soils, it is moderate and for non-lateritic soils, it is weak (Bourman & Ollier, 2002; Schellmann, 1981).

According to the Diop classification, the samples of Thies are all lateritic and ferruginous. The lateritic ferruginous soils, in decreasing order of iron content, include the laterites of Sindia, Lam-Lam, Mont Rolland and Ngoundiane. Among those samples, only the one from Pout belongs to the ferruginous lateritic soils (Figure 5).

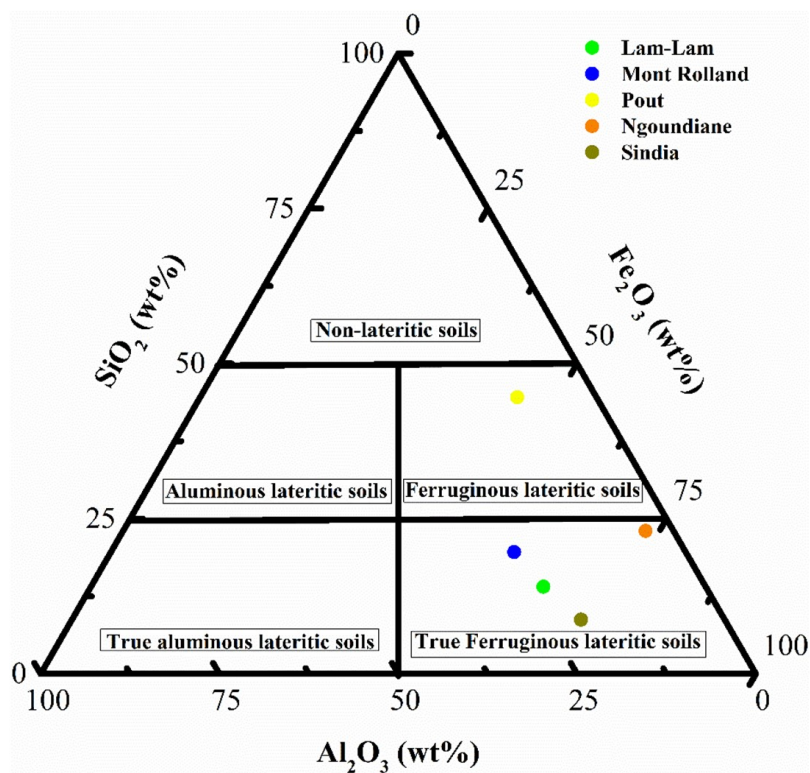


Figure 5. Classification of lateritic soils from Thies in Diop's ternary diagram.

Furthermore, as shown in the diagram (**Figure 5**), the significant concentration of iron and aluminum oxides (**Table 1**) testifies to the lateralization of these soils (Gidigas, 1976; Meza-Ochoa et al., 2023; Schellmann, 1983).

**Table 1.** Chemical composition and oxide ratios of gravel lateritic soils from Thies.

Oxides (wt%)	Sample				
	Lam-Lam	Mont Rolland	Pout	Ngoundiane	Sindia
SiO <sub>2</sub>	9.20	10.50	35.78	16.37	5.07
Al <sub>2</sub> O <sub>3</sub>	14.84	12.81	8.87	2.77	11.64
Fe <sub>2</sub> O <sub>3</sub>	41.41	30.15	35.59	51.91	41.27
CaO	10.24	3.65	5.64	2.55	8.00
MgO	7.36	13.13	2.03	7.33	3.83
SO <sub>3</sub>	1.28	1.86	2.98	2.10	2.74
TiO <sub>2</sub>	-	-	-	-	-
MnO	-	-	-	-	-
Na <sub>2</sub> O	0.90	0.59	0.76	0.97	1.83
K <sub>2</sub> O	0.25	0.31	0.16	0.16	0.21
P <sub>2</sub> O <sub>5</sub>	10.83	14.12	4.76	6.02	17.01
H <sub>2</sub> O	3.70	12.88	3.44	9.81	8.42
Total	100.00	100.00	100.00	100.00	100.00
SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	0.62	0.82	4.03	5.91	0.44
SiO <sub>2</sub> /(Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> )	0.16	0.24	0.80	0.30	0.10
Al <sub>2</sub> O <sub>3</sub> /Fe <sub>2</sub> O <sub>3</sub>	0.36	0.42	0.25	0.05	0.28

### 3.4. Additional Chemical Characteristics for Pedological Analyzes

Additional chemical analyzes carried out on the lateritic gravel samples from Thies gave the following results (**Table 2**).

- The hydrogen potential values in water (water pH) vary from 5.8 for Mont Rolland to 6.5 for Sindia. These water pH < 7 indicate acidic soils.
- The percentages by weight of carbon C (wt%) are low and ranging from 0.07 for Ngoundiane to 0.18wt% for Pout; similarly, the percentages of nitrogen N (wt%) are very low to negligible, ranging from 0.01 for Mont Rolland, Ngoundiane and Sindia to 0.02wt% for Lam-Lam and Pout. Organic matter decomposition rate is significant (C/N < 15) and it is maximum for the Sindia sample (C/N = 12); the samples from Lam-Lam, Mont Rolland and Pout have the same C/N value equal to 10; the Ngoundiane sample has a value of 8; the organic matter decomposition rate is therefore important and the relative low content of carbon justifies the acidity of these soils.

Cation exchange capacity (CEC) ranges from 13 for the sample from Sindia to 20 mEq/100 g for that from Mont Rolland. The soil saturation rates, S/CEC, de-

ducted from the CEC are lower than 50%. Consequently, these soils are nodular ferruginous, with a great abundance of nodules in one or more nodular horizons containing 30 to 60wt% of ferruginous nodules formed in place;

- Organic matter (OM) in the different lateritic gravel samples is low, it varies from 0.12 in the sample from Ngoundiane to 0.42wt% in that from Pout.

The chemical characteristics of these soils, in a pedological consideration, correspond well to those of weakly acid ferruginous lateritic soils, rich in gravelly nodules but poor in organic matter. Based on the French soil reference system (AFES, 2008), the Thies soils studied can be classified as Ferruginosols.

**Table 2.** Chemical characteristics of lateritic gravel horizon from the Thies region.

Profiles	water pH value	C (%)	N (%)	C/N	CEC (mEq/100 g)	M.O. (%)	S/CEC (%)
Lam-Lam	6.1	0.18	0.02	10	17	0.32	32
Mont Rolland	5.8	0.14	0.01	10	20	0.25	23
Pout	6.3	0.24	0.02	10	15	0.42	29
Ngoundiane	6.0	0.07	0.01	8	18	0.12	30
Sindia	6.5	0.16	0.01	12	13	0.29	28

### 3.5. Description of Lateritic Gravel Profiles

In a lateritic gravel soils profile, zones or horizons form layers distinguished by their specific properties (AFES, 2008): color, structure, texture, chemical composition, root frequency, etc.

In geotechnical engineering, according to Ramanoarison (1985), the typical lateritic profile (Figure 6) consists of four zones of varying properties, from bottom to top.

- 1) The deep weathering zone, where fragments of bedrocks coexist with alteration products.
- 2) The silty-clay weathering zone which generally reaches several meters in thickness; it is the zone of new-formed clays.
- 3) The accumulation zone is very heterogeneous. Its upper part consists of quartz sands which are associated with gravels of ferruginous pisolitic grains in a silty-clayey matrix.

The iron sesquioxide accumulations are more or less indurated and range from simple impregnation to the formation of scoriaceous or flaky duricrust. Lateritic gravel used in road construction is extracted from the accumulation zone in lateritic profiles.

- 4) The leaching zone is characterized by very rapid decomposition of the litter. In lateritic gravel borrow pits, this surface area is stripped prior to extraction of materials uncontaminated by organic matter.

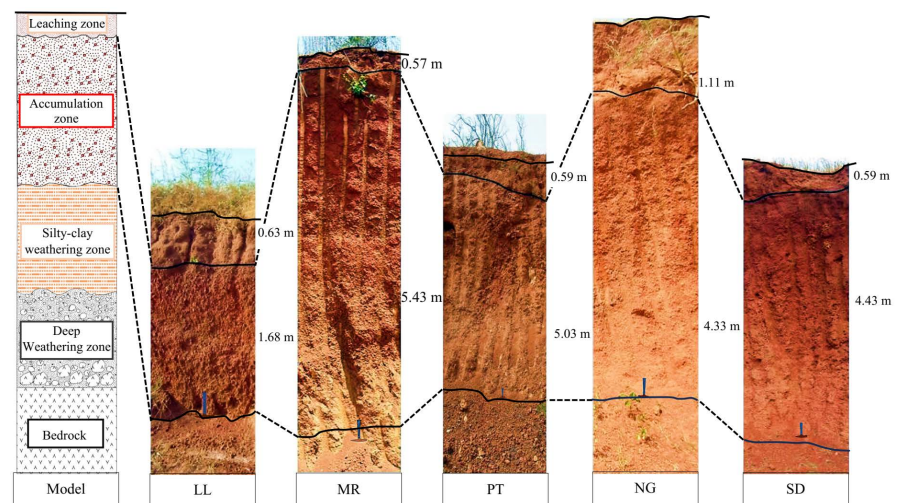
Diop et al. (2023) presented the lateritic weathering profiles of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia. Excavation reveals mineable reserve with thicknesses that vary between 1.68 m (Lam-Lam) and 5.43 m (Mont Rolland). The

overburden, or superficial leaching zone has a thickness varying from 0.57 (Mont Rolland) to 1.11 m (Ngoundiane).

The leaching zone is remarkable in the Lam-Lam and Ngoundiane profiles; however, it is thin in the profiles of Mont Rolland, Pout and Sindia (Diop et al., 2023). The mineable reserve of gravel lateritic soils is highly heterogeneous, and its thickness varies according to the borrow pit considered: from 1.68 for Lam-Lam to 5.43 m for Mont Rolland. A borrow pit of lateritic gravel is mineable when the ratio of the discovery overburden to the mineable lateritic reserve is less than or equal to 0.50 (Diop, 2022). The five borrow pits studied satisfy this condition, which is necessary but not sufficient, because the mineralogical composition and geochemical properties of extracted materials are decisive in building and road construction.

Mineable reserve colors were identified on the basis of the revised Munsell® Color (1994). The yellow-reddish color is remarkable at Lam-Lam (5 YR 6/8) and Pout (7.5 YR 7/8). The color is yellow-reddish for Mont Rolland (7.5 YR 6/8) and dark yellow-reddish for Sindia (7.5 YR 6/4). Ngoundiane has a yellow-reddish color (7.5 YR 7/8) which turns yellow towards the base (10 YR 7/8). In an oxidizing environment, iron gives to laterites a yellow-reddish, ocher or red color while in a reducing environment the color tends to be yellowish.

The characteristic yellowish color of goethite is perceptible in the lateritic gravels studied as is that of the red hematite, which is consistent with the mineralogical and chemical composition of these materials (Figure 6).



**Figure 6.** Presentation of the lateritic profiles of Lam-Lam (LL), Mont Rolland (MR), Pout (PT), Ngoundiane (NG), and Sindia (SD) in correlation with the model of Ramanoarison (1985, modified).

#### 4. Conclusion

X-ray diffraction and infrared spectroscopy were used to identify the minerals making up the gravel lateritic soils of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia. Quartz (inherited mineral), kaolinite (newly formed mineral), hema-

tite and goethite (crystallized minerals) are all present in these materials. This mineralogical composition corresponds well to that of lateritic soils which form in tropical regions with good drainage.

The gravel lateritic soils studied were chemically classified as follows:

- according to the  $R_{JK}$  ratio equal to  $\text{SiO}_2/(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)$  and defined by [Joa-chim and Kandiah \(1941\)](#), the gravel lateritic soils of Lam-Lam, Mont Rolland, Pout, Ngoundiane and Sindia are all classified as true laterites because  $R_{JK}$  is less than 1.33;
- according to the  $R_{GD}$  ratio equal to  $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ , and defined as part of this work by Gbaguidi and Diop, these materials are all in the class of ferruginous laterite soils because  $R_{GD}$  is less than 1.

Thus, the gravel lateritic soils of the Thies region belong to the true ferruginous laterites and ferruginous laterites according to the ternary Diop's diagram. They are also, pedologically, weakly acidic ferruginous lateritic soils, rich in gravelly nodules but poor in organic matter.

Based on their physical and chemical characteristics, these Thies materials contain non-swelling clay and are inorganic and rich in nodules, making them compositionally suitable for road construction. After this encouraging preliminary study, and before being used in road engineering, these materials will be identified and mechanically characterized using geotechnical approaches.

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## Conflicts of Interest

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

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