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Article

Characterisation of Geotechnical Properties of Residual Tropical Soils Used for Road Infrastructure: French Guiana Experience

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Abstract: This paper presents the first laboratory study of four materials (three lateritic soils and one sandy soil) mainly used in road construction in French Guiana. The analysis of macroscopic behaviour by physical tests, following French standards, made it possible to classify and group the samples with respect to the rules specified in the Guide des Terrassements Routiers (GTR). According to the GTR, these raw materials could only be used as backfill materials and under very specific hydric conditions. Chemical and mineralogical characterisation by the X-ray fluorescence analysis, scanning electron microscopy observation supplemented by the X-ray microanalysis, and the infrared analysis revealed differences in the main minerals. Indeed, the presence of mineral species such as kaolinite and gibbsite and oxides such as goethite and hematite was detected. The macroscopic and microscopic characteristics of the four soils made it possible to establish a relationship between their geotechnical and mineralogical properties. Finally, the results of this study led to the conclusion that the mineralogical composition and geotechnical properties of lateritic soils must be known simultaneously to allow correct identification for their application in road construction.

Keywords: Guyane; laterite; tropical soil; geotechnical properties; compressive strength

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1. Introduction

French Guiana has an equatorial climate with two climatic seasons: a dry season and a wet season. Similar to most countries in the inter-tropical zone, it has large resources in terms of lateritic materials which are commonly used for the construction of road infrastructure (forest roads, unpaved tracks, etc.). According to the National Office of Forests and the SAR (Schéma d'Aménagement Régional), 73% of Guyana's road network consists of unpaved rural roads [1].

The alternation of the seasons induces cycles of shrinkage/swelling on these more or less clayey soils and consequently favouring their variation in volume. The main defect of these lateritic materials lies in their characteristics, in terms of fineness and plasticity. They are particularly sensitive to water. Several studies based on laboratory tests have been carried out to define the physical and mechanical characteristics that gravel materials should have for use in road construction [2–5]. According to [6], lateritic gravels with aggregate crushing and LA abrasion values of less than 30% and 34%, respectively, and 10%

of fines can be used satisfactorily for pavement construction on heavily trafficked roads. Krinitsky [7] observed on roads made in Kenya that the laterites had high plasticity index (7–21%), wide ranging of laboratory soaked CBRs (12–96% at 95% BS compaction), and 14–49% of rock fractions finer than 0.063 mm. Other studies in other tropical countries use the criteria based on the Atterberg limits and grain size distribution. Paige-Green et al. [8] discuss the wide range of specifications for lateritic soils and highlight the diversity of soils selection criteria for road construction. To better understand the behaviour of these materials, other macroscopic analyses can allow a better classification of the soils present in the intertropical domain. In Brazil, a classification methodology for tropical soils, the MCT classification (Miniature, Compacted, Tropical) [9,10], classifies soils according to criteria other than granulometry and clay content while presenting conditions for the soil reuse in road infrastructure.

In most of these studies, no chemical analysis is considered. However, some work has shown that mineralogical constituents and microstructure have a significant influence on the geotechnical properties of lateritic soils [11,12]. The mode of formation and the mineralogical composition of the bedrock determine soil cohesion and compressibility characteristics [13]. It is therefore clear that the mechanical and geotechnical characteristics of lateritic soils are variable depending on the local conditions. Research in Brazil, notably by de Carvalho et al. [14], shows the example of a section of a road in the state of Amazonas that deteriorated after a short period of use. They noted that this disorder was not due to a structural design problem but to the interaction between the soil and the atmosphere. There are also many typical examples in French Guiana where cracks are generated in particular by the swelling of the soil in the rainy season. The swelling character of these soils is related to the amount and types of clay minerals present. Indeed, the amount of clay minerals and more particularly those of the smectite type contribute to the swelling phenomenon [15,16]. Thus, identifying and evaluating the potential of lateritic soils for the use in road construction based on their geotechnical properties alone, as recommended by the French standards [17,18], may be misleading given the evolving nature of these soils.

Laterite soils may be different and may also behave differently depending on the paedogenic factors [19,20]. Despite the numerous studies carried out on the soils used in road construction, there are no scientific studies on the geotechnical characteristics of the lateritic soils of Guiana. In this paper, the physical, geotechnical, chemical, and mineralogical characteristics of four tropical soils from French Guiana are studied for their use in road construction. The materials are all from different sites and geological horizons but are representative of what is usually encountered in road construction. The objective of this study is to carry out a macroscopic evaluation supplemented by microscopic analyses to better characterise these soils. For this purpose, the GTR classification defining the soil's conditions of use and its mechanical behaviour measured by geotechnical testing are complemented by chemical analyses to determine the quality of the soils. To have the most comprehensive characterisation possible, a microscopic X-ray fluorescence analysis, scanning electron microscopy, and X-ray microanalysis, as well as an infrared analysis, were carried out. The coupling of geotechnical and mechanical properties and mineralogical and chemical compositions of these soils allows a better evaluation of their suitability as a raw material in road construction.

2. Materials and Methods

2.1. Materials

On-site sampling of the studied materials was carried out in the upper layers after stripping. Figures 1 and 2 and Table 1 show the geological map of French Guiana, the names of the soils studied, and the precise location of the samples. These two geological maps are modified from Delor et al. [21].

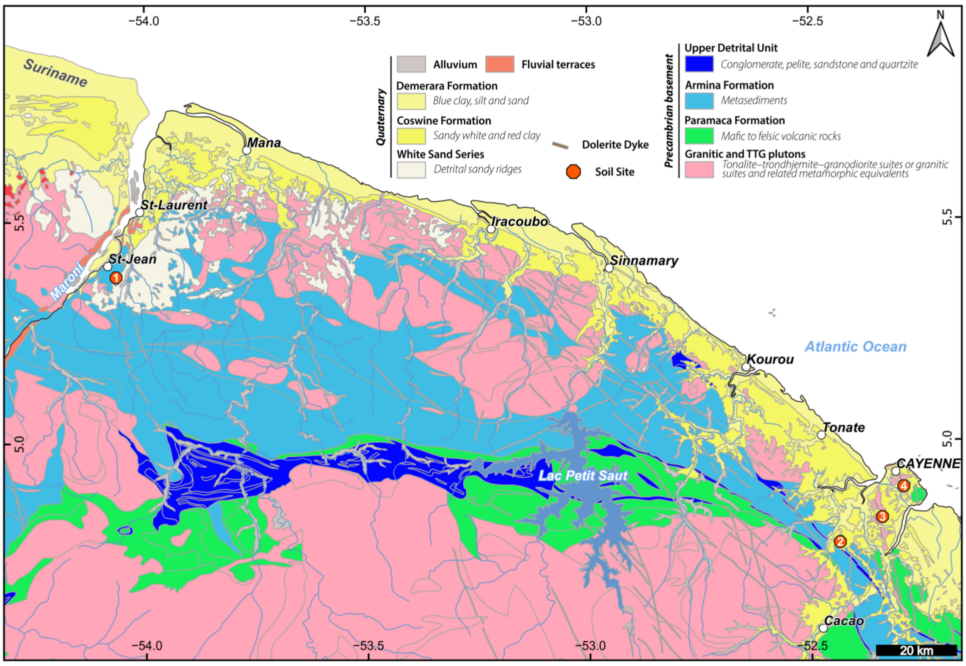

Figure 1. Geological map of French Guiana—positioning of the four different soils.

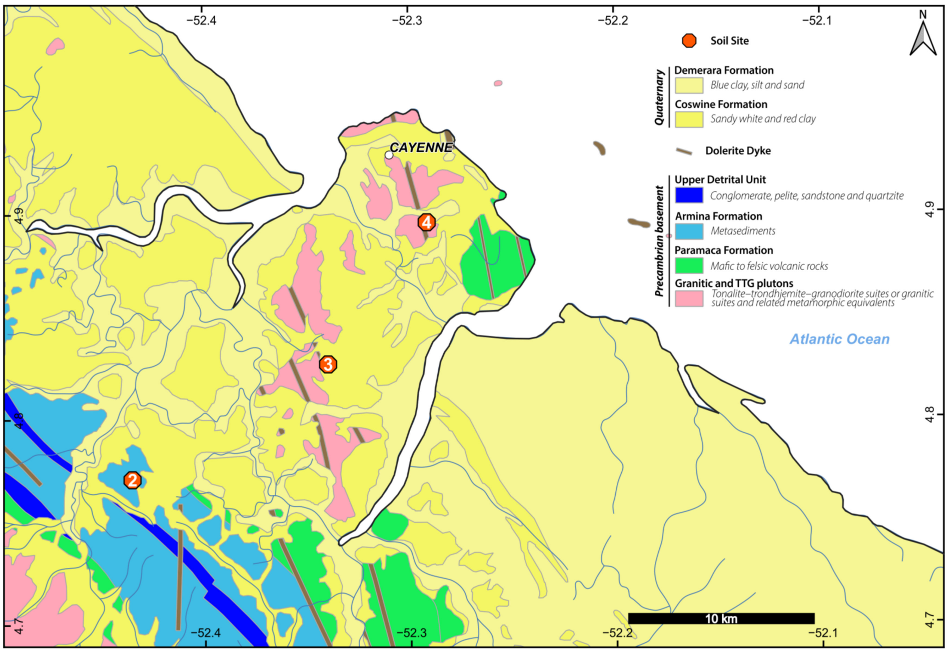

Figure 2. Focus on the island of Cayenne and positioning of soils 2, 3, and 4.

Table 1. Geographic coordinates of the surveyed sites.

Site (Figures 1 and 2)	Soil Designation	Coordinates
1	MTI	5.375194° N–54.065806° W
2	BE42	4.770611° N–52.435111° W
3	Cabalé	4.8265° N–52.339694° W
4	Morne Coco	4.8955° N–52.291306° W

MTI: Pleistocene white sands (Quaternary); BE42: lateritic soil belonging to the Orapu Schist geological series (Precambrian); Cabalé: lateritic soil belonging to the 16 to 18 m marine terraces (Quaternary); and Morne Coco: a discontinuous low-lying lateritic clay-iron armour resulting from the degradation of the gneissic/migmatitic basement (Precambrian).

According to the BRGM (Bureau de Recherches Géologiques et Minières), the French Geological Survey [22–24], the 4 soils are all from different sites and geological horizons. They are referenced as follows.

Figure 3 shows the sampling sites. The Cabalé and Morne Coco soils are ochre-coloured, with a significant presence of coarse elements in the Cabalé soil and a significant presence of sandy fraction in the Morne Coco soil. The BE42 soil is red with a predominance of fines and very weatherable coarse elements. The MTI soil is sandy, with a homogeneous white colour. This sand is comparable to the dune sand of the homometric nature.

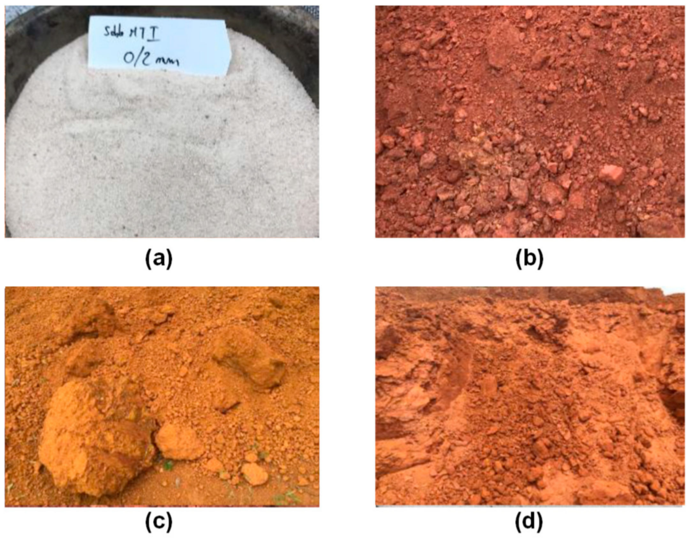

Figure 3. (**a**) MTI, (**b**) BE42, (**c**) Cabalé, and (**d**) Morne Coco.

2.2. Methods

2.2.1. Materials Preparation

Before the tests were carried out, the materials were homogenised and reduced according to the standard [25]. This preparation allows for homogeneity and regularity in the different samples. The materials were then put into 20 kg bags and stored for later reuse.

2.2.2. Macroscopic Characterisation of Soils

Several tests were performed to obtain a complete characterisation of the soils.

The identification tests completed are listed below. They are based on the French standardisation.

The distribution of grains was determined by granulometric analysis carried out on fractions ranging from 150 mm to 80 µm [26]. To characterise fine particles (<80 µm), granulometry by laser diffraction with a Coulter was performed according to ISO 13320: 2020 [27].

To characterise the plasticity of soils, the Atterberg limits were determined according to the standard (EN ISO 17892-12) [28] on the 0/400 µm fraction. The test was completed by measuring the methylene blue value, determined in accordance with the standard (NF P 94-068) [29].

For the determination of the specific surface area of the different materials, a BET/BJH (Brunauer–Emmett–Teller (BET) and Barrett–Joyner–Halenda (BJH)) analysis was performed using a 3D Flex by nitrogen adsorption/desorption. The analysis was carried out on the 0/5 mm fraction.

Various tests were used to characterise the compaction behaviour of the different soils: absolute density (NF EN 1097-7) [30] and standard and modified Proctor analyses [31]. In addition, Unconfined Compression Tests (NF EN 13286-41) [32] were carried out on 5 cm x 10 cm specimens to evaluate the compressive strength of the soils after compaction in order to determine the minimum time for circulation (1 MPa in simple compression allowing the circulation of heavy vehicles according to the GTS.), and 3 time frames were defined: 1, 7, and 28 days. The specimens were kept in a climatic chamber at 30 °C and 90% relative humidity until the day of the test.

2.2.3. Microscopic Characterisation of Soils

In order to assess the quality of the soils, the following tests were carried out: determination of organic matter (XP-P 94-047) [33], humic content (NF-EN 1744-1) [34], pH (NF ISO 10390) [35], cation exchange capacity (NF X 31-130) [36], and cations present in the soil using the cobaltihexamine method (NF X 31-108) [37].

- X-ray fluorescence

Ground and compacted powder of materials < 80 µm were analysed using XRF on a Bruker S4-PIONEER equipped by a 4 kW generator and an anticathode in rhodium.

- Environmental scanning electron microscopy and elemental analysis

The suspended part of materials < 80 µm was placed on a double-sided adhesive carbon tape on the pin stub. Scanning microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX, Edax APEX 2i ApolloX) analysis was conducted using a Quanta FEI 250. EDX calibration was performed between samples with aluminium and copper standard stub. Characteristic X-ray emission spectra of metals were detected with a beam of 20–30 kV, working distance of 10 mm, and 30 s live time acquisition at approximately 10–15% of dead time. Because no suitable standard is available to match the material being assessed, standardless quantitation was used with a phi-rho-z correction and elemental mass reported qualitatively as trace (<0.5% mass dry weight), minor (a few percent), or major (>5–≥20% mass weight) [38].

- Attenuated total reflectance Fourier-transform mid-infrared spectroscopy (ATR-FT-MIR)

The same samples were used for MIR (mid-infrared) spectroscopic analysis. MIR range spectra were collected on a Tensor 27 FTIR spectrometer (Bruker) equipped with a diamond-lens attenuated total reflectance module (ATR) from 4000 cm^{-1} to 400 cm^{-1} at 4 cm^{-1} resolutions. One hundred and twenty-eight scans were recorded and averaged for each spectrum. Each soil powder sample was measured three times with three samples per soil.

Figure 4 presents a summary of the tests conducted.

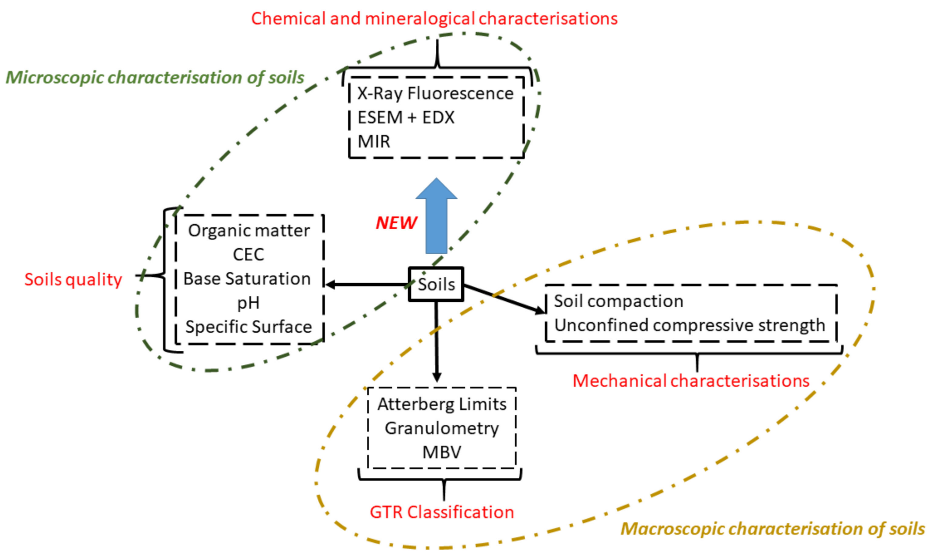

Figure 4. Summary of the tests carried out in this study.

3. Results

3.1. Soil GTR Classification

3.1.1. Particle Size Distribution Curve

For the finer analyses, only 1 kg was required. The results of the wet sieving analysis are shown in Figure 5.

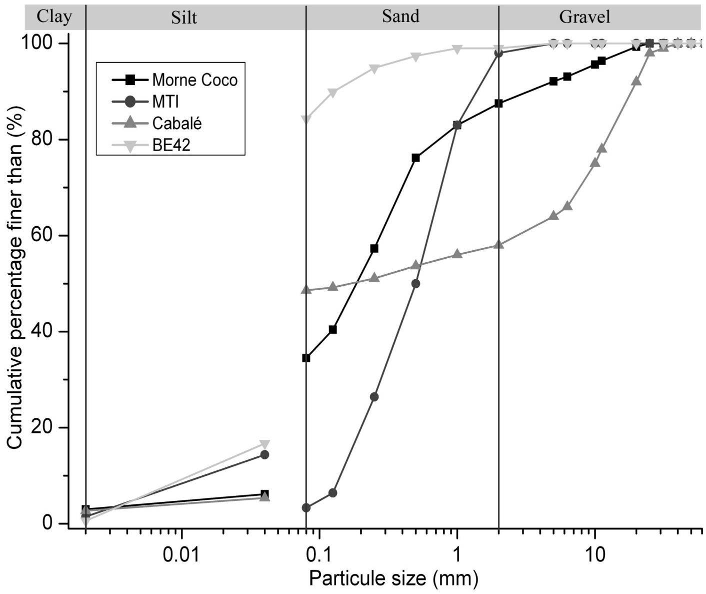

Figure 5. Granulometric analysis of the 4 studied soils.

The particle size analysis of the different materials shows three different outlines:

The grading curve of the MTI soil resembles that of a poorly-graded medium sand. It has a predominantly sandy fraction with only 3% of the material passing through the 80 μm sieve and has a D_{max} of 2 mm.

The grading curve of the Morne Coco soil closely resembles that of a well-graded gravel-sand. The soil is predominantly sandy with 30% of fines of the material passing the 80 μm sieve, and the Cabalé soil is gravelly with 50% of fines, with D_{max} of 20 mm and 40 mm for the Morne Coco and Cabalé soils, respectively.

The grading curve of the BE42 soil is comparable to that of a sandy silt. It has a fraction of fine elements from 80 to 85% of the material passing the 80 μm sieve. The D_{max} of this material is 2 mm.

3.1.2. Atterberg Limits and Methylene Blue Values

To look at the absorption properties of the clays and to characterize the clayiness of the materials present in the different soils, the methylene blue values (MBV) and Atterberg limits were determined. The results are given in Table 2.

Table 2. Results of Atterberg limit test and MBV test measurements.

	BE42	**Cabalé**	**Morne Coco**	**MTI**
Liquid Limit, wL	55	55	32	ND *
Plastic Limit, wP	38	35	26	ND *
Plasticity Index, PI	17	20	6	ND *
MBV (g/100 g)	0.53	0.31	0.09	0.02

* Not Determined.

The BE42 and Cabalé soils have relatively similar plasticity index (PI) values (17 and 20). These soils are classified as high-plasticity clayey silts. For the Morne Coco soil, the plasticity index (PI) of 6 indicates a sandy soil with little clay, i.e., a soil of slight plasticity.

For the fourth, MTI, soil, it is not possible to measure the plasticity index of the soil because the material has very little plasticity (3.3% of the material passing the 80 µm sieve).

The results of the methylene blue tests (MBV) indicate low values. These values corroborate the conclusions of the particle size analysis and the determination of the Atterberg limits. The MBV of the MTI and Morne Coco soils (MBV < 0.1) indicates a near absence of clay fines. However, for the BE42 and Cabalé soils, the MBV ($0.2 \leq$ MBV < 1.5) highlights the presence of very small amounts of silty-clay particles.

3.1.3. GTR Classification

Figure 6 shows the GTR (Guide de Terrassement Routier) classification of the soils according to the plasticity index and the 80 µm sieve passing. The GTR (Standard NF P 11-300) [18,39] organises soils into three classes: fine soil (A1 to A4), sandy or gravelly soils with fines (B1 to B6) and waterproof soils (D1 and D2). It specifies that for class A soils with a plasticity index greater than 12, only the plasticity index is used for the GTR classification (Figure 6).

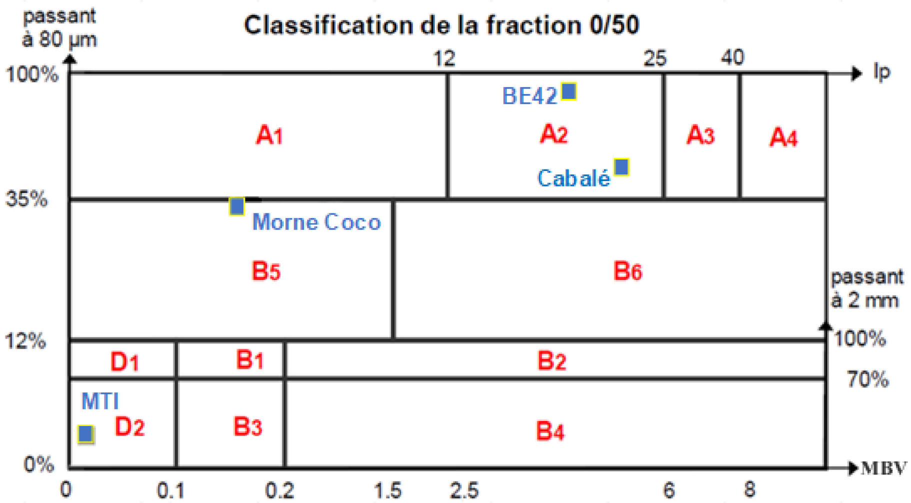

Figure 6. GTR classification according to the PI, MBV, and the sieve passing below 80 µm.

The Cabalé and BE42 soils are classified as fine soils with fine clayey sand (A2). The Morne Coco soil is classified as a gravelly soil with the presence of fines (B5), and the MTI soil is classified as a water-insensitive soil of alluvial sand nature (D2).

Table 3 gives the conditions for the use of these soils in road construction according to the GTR.

Table 3. Soil use according to the GTR.

Soil	Classification GTR	Use
BE42 and Cabalé	A2	Depending on their water content, they can be used as fill (A2m/A2s) or not (A2Th/A2Ts).
Morne Coco	B5	If the soil is very wet or very dry, it is difficult to use as fill because it is prone to cushioning. If the soil is dry or moderately wet, it is very difficult to compact and sensitive to water.
MTI	D2	Soil that can cause traffic problems. Needs compaction to be less erodible.

Status: A2m: medium water content; A2s: dry water content; A2Th: very wet water content; A2Ts: very dry water content.

Thus, according to the GTR [17], these raw materials could only be used as backfill and under very specific hydric conditions. The analysis of mechanical parameters will allow a more detailed analysis to assess their use in road infrastructure.

3.2. Soil Compaction

As the soils studied are used in road construction, the compaction references of the different soils were determined by standard and modified Proctor tests. Figure 7 shows the density variation as a function of moisture content after compaction for the four studied soils (Figure 7A–D). These curves can be used to determine the maximum dry density and the corresponding water content (also known as the optimum water content).

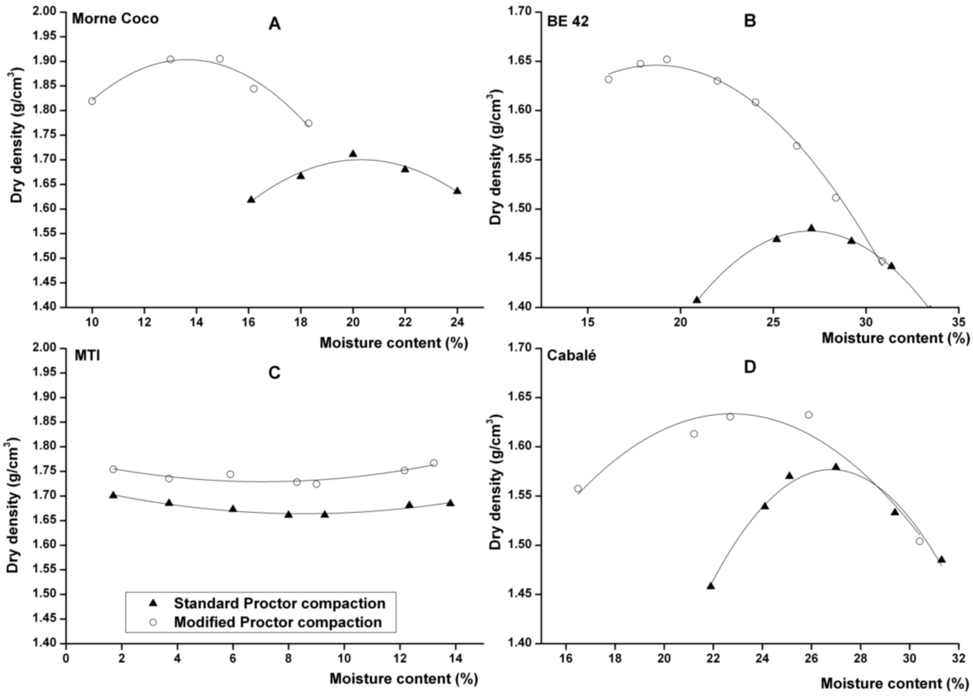

Figure 7. Standard and modified Proctor compaction curves ((**A**): Morne coco, (**B**): BE42, (**C**): MTI and (**D**): Cabalé soils).

Table 4 presents the references of the compaction materials obtained during the soil compaction test to characterise their water status.

Table 4. Compaction references.

Properties	BE42	Cabalé	Morne Coco
Maximum dry density for standard Proctor test (g/m^3)	1.48	1.58	1.70
Optimum moisture content (OMC) for standard Proctor test (%)	27.0	27.0	20.1
Maximum dry density of modified Proctor test (g/m^3)	1.65	1.63	1.91
Optimum moisture content (OMC) for modified Proctor test (%)	19.3	24.5	14
Compaction improvement with modified energy	11%	3%	12%
Absolute density (Mg/m^3)	2.66	2.85	2.79

Unlike other soils, the MTI soil did not have compaction curves with a well-defined maximum dry density and optimum moisture content. As shown in Figure 7c, the moisture–density curve of this soil is relatively flat with little change in dry density over a wide range of moisture content. For standard Proctor compaction, the maximum dry density was obtained at moisture content close to zero (1.70%), while no noticeable change in dry density was noted for modified Proctor compaction. This behaviour is typical for poorly graded sands (coefficient of uniformity $C_u < 6$ [40]. The higher compaction energy in the modified Proctor test significantly improved the compactness of the material by 3% to 12% and reduced the optimum moisture content (OMC) across the material. However, this variation remained negligible for the MTI soil which is insensitive to water.

The Morne Coco soil has the highest dry density among the soils studied, while the Cabalé soil has the highest true density. In the case of the Morne Coco soil, the granular arrangement is better, so a greater mass of soil is present in the same volume (Table 4).

3.3. Unconfined Compressive Strength

To study the effect of compaction on the compressive strength of the soil, cylindrical specimens of 5 cm diameter and 10 cm in height were prepared after the Proctor tests. For each soil and for each test period, three specimens were tested in unconfined compression at maximum dry density and OMC for each condition. Figure 8 shows the mean values and standard deviations of the compressive strength of BE42, Morne Coco, and Cabalé. The tests could not be carried out on the MTI soil because the specimens could not be prepared due to a lack of cohesion.

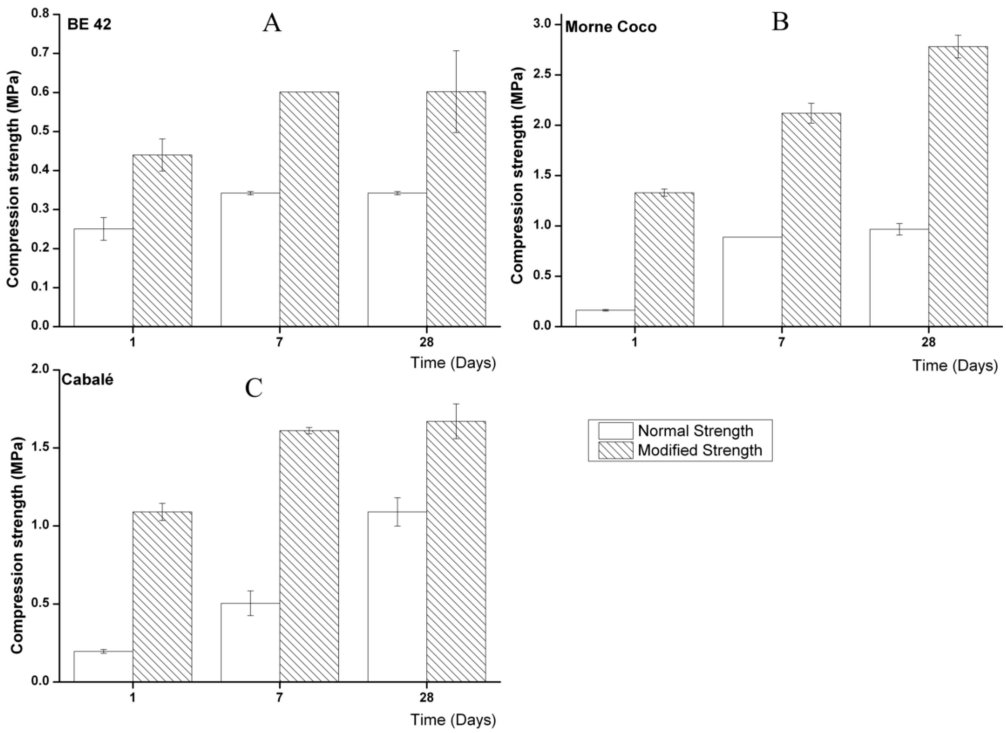

Figure 8. Compressive strength of studied soils ((**A**): BE42, (**B**): Morne coco, (**C**): Cabalé soils).

The standard deviation values show that the measurements are homogeneous and repeatable. For the specimens made with standard Proctor energy, an increase in unconfined compressive strength was observed from 1 to 7 days. However, from 7 to 28 days, no improvement in compressive strength was observed for the BE42 and Morne Coco soils, whereas the compressive strength of the Cabalé soil practically doubled during this period. The increase in values over time is related to water loss even in a controlled environment. For BE42, the percentages of water content at crushing in simple compression are 23.2, 5.7, and 5.7 at 1, 7, and 28 days, respectively. The specimens were placed without a case in the environmental chamber, and water loss occurred; however, the value of water content at crush was not available for all specimens and therefore is not presented. Furthermore, the curves show the improvement of the unconfined compressive strengths of the three soils by considering the modified Proctor energy. This compaction energy considerably increased the unconfined compressive strength from 50% to 180% at 28 days compared to that of the standard Proctor test.

3.4. Laser Particle Size Analysis and Specific Surface

A finer evaluation of proportion and median particle diameter (below 80 µm) was carried out using the particle size analysis. Specific surface tests were used to estimate the clay content. The results presented in Table 5 show the median particle diameter (here, used on a volumetric basis, i.e., 50% by volume of the particles is smaller than this diameter, and 50% is larger) for particles below 80 µm: for the BE42 and MTI soils its value is 16.7 µm and 14.36 µm, respectively, whereas for the Cabalé and Morne Coco soils, it is 5.37 µm and 6.14 µm, respectively. It can be deduced that the fines present in the MTI, BE42, and Cabalé soils are silty, whereas for the Morne Coco soil, the relatively small average size indicates that the fine fraction is sandy loam.

Table 5. Synthesis of the fine fraction (<80 µm) and the specific surface.

Test	BE42	Cabalé	Morne Coco	MTI
Proportion of soil fines < 80 µm (%)	88	51	35	3.3
Median particle diameter < 80 µm (µm)	16.7	5.4	6.1	14.4
Clay content < 2 µm (%)	0.6	2.7	3	1.45
Specific surface (m^2/g) *	14.2	36.3	12.2	0.09

* Values of the specific surface were obtained on the fraction of 0/5 mm.

The difference in the specific surface area between the BE42 and Cabalé soils (14.2 m^2/g and 36.2 m^2/g) and the percentage of clay content (0.6% and 2.7%) indicate that the BE42 soil contains more of the silt fraction and therefore slightly fewer active particles. These results are consistent with the median particle size of less than 80 µm.

3.5. Soils Quality

The results of the chemical analyses of the different soils are presented in Table 6. The organic matter was determined by calcination and the cation exchange capacity (CEC) was used to measure the activity of the clays as well as the base saturation determined by the percentage of the CEC occupied by the base cations (Ca^{2+}, Mg^{2+}, Na^+, K^+).

Table 6. Chemical analyses of the different soils.

Soil	Organic Matter Content (%)	pH		CEC (meq/100 g)	Base Saturation (%)
		H_2O	KCl		
BE42	9.2	4.90	4.18	2.49	6.4
Cabalé	12	5.2	5.05	1.93	21.2
Morne Coco	11.3	4.95	5.37	0.48	15.4
MTI	0.1	5.49	4.97	0.24	37.3

The sandy material of MTI has almost no organic matter. For the other materials, the organic matter content is around 10%. All the pH values measured in the water or in the KCl solution are around 5, indicating a significant acidification of the studied soils. The saturation base values determined by the CEC reveal that the BE42 soil has more acid cations (H^+ and Al^{3+})

The activity of the clays measured by the cation exchange capacity indicates a low activity of the clays suggesting that they are mainly composed of kaolinite (CEC (meq/100 g) < 3) [41].

3.6. Chemical Analysis Results

All the chemical tests were performed on the fine fraction (<80 µm). The sample was divided into two batches: one batch for the X-ray fluorescence analysis and one batch for the infrared mineralogical interpretation. A SEM-EDX analysis was carried out on the crude soil fraction.

The X-ray fluorescence analysis provides the semi-quantitative chemical composition of the four materials studied (Table 7). Only elements detected but greater than 0.10% are listed. Elements detected between 0.01 and 0.1% are reported as traces. The main elements are silica alone or associated with aluminium and iron oxides.

Table 7. Semi-quantitative chemical composition based on X-ray fluorescence.

	O (%)	Si (%)	Al (%)	Fe (%)	Ti (%)	K (%)	S (%)	Ca (%)	Traces (%)
BE42	55	18.7	17.5	7.4	0.6	0.5			0.3
Cabalé	53.1	13	16.8	15.2	1.6		0.1		0.2
Morne Coco	56.4	14.7	18.3	8.8	0.8	0.2	0.1	0.5	0.3
MTI	53.7	45.7	0.2	0.2					0.2

For the Cabalé and Morne Coco soils, the percentage of silica is lower than that of aluminium, which shows that the soils are more weathered than the BE42 soil. For MTI, the chemical analysis shows a significant proportion of silica which is the composition of quartz (SiO_2).

The scanning electron microscopy images only provide information on the soil texture. The soils' texture is associated with their respective X-ray spectra presented in Figures 9–12.

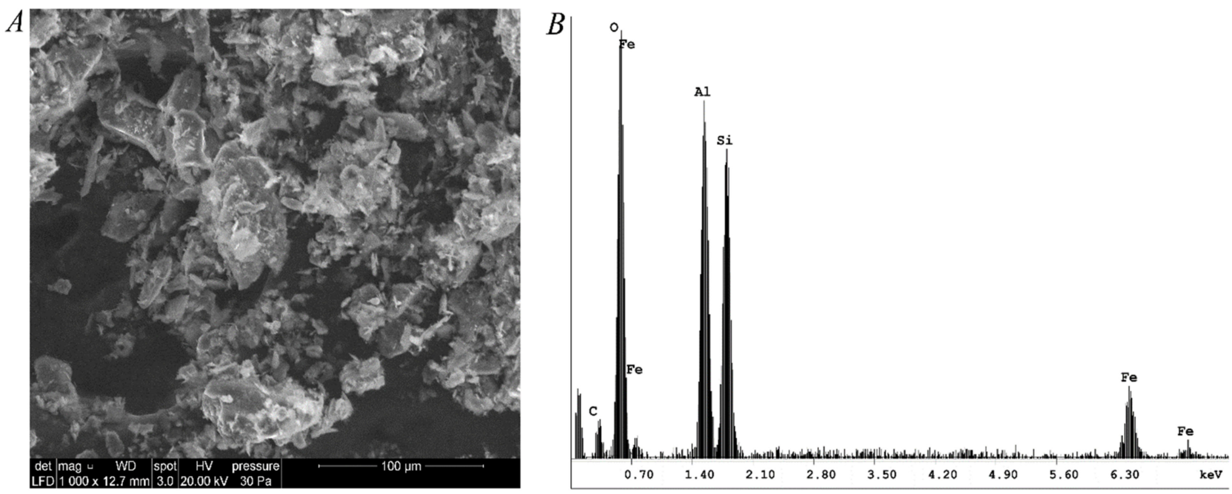

Figure 9. BE42 soil: secondary electron image (**A**) and EDX spectrum of the crude fraction (**B**).

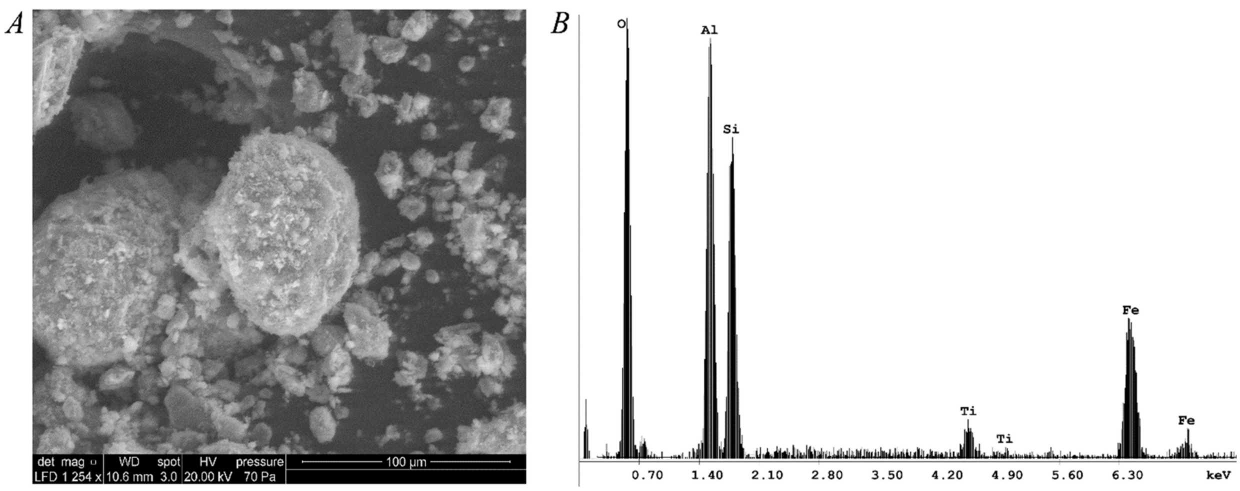

Figure 10. Cabalé soil: secondary electron image (**A**) and EDX spectrum of the crude fraction (**B**).

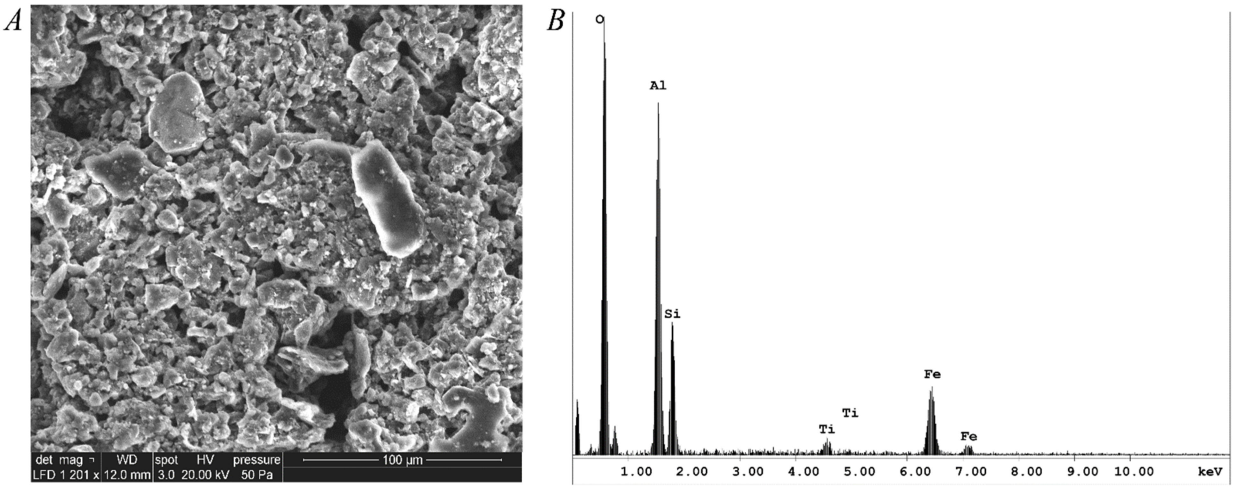

Figure 11. Morne Coco soil: secondary electron image (**A**) and EDX spectrum of the crude fraction (**B**).

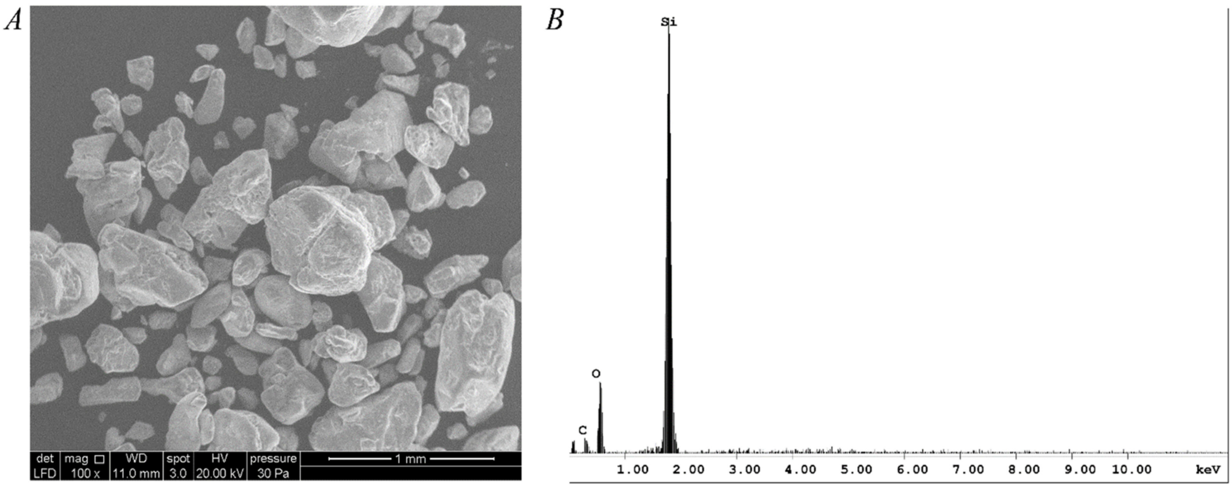

Figure 12. MTI soil: secondary electron image (**A**) and EDX spectrum of the crude fraction (**B**).

3.6.1. BE42 Soil

The secondary electron image (Figure 9A) shows that the particles composing the raw fraction are single or agglomerated lamellae covered by silt and clay particles.

Microanalysis of the X-ray spectrum allowed the determination of the percentages of the elements O (53.8%), Al (17.9%), Si (21%), and Fe (7.3%).

3.6.2. Cabalé Soil

The secondary electron image (Figure 10A) shows that the particles in the crude fraction have a lumpy structure in the form of grains covered by silt and clay particles.

Microanalysis of the X-ray spectrum allowed the determination of the percentages of the elements O (49.1%), Al (19.5%), Si (18.5%), Fe (11.3%), and Ti (1.7%).

3.6.3. Morne Coco Soil

The secondary electron image (Figure 11A) shows an organisation of particles in the crude fraction forming a compact and lumpy structure covered by silt and clay particles.

Microanalysis of the X-ray spectrum allowed the determination of the percentages of the elements O (49.3%), Al (23.9%), Si (11.6%), Fe (13.7%), and Ti (1.5%).

3.6.4. MTI Soil

The secondary electron image (Figure 12A) shows that the particles in the raw fraction have a grain-like structure.

Microanalysis of the X-ray spectrum allowed the determination of the percentages of the elements O (65.7%) and Si (34.3%).

These images show us quartz grains for the MTI soil. The B42, Morne Coco, and Cabalé soils contain grains of quartz and iron oxide coated by clay minerals. The clay minerals have nucleus habits in the Morne Coco and Cabalé soils and a clay network structure in B42.

Figure 13 shows the mid-infrared absorption spectra of the four soils. The mineralogical interpretation of the IR spectra reveals the presence of two mineral species (kaolinite and gibbsite) and three oxides (quartz, hematite, and goethite).

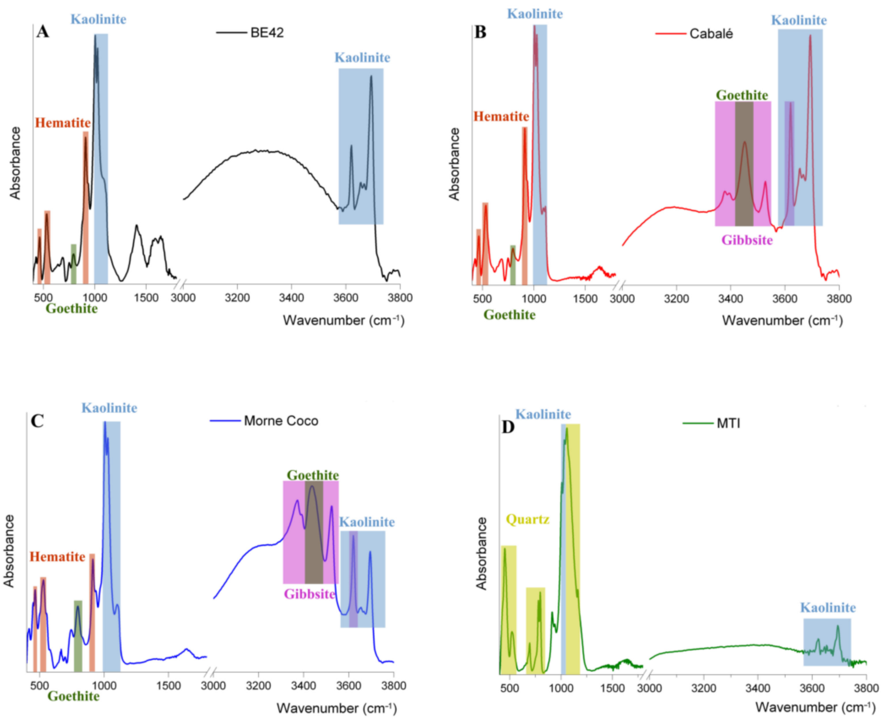

Figure 13. FTIR spectra of the 4 soils: (**A**) BE42, (**B**) Cabalé, (**C**) Morne Coco, and (**D**) MTI. The IR bands, characterised for mineral species and oxides, are marked by a colour for simplified interpretation. Overlapping colours mean that bands are labelled for more than one mineral.

The IR spectra of the three soil samples (Figure 13A–C) show the same well-defined characteristic bands of kaolinite at 3695 (strong), 3667 (weak), 3654 (weak), and 3620 cm^{-1} (strong). Only the MTI soil (Figure 13D) suggests traces of this mineral species at 3695 and 3620 cm^{-1} but shows mostly characteristic quartz peaks: 1057 (broad); 795, 779, 694 (medium); 521 and 450 cm^{-1} (strong) [42–44]. The BE42, Cabalé, and Morne Coco soils (Figure 13A–C) show bands at 1113 (weak), 1094 (weak), 1029 (strong), and 1008 (strong) cm^{-1} characteristic of kaolinite as well as the band at 797 cm^{-1} (medium) characteristic of goethite, while the bands at 912 (medium), 520 (medium), and 464 cm^{-1}(medium) are characteristic of hematite [45].

Only the spectra of the Cabalé and Morne Coco soils (Figure 13B,C) show an intense band characteristic of gibbsite at 3620 cm^{-1}, which has its other bands in common at 3526, 3447 (broader), 3395, and 3373 cm^{-1} [46]. In addition, the broad band with a maximum of 3447 cm^{-1} also coincides with goethite [47,48].

4. Discussion

The macroscopic characterisation of the four soils made it possible to determine the type of soil by granulometry. The GTR classification allowed the soils to be categorised for their use in infrastructure: the MTI soil is an alluvial sand, the Morne Coco soil is classified as a gravelly soil, while the Cabalé and BE42 soils are classified as fine clayey sands.

However, no correlation was found between the results of the MBV test, sedimentometry, specific surface area, and laser granulometry tests. According to Autret [49] with respect to African tropical soils, the characterisation of the clay fraction does not give significant results for gravelly lateritic soils. Despite similar MBV values and Atterberg limits between BE42 and Cabalé, the unconfined compressive strength tests, with a compaction energy of the order of the modified Proctor test, show a better strength for the Cabalé soil of about 1.5 MPa compared to 0.4 MPa for BE42 (Figure 7). The specific surface test was performed on the 0/5 mm fraction, which is at Dmax for the BE42 soil (Figure 5). There is therefore a better particle size distribution for Cabalé than for BE42 which presents too fine material; this could explain the difference between the compression test value and the value of the modified Proctor test (<1 MPa) and also explain the gain in unconfined compressive strength.

These analyses enabled us to classify the materials according to the NF P11-300 standard (GTR). According to this standard, all materials are suitable for reuse as backfill. The GTR classifies the BE42 and Cabalé (A2) soils as easy for construction implementation, while the Morne Coco (B5) soil is presented as difficult for construction implementation because of its sensitivity to water. The MTI soil (D2) is problematic for construction implementation because of its uniform grain size (0/2 mm—see Figure 5) and requires a lot of water for processing. The other analyses carried out, in particular the modified Proctor and unconfined compression tests, showed that these materials have the capacity to withstand higher stresses, which explains their use in Brazil and Senegal as a stabilising layer with the references of the modified Proctor test.

The presence of clay in the different soils remains relatively low and consistent with the PI values. Indeed, the BE42 soil, although presenting a very high percentage of the material passing the 80 μm sieve (88%), has a specific surface area of 14.2 m^2/g, much lower than that of the Cabalé soil (36.2 m^2/g) whose percentage passing the 80 μm sieve is only 50%. In addition, the average diameter of the fine particles contained in the two soils indicates that the BE42 soil contains siltier fractions and therefore slightly fewer active particles. Thus, it can be expected that the increase in standard compressive strength for all soils could be due to two mechanisms: the loss of water during curing due to storage without a case in a climatic chamber, on the one hand, and on the other hand, to the granulometry of the soils. Consequently, we have a variation in compressive strength (±50% between 7 and 28 days). (Figure 8C).

The organic matter content of the three lateritic materials (BE42, Cabalé, Morne-Coco) is around 10%, while the CEC value is different (from 0.24 to 2.49). This is due to the composition of the minerals present in the soil, which interact with our exchangeable bases. The Cabalé and Morne Coco soils show a better saturation rate in the CEC analysis than BE42 despite similar specific surface areas of Morne Coco and BE42.

According to the recommendations of the GTR, the compaction references for subgrades use the values of the standard Proctor test, except for airport platforms where the compaction references are those of the modified Proctor test.

A Brazilian study on the use of lateritic materials as a structural layer presents tests on clay soils (plasticity index from 22 to 46) and concludes that it was possible to consider them as structural materials for the rehabilitation of road infrastructure when the modified Proctor compaction energy is used (Lima et al., 2018 [10]). Similarly, in Senegal, for the construction of "in situ soil or reworked soil" platforms supporting pavement layers, the use of the modified Proctor energy is recommended [50].

The multifactorial analysis (chemical, microscopic, and mineralogical) allowed us to make certain assumptions. The X-ray fluorescence results and the microanalysis of the

EDX spectrum gave different percentages of the major elements. This difference is due to the precision of the analysis. Indeed, during the acquisition of a spectrum, the EDX may give differences percentages at different spots for an inhomogeneous surface. To complete these semi-quantitative evaluations of chemical elements, an infrared spectrum of each soil was carried out. This allowed us to appreciate the clay mineral group of each soil. The infrared analysis shows the presence of kaolinite, goethite, and hematite in these three soils (Figure 13A–C) but only gibbsite in Cabalé and Morne Coco (Figure 13B,C). This presence indicates a more important alteration of the Cabalé and Morne Coco soils corroborating the percentages obtained by the X-ray microanalyses (EDX and X-ray fluorescence)

Some geotechnical properties are therefore partially explained by the amount of iron oxide such as goethite. Indeed, Morne Coco and Cabalé show the highest values in unconfined and modified compression, which could be due to both the base saturation and clay content. Another hypothesis, supported by Goldberg [51], would be that the aluminium and iron oxides would reinforce the soil structure, but their role is not clearly understood. Rajabi et al. [52] demonstrated that the addition of iron oxide nanoparticles in a clay soil increases the strength parameters. As demonstrated by Kiki et al. [53], this double analysis highlighted some relationships between the micro and macroscopic analyses. However, it is only possible to have a trend by studying and comparing several grain sizes.

5. Conclusions

In this work, four types of soil from French Guiana were analysed. The different soils have different chemical and mechanical characteristics. They come from four different geological horizons. Their main defects lie in their sensitivity to water. The latter is judged with simple tests such as MBV, particle size analysis, Atterberg limits, and sedimentometry, based on clay activity. As the materials are mainly silty, the activity of the clays is low, and their sensitivity to water is average. The chemical analysis of the soils highlights their alteration by the presence of iron and aluminium oxides characteristic of tropical soils.

As it stands, the techniques used are not suitable for the direct use of these soils as a base course layer. Constructive measures, other than a simple two-layer overlay, must be taken to guarantee the waterproofing of the pavement during rainy season episodes.

Through the study of the four different materials, it was shown that although the two soils BE42 and Cabalé have identical classification according to the GTR (A2), their behaviour is different. Indeed, the Cabalé soil has superior mechanical characteristics to those of BE42 in unconfined compression, making it more suitable for supporting vehicle traffic.

Finally, the GTR classification alone does not allow the dissociation of two soils with very similar grain sizes.

On the other hand, the use of chemical and mineralogical tests (CEC, MBV, granulometric analysis by laser diffraction, analysis by mid-infrared spectroscopy, scanning electron microscopy with energy dispersive X-ray spectroscopy (ESEM + EDX)) provides an improvement in the GTR classification of the various soils by classifying the materials based on criteria other than particle size and clay content. In particular, it allowed a better separation of the BE42 and Cabalé soils, which differ in their iron oxide content, which explains their different behaviour. In French Guiana, where laterite materials are used without any regulatory framework, the use of chemical and mineralogical tests could, as a complement to the GTR, enable better selection of laterite soils in order to assign them the best conditions for reuse. To complete this study, which combines the microscopic and macroscopic aspects of Guyanese clay soils, it is necessary to subject other laterite samples to these tests in order to verify the first hypotheses and thus create a database specifically for the Amazonian laterite. On the other hand, the use of the MCT (Miniature, Compacted, Tropical classification) methodology, used by our Brazilian neighbours, could make it possible to classify materials on the basis of criteria other than particle size and clay content. According to this new classification, it is possible to envisage methods of using materials according to their characteristics and, in particular, their resistance to water based on the loss of mass by immersion tests.

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