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Chemical and Mineralogical Characterisation of Clayey Sands from the Ivorian Sedimentary Basin in Road Construction

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Abstract

In Ivory Coast, particularly in the south, most paved and unpaved roads are made of clayey sand, given its availability. The early degradation of roads is related to a strong sensitivity of certain materials to the environment (climate, geology, and degrees of alteration) and a poor knowledge of the geotechnical properties could slow down their use in road construction. Within this framework, this paper focuses on determining the chemico-mineralogical nature of the clayey sands of the localities of Bingerville and Samo, in the

South-East of Ivory Coast. Tests were conducted based on the chemical and mineralogical analyses. Chemical elements were determined by atomic absorption spectrometry, colorimetry, complexometry, and gravimetry. Organic matter was determined using the Rock-Eval 6 pyrolysis method, while the mineralogical composition was determined using a Bruker D8 ADVANCE diffractometer. The chemico-mineralogical analyses reveal that the clayey sands from Bingerville and Samo are more enriched in silica oxide (SiO2) but less enriched in iron oxide (Fe2O3). All the soils studied have a degree of laterization greater than 2, which suggests that they are non-lateritic soils. The low Total Organic Carbon (TOC) values lies between 0.1 and 0.15% by weight, which reflects the extremely low amount of organic matter in these soils. This indicates the possibility of treating these soils with hydraulic binders. The mineralogy of the studied soils denotes that they are composed of kaolinite and illite.

Keywords: Clayey sand, Characterization, Chemico-mineralogical, road, Sedimentary basin, Ivoirian

1.0. Introduction

In Africa, several studies conducted in the field of road construction (LBTP, 1977; Autret, 1983; Messou, 1980; Bohi, 2008; Souley, 2016) have shown the use of lateritic soils (Souley et *al*., 2015). However, their systematic use as road building materials makes them a scarce resource in the West African sub-region (Bohi, 2008; Samb et *al.*, 2013; Boudlal et *al*., 2017). The same is true in some parts of Ivory Coast as most of the roads made of lateritic soils are experiencing degradation, especially in the coastal regions such as Abidjan, San Pedro, and the south of the country. Therefore, the evolution of the economic context and the objectives of sustainable development (SDGs) identify the need to promote alternative raw materials. Examples of these natural materials include shales and marls (Boudlal et *al*., 2017), recycled materials, concrete debris, glass debris (Boudlal et *al*., 2017; Djomo, 2017), and clayey sands. Clay sands, given their availability and abundance in the terrains encountered in the south of Ivory Coast (LBTP, 1977; Sodemi, 2010), could constitute a novel approach that integrates the Sustainable Development Goals (SDGs). Occasionally, these have been used in the design of roads. In road works, the use of clayey sands in their natural state, especially with or without treatment and appropriate mixtures of hydraulic binders, often poses problems from chemical and mineralogical points of view (Djedid, 2020).

The early degradations of roads made with natural clayey sands are recurrent and are due to its plastic state, the volume swelling, the organic matter, and the clay of the raw material. Diop (2002) reveals that during the construction of the Dakar-Thies highway, the presence of swelling clayey soils was observed in the area connecting the two localities. Therefore, this study aims to determine the physico-chemical and mineralogical nature of the clayey sands of the localities of Bingerville and Samo, in the South-East of the Ivory Coast, to apprehend their behavior in the structures under loads such as road infrastructures.

2.0 Site and Experimental Methods

2.1. Raw Material and Sampling Site

The subject focus of this study is reworked soils which were taken, according to the XP P 94-202 standard (1995), on sites previously identified by the Building and Public Works Laboratory (LBTP). These sites are located onshore in the sedimentary basin, which is specifically in the southeastern part of Ivory Coast in geotechnical region R1, according to the LPTP (1977).

The Ivorian sedimentary basin owes its existence to the opening of the Atlantic Ocean. It covers an area of 30,000 km^2, thus stretching from Sassandra in the west to Axim in Ghana in the east. It is an open basin, most of which is currently offshore, with a small part emerging. Deep drilling for hydraulic and petroleum exploration, as well as seismic and gravimetric studies, have shown that a stratigraphic gap between the basement, made up of Eburnian schists and granites, and the first deposits of sedimentary cover in the Upper Jurassic is equivalent to 1600 m.y. During this period, the area of today's Ivorian coasts was not yet reached by marine waters. Only veins of basic and ultrabasic rocks (dolerites, kimberlites, etc.), dated between 1700 and 280 m.y., bear witness to this prolonged period (Tagini, 1972). This basin is characterized by two distinct domains (Spengler & Delteil, 1964), which includes a crescent-shaped continental or "onshore" basin and a marine or "offshore" basin.

From a structural geology point of view, this part of the country is characterized by three major structures (Figure 1), namely: the lagoon fault, the Ghana-Ivory Coast wrinkle, and the bottomless pit (Aka, 1991; Assale, 2013). The lagoon fault divides the sedimentary basin into two distinct zones: a southern zone made up of the low coastal plain and the low plateau, where there is a sandy cordon, and a northern zone known as the high plateau between 50 and 110 meters above sea level. In this northern zone, fine clay soils are found (Kouakou, 2005). These include reworked soils sampled from several borrow pits, with a focal point around which three other sampling points within a 2-3 m radius are located at the Bingerville and Samo sites. In January 2017, a total of two (2) sampling points was estimated. The locations were established using the GPS receiver, which are presented below in Table 1.

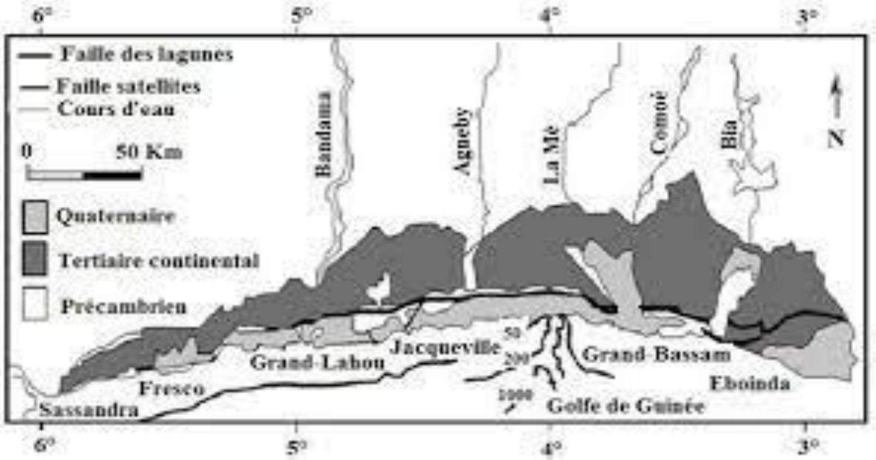

Figure 1. Ivoirian Sedimentary Basin

Table 1. Location of Raw Material Collection Sites (Geographic Coordinates and NTU)

Longitude (° ' '')	Latitudes (° ' '')	Altitudes (m)	Localities
3° 53' 32 W	5° 21' 38'' N	45,5	Bingerville
	400 612 m	400 612 m	
3°30'53'' W	5°17'28'' N	51,14	Samo
	278 102 m	400 612 m	

These samples were taken at variable depths ranging from 1 to 5 m on average, with 3 to 5 m average widths. First, they were placed in transparent plastic bags at room temperature. Thereafter, they were transported and conditioned in the laboratory around 25°C. The sampling or borrowing sites are shown in Figure 2 below.

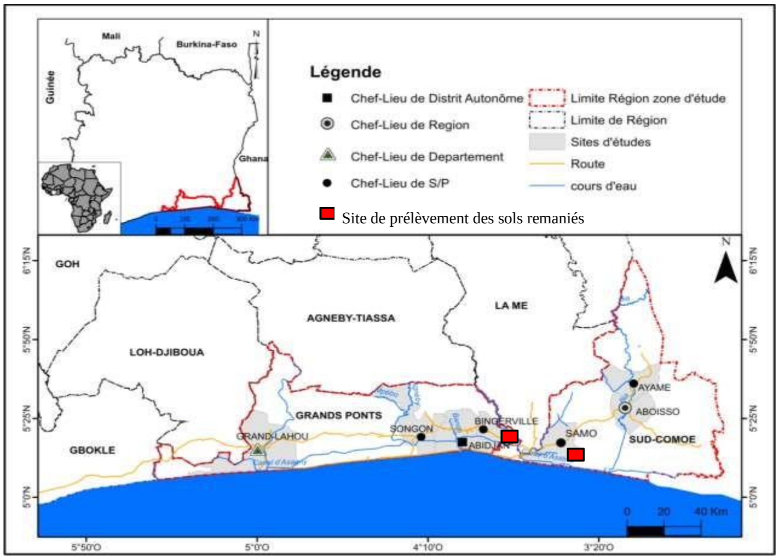

Figure 2. Location of Reworked Soil Sampling Sites

2.2. Experimental Methods

2.2.1. Chemical Characterization Methods

The chemical composition was determined after the samples were put into solution by a tri-acid attack (sulpho-nitric mixture and hydrochloric acid according to the protocol proposed by Njopwouo et *al*., 1979). The analysis was conducted in the laboratory of the company to ascertain the mining development of Ivory Coast. Chemical elements, iron oxide (Fe_2O_3), silica oxide (SiO_2), and others were determined by atomic absorption spectrometry, colorimetry, complexometry, and gravimetry. The spectrophotometer used is a Perkin Elmer Analyst 100, while the colorimeter used is a Jenway 6300 spectrophotometer. Organic matter was examined using the Rock-Eval 6 pyrolysis method at the Société Nationale d'Opération Pétrolière (PETROCI) analysis and research center. Total Organic Carbon (TOC) was utilized to examine organic matter content based on analyzed samples. Thus, it is possible to identify the capacity of soil to support loads under traffic. The organic matter content is qualified according to Espitalie et *al.* (1977) and Peters et *al.* (1994), as shown in Table 2.

Table 2. Classification of Organic Matter and Suitability of Soil for Use Under Traffic in Road Techniques (Espitalie et *al*., 1977; Peters et *al*., 1994; Copard, 2002)

TOC (weight %)	CLASSES	SOIL SUITABILITY
< 0,5	Poor	suitable
0,5-1	Means	suitable
1-2	Good	suitable
2-4	Exceptionally good	unsuitable
>4	Excellent	unsuitable

Within the framework of the design of road works, the soils suitable for use must have an organic matter content of less than 2% of good to poor classes (CEBTP, 1980).

2.2.2. Mineralogical Characterization Methods

The mineralogical composition was determined using a Bruker D8 ADVANCE diffractometer. Sample powder ground to a particle size of less than 80µm was used for X-ray diffraction analysis. According to Stokes law, the fine fraction (<2 µm) was extracted by sedimentation to determine its mineralogical composition. The identification of minerals after analysis was done using the Fityk software (Caner, 2011) and is based on the positions of peaks at certain reticular distances in the (001) plane, according to the diffractograms (Thorez, 1976; Coulibaly et *al*., 2020). Furthermore, the analysis by X-ray diffraction (XRD) can be done on three types of complementary tests (the normal slides, the glycol slides and the heated slides).

Regarding the normal slides (N), the recorded diffractograms of DRX are used as reference to appreciate the displacements of lines caused by the other tests. The glycol slides (EG) contain ethylene-glycol, and the swelling minerals, such as smectites, are stored in the sample "swell". The heated slides are intensified to 500°C to destroy kaolinite. However, this has no effect on chlorites. The minerals of the vermiculite and smectite family are irreversibly dehydrated at this temperature. This loss of water causes a shift of the 001 line from 15 to 10 Å. These clays are said to close at 10 Å after heating. This closure of minerals is a characteristic for their identification, especially for the identification of interlayers containing smectic and vermiculite mineral sheets.

3.0 Results

3.1. Chemical Characterization of Clayey Sands of Bingerville and Samo in their Natural State

3.1.1. Content in Oxides

The proportions of the contents in oxides realized on the clayey sands, which was crushed and returned in powder form (diameter between 75 nm and 100 nm), are illustrated in Table 3.

Table 3. Proportion of the Contents in Oxides of the Various Clayey Sands of Samo and Bingerville

	Mass Proportion of the Measured Oxides				
Clayey sands	% SiO_2	% Al_2O_3	% Fe_2O_3	% TiO_2	%MgO
Bingerville	60.03±0.02	12.21±0.02	8.8±0.02	1.28±0.02	0.06±0.01
Samo	62.39±0.02	9.79±0.02	12.68±0.02	1.09±0.02	0.05±0.01

This table of proportion of oxide contents shows that the clayey sands of Bingerville and Samo are more enriched in silica oxide (SiO_2) but less enriched in iron oxide (Fe_2O_3). The variation in the chemical composition of these different soils could be explained by the environmental factors that influence the process of laterization, such as climate (temperature, water balance), topography (erosion and drainage), and vegetation (organic matter, bacteria, humic acids, and parent rocks).

These clayey sands were collected from the same climatic zone, specifically in the southern region of Ivory Coast within the sedimentary basin in the northern part of the lagoon fault. This area experiences high rainfall alternating with sunny weather, which could explain the variation in the proportions of oxides in these soils.

Also, the variable coloration of the soils ranging from red to yellow ochre is an indicator of different degrees of oxidation of these clayey sands. Thus, the oxidation of iron contained in the minerals of soils, such as iron oxides and/or hydroxides, can be identified. The values of the degree of laterization of the various clayey sands determined by the ratio S/R are presented in Table 4.

Table 4. Values of the S/R Ratio of Different Clayey Sands

Clayey sands	S/R Ratio
Bingerville	2.18
Samo	5.93

As seen from Table 4, all the clayey sands present ratios of S/R superior to two (2). This shows the lagoon fault from East-West or from West to the East. It was further established that the silica oxides dominate the iron oxides. According to this classification, they are non-lateritic clayey sands. Thus, it is necessary to look for the content of organic matter in these different reworked soils.

3.1.2. Organic Matter Content

Based on the different clayey sands studied, Table 5 presents the results of the values of organic matter contents, which is expressed in total organic carbon.

Accordingly, the values of Total Organic Carbon (TOC) of the clayey sands vary between 0.10 and 0.15% by weight. As such, the organic matter content is low. In other words, the quantity of organic matter is low in the clayey sands of Bingerville and Samo. The rate of organic matter is less than 1 (< 1%) by weight. In such conditions, the clayey sands of this study can be treated with hydraulic binders and used as road base layers.

Table 5. Values of Organic Matter Contents of Different Clayey Sands

Clayey sands	TOC (weight %)
Bingerville	0.15±0.1
Samo	0.10±0.2

3.2. Mineralogical Characterization of the Clayey Sands of Bingerville and Samo

3.2.1. Analysis of the Clayey Sands of Bingerville

The cross analysis of the diffractograms, based on the fine fraction of the clayey sands of Bingerville, reveals that the clayey minerals are composed of kaolinite at 96% and a small proportion of illite at 4% (Figure 3). Kaolinite was detected by peaks observed at reticular distances of 7.1 Å (001), 3.55 Å (002), and 2.36 Å (003), especially on the diffractograms of the natural (N) and ethylene-glycol (EG) samples. Figures 4 and 5 confirmed the absence of peaks at these same distances on the diffractogram of the heated phase (CH500). Illite was recognized from the peaks observed on all diffractograms (Figures 3 and 4), which had the same respective lattice distances of 10 Å (001), 5 Å (002), and at 3.3 Å (003).

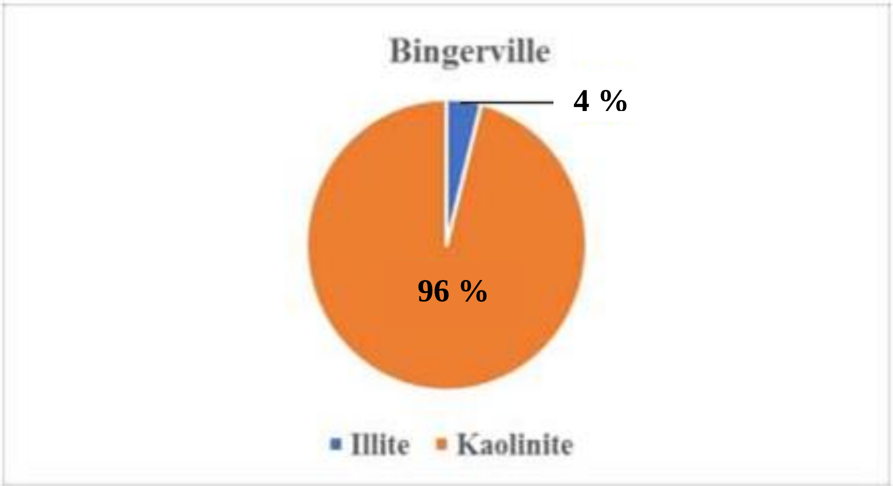

Figure 3. Mineralogical Composition of the Fine Fraction of Bingerville Clayey Sands

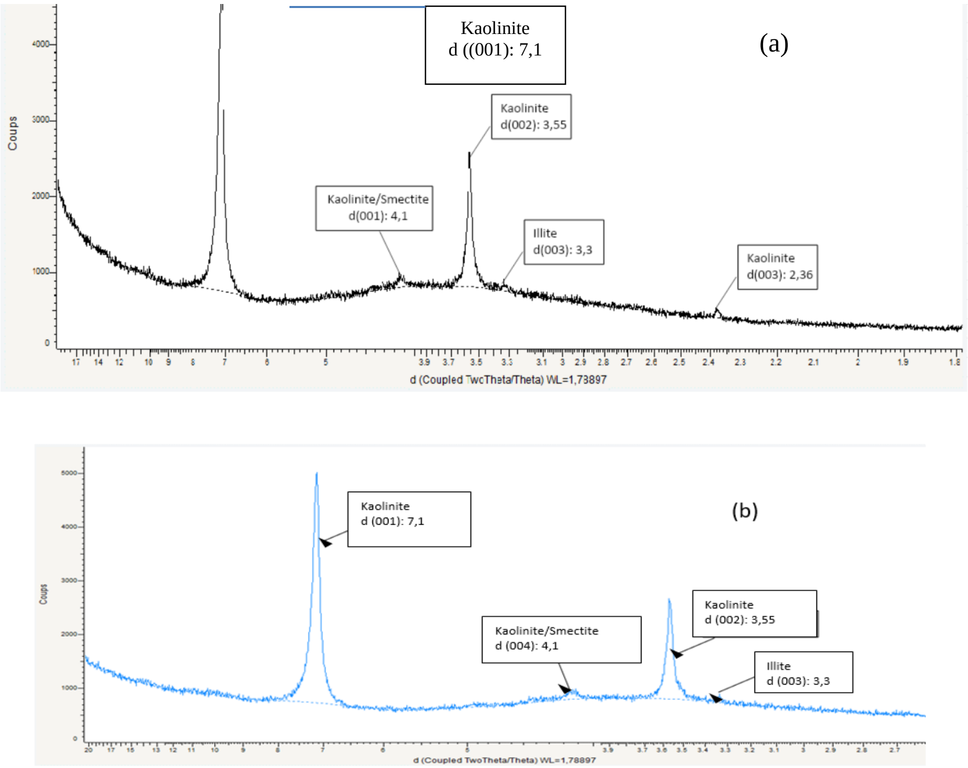

Figure 4. Diffractograms of the Fine Fraction of Bingerville Clayey Sands Performed on Normal (a) and Glycol Slides (b)

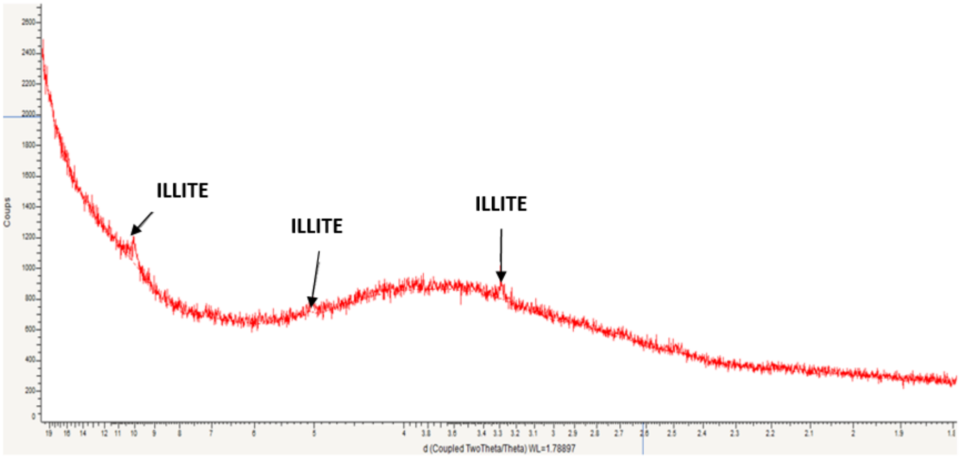

Figure 5. Diffractogram of the Fine Fraction of Heated Bingerville Clayey Sands

3.2.2. Analysis of the Clayey Sands of Samo

The clay mineralogy of the Samo sands is composed of kaolinite and illite.

Certainly, the lines observed at 7.1 Å (001), 3.55 Å (002), and 2.36 Å (003) on the diffractograms of the sample conducted on normal and glycol slides indicate the presence of kaolinite. This is confirmed by the disappearance of these peaks in the heating treatments. Kaolinite is dominant with a proportion of 93.7% against 6.3% of illite (Figure 6). The illite lines were observed at 10 Å (001), 5 Å (002), and 3.3 Å (003) on the diffractograms of the sample in normal, glycol, and heated slides (Figures 7 and 8).

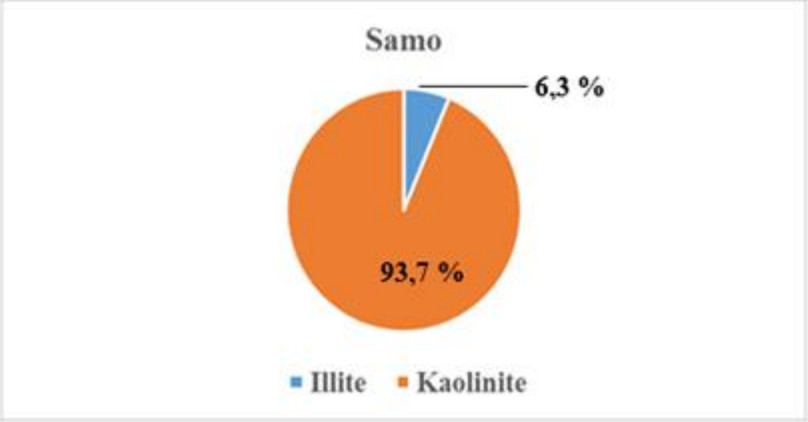

Figure 6. Mineralogical Composition of the Fine Fraction of Samo Clayey Sands

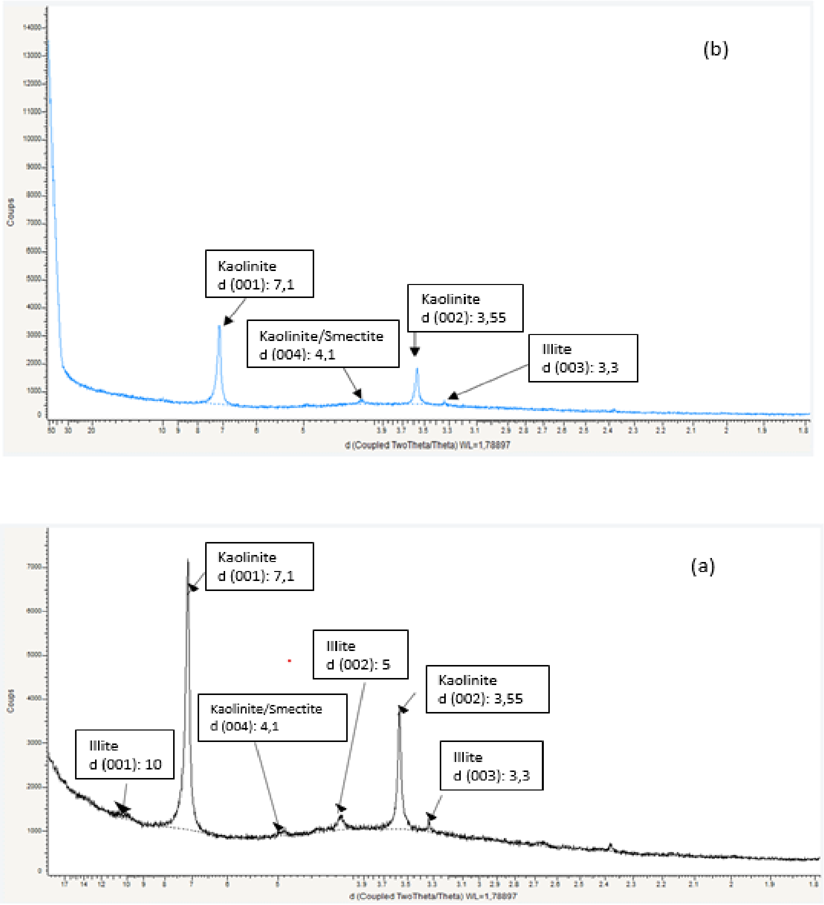

Figure 7. Diffractograms of the Fine Fraction of Samo Clayey Sands Performed on Normal (a) and Glycol Slides (b)

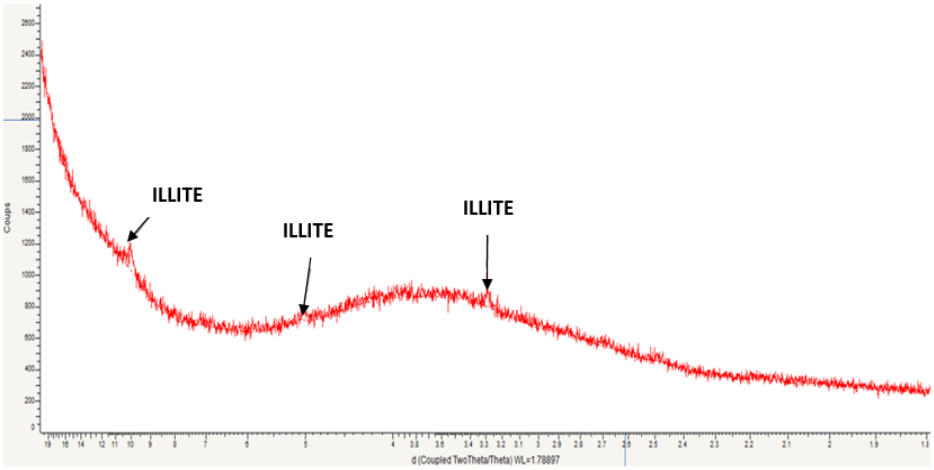

Figure 8. Diffractogram of the Fine Fraction of Samo Clayey Sands on a Heated Slide

4.0 Discussion

According to Assale et *al*. (2012), the clayey sands of Bingerville are enriched in quartz. This signifies the presence of certain minerals such as goethite, limonite, and hematite. These minerals influence the coloration of the soils as well as the variation of the degree of oxidation.

This predominance of quartz proves its resistance to weathering phenomena during erosion and transport processes in the tropical environment (N'zi et *al*., 2018). Subsequently, these results are in line with this study.

Regarding mineralogy, the analysis of the soils studied by X-ray diffraction indicates that they are composed of kaolinite and illite. This was detected at the reticular distances corresponding to reflections 001, 002, and 003.

Kaolinite minerals are still dominant and do not show significant variations. This is the result of extensive feldspar diagenesis in a humid (hot and humid) tropical environment on the continent (Yao, 2012; Assale, 2013). In addition, Wazir (2014) describes kaolinite in the marine environment as a detrital mineral, especially in the marginal zone of the sedimentary basin, where there is no significant variation. This implies that kaolinite is the only simple clay mineral.

However, Illite is derived from the alteration of primary potassic minerals through the progressive loss of potassium (Yoboué et *al*., 2014).
In line with Benzerara (2014), the balance of crystallographic variations, according to physicochemical treatments, is summarized as follows:

- Illite is detected by the presence of lines at 10 Å, 5 Å, and 0.34 Å. This corresponds to the reflections 001, 002, and 003 of an illite phase, which is unaffected by ethylene glycol treatment and heating to 550°C.

- Kaolinite is highlighted by the presence of reflections 001 and 002 at 7.15 Å and 3.5 Å in the natural state. However, it is unaffected by ethylene glycol treatment but disappears after heating to 550°C (dihydroxylation of kaolinite).

Based on the physical, chemical, and mineralogical characteristics, these clayey soils present aptitudes for its use in road construction. They have an average content of Al_2O_3 and do not contain enough swelling clay minerals of the smectite type such as montmorillonite. Also, there is an extremely low presence of Total Organic Carbon (TOC) in these soils. Nonetheless, it can be stabilized with hydraulic binders such as Portland cement (Molard et *al*., 1987; Temimi et *al*., 1998). While establishing an order of magnitude of mechanical strengths of clays, which is stabilized with cement and lime, Leroux (1969) showed that the best mechanical strengths are obtained with kaolinite and illite. As for smectites, they are less suitable for this type of stabilization because they consume all the Ca^{2+} ions released by the cement during its hydration, thus preventing its setting. However, Amor (1995) reports that kaolinite only fixes two thirds of these ions.

Conclusion

The chemical analyses showed that the samples contain three oxides: SiO_2, $A1_2O_3$, and Fe_2O_3. The content of oxides reveals that the clayey sands of Bingerville and Samo are more enriched in silica oxide (SiO_2) but less enriched in iron oxide (Fe_2O_3). Also, the low values of TOC are between 0.1 and 0.15% by weight. This reflects the extremely low amount of organic matter in these soils. Therefore, it is possible to treat these soils with hydraulic binders (Lime and cement).

As far as mineralogy is concerned, these clayey soils are suitable for road construction. The analysis of the soils studied by X-ray diffraction indicates that they are composed of kaolinite and illite.

This study shows that clay soils can support loads and are suitable for treatment with hydraulic lime and cement binders to improve their mechanical properties. As a result, they can be used in road construction in T1 and T2 type low-traffic structural pavement.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: All of the data are included in the content of the paper.

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