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Research Article

Geotechnical Suitability of Soils in Road Construction for Sustainable Development in Tropical Africa: Case of Lateritic Graveled Soils of Bandjoun (West, Cameroon)

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The environmental impact of the exploitation of geomaterials and their relatively high cost, coupled with the increasingly low financial capital in developing countries, are pushing road actors to turn to inexpensive local ecological materials. The present study is conducted on lateritic graveled soils of Bandjoun (LGSB) in the West Cameroon Region. The aim is to determine whether lateritic gravel soils, particularly those in Bandjoun, can be an ecological and economical alternative to rock aggregates in road construction, considering their geotechnical parameters and environmental impact. These soils were described in the field and were also subjected to complete geotechnical identification in the laboratory. The LGSB presents Californian bearing ratio indices ranging from 26% to 83.3%, a plasticity index of 10.11%, a fines content of 12.05%, an average methylene blue value of 4.25, a water content at the Proctor optimum of 27.6% and a dry density of 1.75 g/cm^3. They are silty or clayey gravels and sands of subgroup A-2-7 according to the Highway Research Board classification; sandy and gravelly soils with fines of class B according to the classification of the Road Construction Guide; and silty gravels according to the classification of the Central Laboratory of Bridges and Highways. These soils can be used naturally in pavement layers, in particular in subgrade for all traffic classes and in subbase for low traffic. The tonnage of these soils has been estimated at 18,389 t. The global warming index shows that the use of these soils (18,389 t) in road construction can reduce 31,629–62,706 kg of carbon emissions. The use of lateritic soils in road construction is a very interesting alternative to reduce the environmental impacts associated with the manufacture of rock aggregates. So, lateritic soils should be used instead of rock aggregates for cleaner, more environmentally friendly road construction. The present work presented a specific evaluation of the geotechnical properties and ecological impact of lateritic graveled soils for road construction, as well as their potential for ecological and economic utilization.

1. Introduction

Just like housing infrastructure, transport routes, in general, are large consumers of geo-materials. Geo-materials are geological earth materials from excavation, such as cut stone, gravel, sand, clay, or soil. Geo-materials are the primary natural resource for construction. They are used in the composition of concrete, asphalt or road base layers, cement, ceramics, bricks, cob, quicklime, plaster, tiles, embankments, dykes or walls, and ornamental [1]. Eighty percent of the rock aggregates produced are absorbed by road construction. Similarly, 1 km of highways requires 30,000 t of rock aggregates of different types and sizes [1]. However, the use of rock aggregates in road construction is becoming more and more difficult due to the nonrenewable nature of these rock geomaterials, the fossil fuels used in the processing or crushing, the environmental impact of their exploitation, and their relatively high cost. Thus, the search for low-cost and less environmentally damaging sustainability materials is becoming more and more important in road construction. The objective of this study is to valorize soils in road construction in order to minimize the cost of their realization. Soils encountered in the tropical and subtropical zones are qualified as "lateritic soils" [2].

Lateritic soils are a particular type of soil found in humid tropical areas [2–4]. According to Buchanan [5], laterites or lateritic soils are better building materials, full of cavities and pores, with large amounts of iron, red and yellow. Similarly, a lateritic graveled soil (LGS) is a loose lateritic soil of granular class 0/20–0/40 mm with 10%–35% fines passing the 80 μm sieve and a skeleton of 20%–60% [6]. In the intertropical zone and, more specifically, in developing countries, LGS constitute almost 100% of subbase layers and 60%–70% of pavement base layers [7]. Lateritic soils cover about 70% of the area of Cameroon. Thus, due to the availability of these materials along road routes and their low operating costs, they are a highly valued resource in the Cameroonian construction industry, especially in the construction of paved and unpaved roads [3, 8]. However, the road network in many countries in the tropics and sub-Saharan Africa in particular, in addition to being weak, is in an advanced state of degradation. Similarly, the Cameroonian road network is estimated at 50,000 km [9], and a diagnosis of the state of the road infrastructure by the Road Master Plan [10] reveals that of the national priority network, only 12% of asphalt roads and 5% of rural roads are in good condition, while almost all non-priority and rural roads are in poor condition. It has been observed that most of the disorders on the pavements are either linked to poor characterization of the lateritic gravels, a problem with the implementation, a problem of sanitation, or concern with control and regulation of the axle load. In either case, the optimization of road construction on lateritic soils in tropical Africa in general, and in Cameroon, in particular, must be at the center of projects to ensure a satisfactory economic return.

It is in this perspective that in Cameroon, respectively, in Boumpial, on the southern flank of Mount Bamboutos, in the South, in Batoufam, in Banka, and on the northern flank of Mount Bangou [11–16] evaluated the engineering index properties of lateritic graveled soils in road construction. However, the geotechnical suitability of lateritic graveled soils in Bandjoun, which are largely used in road construction, remains poorly studied, even though many rehabilitation and communal road construction projects are underway in this locality. This lack of geotechnical data on the lateritic graveled soils of Bandjoun (LGSB) would explain the poor state of the roads in this locality. These geotechnical data are necessary to classify the soils, determine the thickness of the pavement layers, determine the limits of use of the pavement layers, the specificities of use of the materials in the road, to determine the lifetime of the future pavement, and to ensure the overall stability, durability, and performance of the road infrastructure. Furthermore, the achievement of long-term sustainable development is undoubtedly one of the major challenges for our society today [17]. This development implies a balance between economic growth, social progress, and maintenance of the ecological balance [17]. In road construction, reducing the consumption of raw materials, reusing construction waste, managing energy, limiting noise pollution, and using eco-materials in pavement layers such as soils can contribute to sustainable development [17]. This is the reason why this study is justified in more than one way. Thus, the aim is to determine whether lateritic gravel soils, particularly those in Bandjoun, can be an ecological and economical alternative to rock aggregates in road construction, considering their geotechnical parameters and environmental impact. The physical parameters of these soils were evaluated using the Atterberg limits, the methylene blue value, the specific gravity, and the granulometric analysis by sieving. Similarly, the compaction and bearing capacity characteristics were evaluated through the Proctor and Californian bearing ratio (CBR) tests.

2. Natural Setting

2.1. Geographic Setting. Geographically, the study area is located in the Arrondissement of Poumougne, Department of Koung-khi, West Cameroon Region. It is located to the Northwest of Mount Bangou and belongs to the volcanic line of Cameroon. It is located between parallels 5°20′ and 5°24′ north latitude and meridians 10°25′ and 10°30′ east longitude, covering an area of about 69 km^2 (Figure 1). Altitudes vary from 1,000 to 1,650 m. This area reflects a plateau landscape of little accidents [18]. Koung-khi has a humid tropical climate [19], tempered by the two-season altitude, with an estimated average annual rainfall of 1,697 mm.

On microscopic observation, the parent rock of the LGSB is an aphyric basalt consisting of Olivine, plagioclase, pyroxene, and the opaque minerals described by NF P 94-093 Standard [20]. It also shows secondary crystallization geodes and fissures of calcite, zeolites, and quartz in some samples. The Bandjoun locality and its surroundings have not yet been the subject of a detailed pedological study. However, according to the soil map drawn up by Segalen [21, 22], the study area is occupied by red ferralitic soils developed on the basement materials and the basalt of the plateaus.

2.2. Materials. LGSB are contained in the mineral B horizon of the soil profiles. The quarries from which these materials are taken consist of an organo-mineral horizon, a thick gravelly mineral horizon, and a clay mineral horizon structured in successive strata. Nodules of a millimeter to multicentimeter size predominate in the graveled mineral horizon (Figure 2).

3. Materials and Methods

The fieldwork consisted of selecting a transect on representative lateritic soil formations. Four (04) pits were installed along this transect following the topo sequential method. The pits were located at the top, mid, and bottom of the slopes of the graveled area. One raw sample was taken along the graveled mineral horizon only in each soil pit (Figure 2). These samples were described macroscopically in the field. Raw samples of approximately 70 kg of LGS were packed in polyethylene bags for laboratory work. Depending on the samples collected, labeling was adopted. The laboratory work consisted of the determination of physical parameters such as Atterberg limits, methylene blue value, specific gravity, and particle size analysis. Similarly, the compaction and bearing characteristics of the LGS were assessed by the Proctor and CBR tests. The laboratory tests were carried out by French standards. The procedure for these tests is presented below.

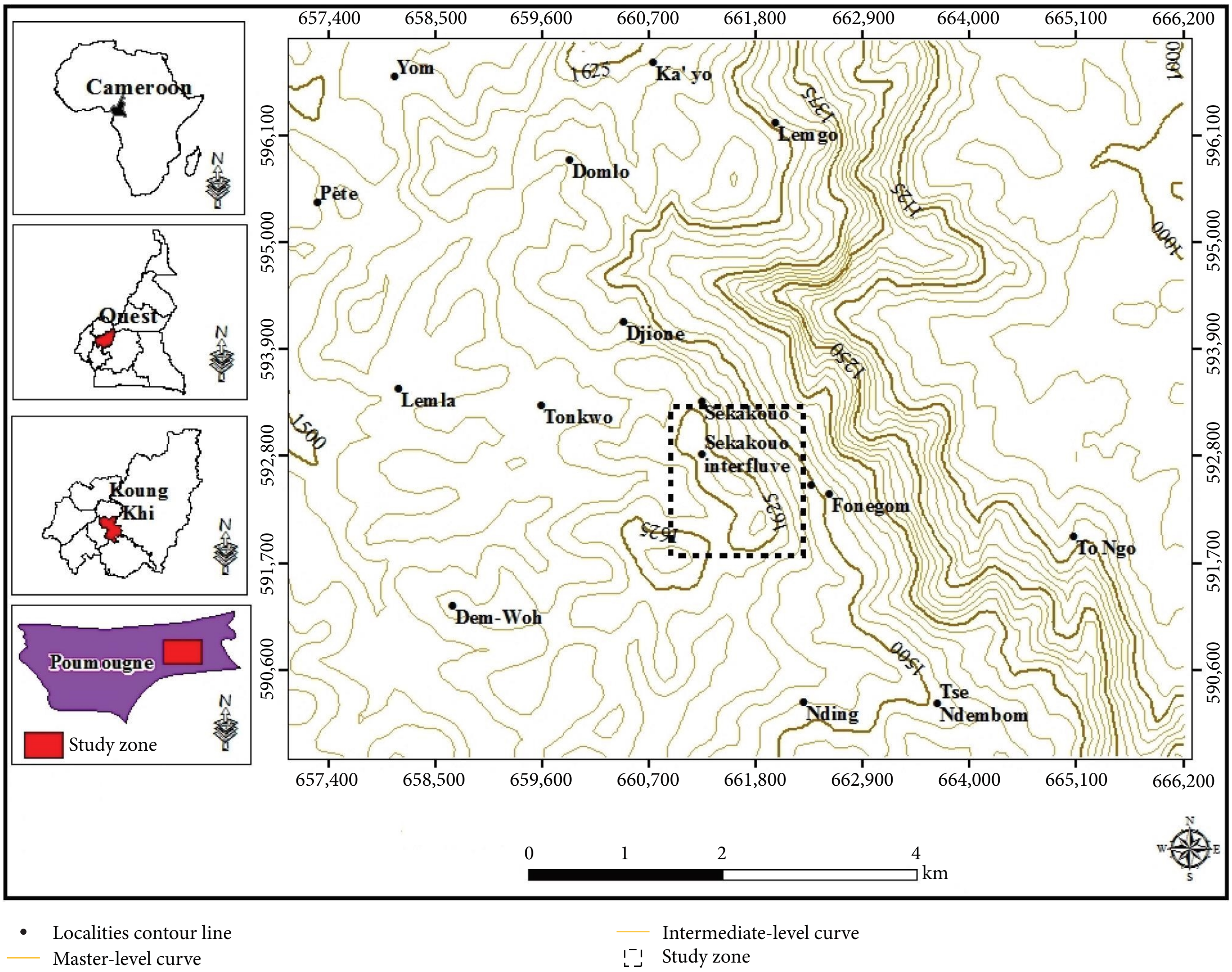

Figure 1: Location map.

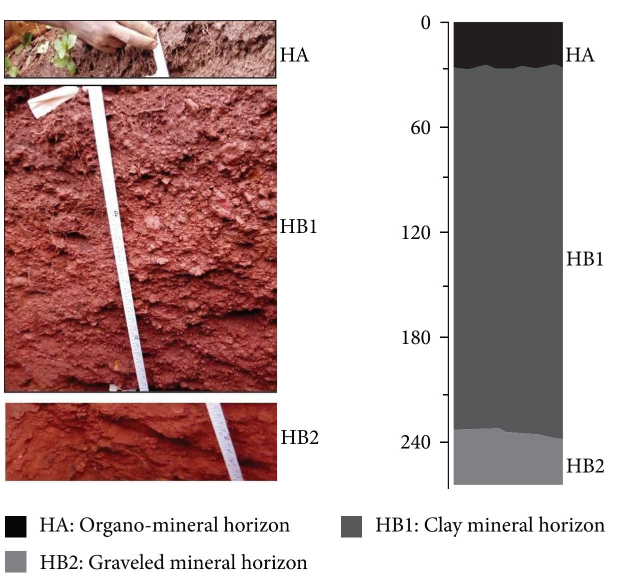

Figure 2: Lateritic graveled soils of Bandjoun were observed in the field.

3.1. Particle Size Analysis. The particle size analysis has been used to determine the distribution of the different grain size classes in the studied soils by weighing. It is of interest for soil classification. According to Mailloux and Chenard [23], the aim of moisture particle size analysis is two-fold, namely, to determine the distribution of the different grain sizes of granular material and to determine the granular classes. This classification is essential to determine their suitability for use in different pavement layers. The choice of the particle size analysis method is clarified and justified due to its ability to determine the distribution of particle sizes in soil. This information is important for understanding the soil's engineering properties, such as permeability, compaction, and shear strength. It helps in selecting suitable materials for road construction and designing effective drainage systems. By the standard [24], the test consisted of separating the agglomerated grains from the soil by stirring underwater and fractionating them after drying. Subsequently, the accumulated rejection on each sieve was weighed successively. The mass of accumulated rejection on each sieve is related to the total dry mass of the sample submitted for analysis. This is done using a column of sieves whose dimensions are expressed in millimeters of the square mesh of successive sieves.

3.2. Atterberg Limits. This test permitted the characterization of the state of the studied soils using its consistency index (CI) and to determine the conventional physical constants that indicate the limits between their states [25]. This test can be used to predict the behavior during earthworks, particularly under the action of the water content. This test will enable informed decisions to be made about lateritic graveled soils when designing and building roads to ensure their stability and durability. The choice of the Atterberg limits method is clarified and justified due to its ability to determine various properties of clayey soils, such as the liquid limit, plastic limit, and plasticity index. This information is essential for assessing the plasticity and compressibility of soils, which is crucial for the design and construction of stable and durable roads. Carried out by the standard [26], this test is carried out in two phases: a water content research phase in which a groove made in soil placed in a cup of imposed characteristics closes when the cup and its contents are subjected to repeated shocks (liquidity limit (LL)); and another water content research phase in which a roll of the soil of a fixed size and made cracks manually (plasticity limit). Depending on the variation in the water content of the soil studied, it changes from solid to plastic, from plastic to liquid, and back again. These limits are geotechnical parameters designed to identify soil and characterize its state using its using index. Two of these limits are of particular interest:

(i) The LL, which is the water content separating the liquid state from the plastic state, the [27] cone penetrometer was used to corroborate the liquid limit results.

(ii) The plasticity limit (ω_p), which is the water content separating the plastic state from the liquid state.

This test was performed on the fraction passing the 400 μm sieve (mortar). The plasticity index measures the extent of the plastic domain of the soil. It is expressed as a percentage by the following relationship:

$$\mathrm{PI} = \mathrm{LL} - \omega_p. \tag{1}$$

The CI is expressed by the following formula:

$$\mathrm{CI} = \frac{\mathrm{LL} - \omega_{nat}}{\mathrm{PI}}, \tag{2}$$

where $\boldsymbol{\omega_{nat}}$: water content, CI: consistency index, LL: liquidity limit, PI: plasticity index.

3.3. Methylene Blue Value. The methylene blue value test (VBS) was used to characterize the clay content of the soils studied. The choice of the methylene blue value method is clarified and justified due to its effectiveness in evaluating the clay content and potential for clayey soil swelling. This method provides valuable information for assessing the suitability of soil for road construction, particularly in terms of its potential for swelling and subsequent damage to road infrastructure. It reflects the overall quantity and quality of the clay fraction of the soil. In the present work, the VBS was determined by the standard [28]. The crystalline structure of the clay minerals gives them a set of properties and behavior linked to their affinity with water (clay activity), which leads to swelling, plasticity, and cohesion phenomena in these soils. This test was carried out to assess the water retention capacity and plasticity of lateritic graveled soils. The VBS consisted of fixing molecules of methylene blue on the clay grains and using a simple test, the quantity of blue fixed was evaluated. The VBS of the soil is thus deduced, which is an essential indicator in the classification of the soils concerned by earthworks.

Consider B as the mass (g) of the methylene blue solution used until a positive test is obtained and Ms as the dry mass of the test sample (g):

$$\mathrm{VBS} = \frac{B}{\mathrm{Ms}} \times 100. \tag{3}$$

The test results are expressed as mass (g) of methylene blue adsorbed per 100 g of soil.

3.4. Specific Gravity. The specific gravity (γs) is used to determine the true density. The γs are the mass of the solid constituents of the soil about their volume. It gives an idea not only of the strength and bearing capacity of lateritic graveled soils but also of their resistance to water infiltration. The choice of the specific gravity method is clarified and justified due to its ability to measure the density of a material relative to the density of water. This allows for the evaluation of the quality and compactness of materials used in road construction, which is essential for ensuring road durability and strength. The γs test consists of taking two or three samples of material that have been dried in an oven at 105°C for 24 hr. The pycnometer is then weighed successively in the empty pycnometer, the water-filled pycnometer, the material-filled pycnometer, and the material + water-filled pycnometer. During the analysis, the temperature of the water is taken each time for density correction. Also, the pycnometer containing the material + water must be shaken to remove air bubbles. All the measurements recorded on the test file are used to determine the mass and volume of the grains to deduce the γs. The test is based on Archimedes' law and is carried out according to the standard [29].

3.5. Modified Proctor Test. The study of compaction is carried out using a standardized grooming test known as the "Proctor test." This test was carried out to assess the compaction characteristics of lateritic graveled soils and ensure that they meet the required standards in terms of stability and load-bearing capacity. The choice of the Modified Proctor test method is clarified and justified due to its ability to determine the maximum dry density (MDD) and optimum moisture content of the soil, which are important parameters for road construction. This method provides valuable

Table 1: Summary of the different physical characterization results.

Parameter	γs	VBS	LL (%)	ω_p (%)	PI (%)	CI	GI	Particle size analysis (%)				
								Pebbles	Gravel	Coarse sand	Fine sand	Fines
Samples												
CP1	2.18	4.25	53.00	43.66	9.34	3.91	0.00	15.50	58.30	6.00	1.00	18.60
CP2	2.25	4.00	50.00	40.70	9.30	3.44	0.00	12.50	72.70	5.70	0.60	7.70
CP3	2.34	4.25	51.00	40.70	10.30	3.23	0.00	5.70	89.20	0.40	0.40	0.60
CP4	1.90	4.50	47.00	34.50	11.50	1.98	0.12	14.50	55.00	6.10	1.00	23.10
Max	2.25	4.50	53.00	43.66	11.50	3.91	0.12	15.50	89.20	6.10	1.00	23.10
Min	1.90	4.00	51.00	34.50	9.30	1.98	0.00	5.70	55.00	0.40	0.40	0.600
Average	2.17	4.25	50.25	39.90	10.11	3.14	0.03	12.05	68.80	4.55	0.75	12.50
Deviation	0.19	0.20	2.50	3.85	1.04	0.82	0.06	4.41	15.62	2.77	0.30	10.23

γs = specific gravity, LL = liquidity limit, ω_p = plasticity limit, PI = plasticity index, VBS = methylene blue value, CI = consistency index.

information for compaction control and ensures the stability and durability of the road. This test was carried out to determine the moisture content at which the soils under investigation should be compacted to obtain the MDD. The moisture content thus determined is known as the "optimum Proctor moisture content." This test was performed according to the standard [20]. The modified Proctor test was carried out within the framework of these studies because of its conformity with road-building works. The Proctor test consists of compacting the soil at constant compaction energy and different water contents to determine the optimum water content (ω_{opm}) for which the compaction action leads to an MDD. This allows proposals to be made for use as road material. Indeed, if we vary the water content of a soil sample and represent the variation of the dry density as a function of the water content, we obtain a bell-shaped curve that represents a high point that we call the Proctor optimum. This test was carried out on the lower 20 mm soil fraction.

3.6. CBR Test. The CBR test was used to determine the bearing capacity of LGSB. This test will determine the suitability of gravelly lateritic subbase soils for road construction, pavement design, and maintenance planning. The choice of the CBR test method is clarified and justified due to its proven reliability and scientific validity in assessing the strength of road materials. It is also in accordance with the prevailing standards and regulations in the field of road construction. The purpose of the test is to experimentally determine indices that will be used to determine the thickness of subbase layers, establish a classification of soils, and study the trafficability of earth-moving machinery. The standard [30] specifies that the general principle consists of measuring the forces to be applied to a cylindrical punch to make it penetrate a specimen of material at a constant speed. The particular values of the two forces that caused two conventional indentations are respectively related to the values of the forces observed on reference material for the same indentations. The index sought is conventionally defined as the larger value expressed as a percentage of the two ratios thus calculated. The CBR index expresses the ratio (%) between the pressure obtained on the sample and the pressure of a reference sample for the same indentation. The reference pressures are 70 bar for a 2.5 mm indentation and 105 bar for a 5 mm indentation. The CBR index is the greater of these two values.

3.7. Evaluation of Soil Tonnage and Ecological Value. Using a simple calculation, the tonnage of the soils studied was evaluated by taking into account the average thickness of the gravelly level and the total surface of the target borrow area. The total surface area is determined with the help of the Global Mapper software, after having surveyed the GPS coordinates of the perimeter of the borrow area in the field. The thickness (E) of the gravelly level is then equal to the average thickness of the nodular level. Thus, knowing the total area of the borrow area and the average thickness of the nodular level, the specific gravity, the tonnage of the Bandjoun lateritic graveled soils was determined by the following formula:

$$T = A \times E \times \gamma s, \tag{4}$$

where T: tonnage of the borrow, γs: specific gravity, A: total area, E: thickness of the gravelly level.

Moreover, starting from the energy requirements for the production of one tonne of aggregates established by Martaud [31] following an environmental assessment of the production of aggregates in quarrying. This author establishes that the energy requirements for the production of one tonne of aggregates vary between 0.78 and 7.2 kW h/t in electricity and between 4.19 and 8.75 kW h/t in fossil fuels. It also establishes that the global warming index per tonne of aggregate produced varies from 1.72 to 3.41 kg equivalent carbon.

4. Results

4.1. Physical Identification Parameters. The methylene VBS of the LGSB range from 4.00 (CP1) to 4.50 (CP4). The mean VBS value of the studied samples is 4.25, with a standard deviation of 0.08. The specific gravity (γs) values obtained vary from 1.907 to 2.341 (Table 1). The mean γs value of LGSB is 2.17 with a standard deviation of 0.19. The group indices (GI) of LGSB are very low and range from 0 (CP1) to 0.12 (CP4). The mean value of the GI of the samples studied is 0.003 with a standard deviation of 0.06. The values of the LL vary between 47% and 53%. The highest value

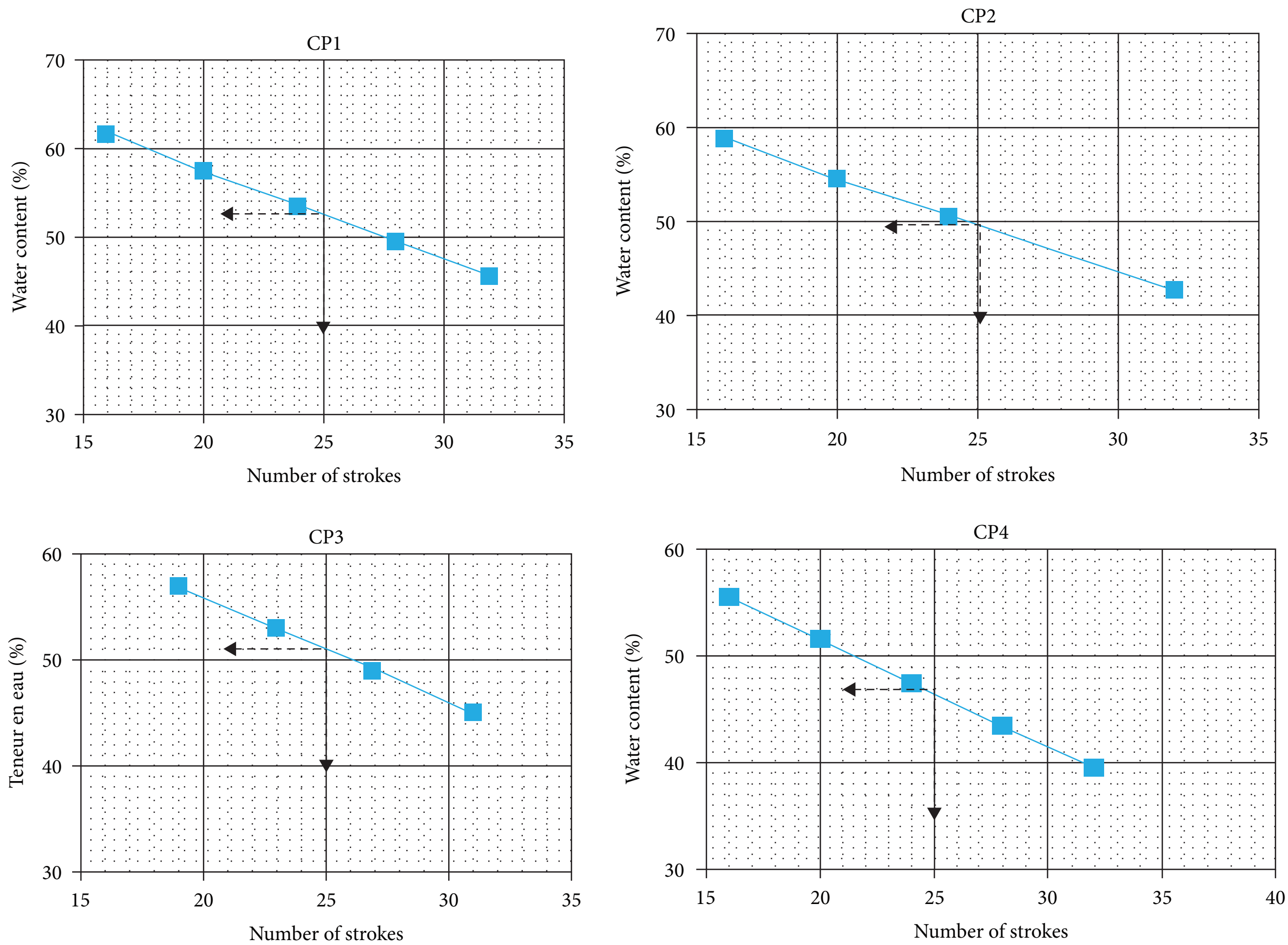

Figure 3: Liquidity limit of samples.

corresponds to sample CP1 taken at the foot of the graveled zone and the lowest value corresponds to sample CP3 taken to the north of Pit 1 of the graveled zone (Figure 3). The average LL of the LGSB is 50%, with a standard deviation of 2.50.

As for the plasticity limits (ω_p), the values vary from 34.50% to 43.66%. The highest value was found in sample CP1, taken from the foot of the graveled area, and the lowest value was found in sample CP4, taken from the top of the graveled area (Table 1). The average ω_p, of the studied materials, is 39.90% with a standard deviation of 3.85.

The plasticity index values vary from 9.30 (CP2) to 11.50 (CP4) (Table 1). The average value for these four samples is 10.11, with a standard deviation of 1.40. The CI values range from 2.03 (CP3) to 3.91 (CP1) (Table 1). The mean CI value of LGSB is 3.14, with a standard deviation of 0.82. The numeric results obtained from the particle size analyses led to the establishment of the grading curve below (Figure 4).

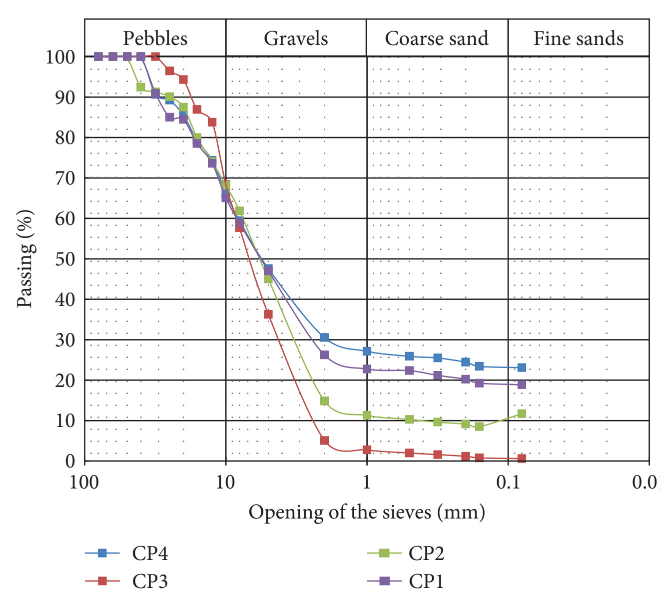

Figure 4: Grading curves of the samples.

4.1.1. Sample CP1. The grading curve of sample CP1 shows that the dominant fraction is gravels, which represent 58.3%

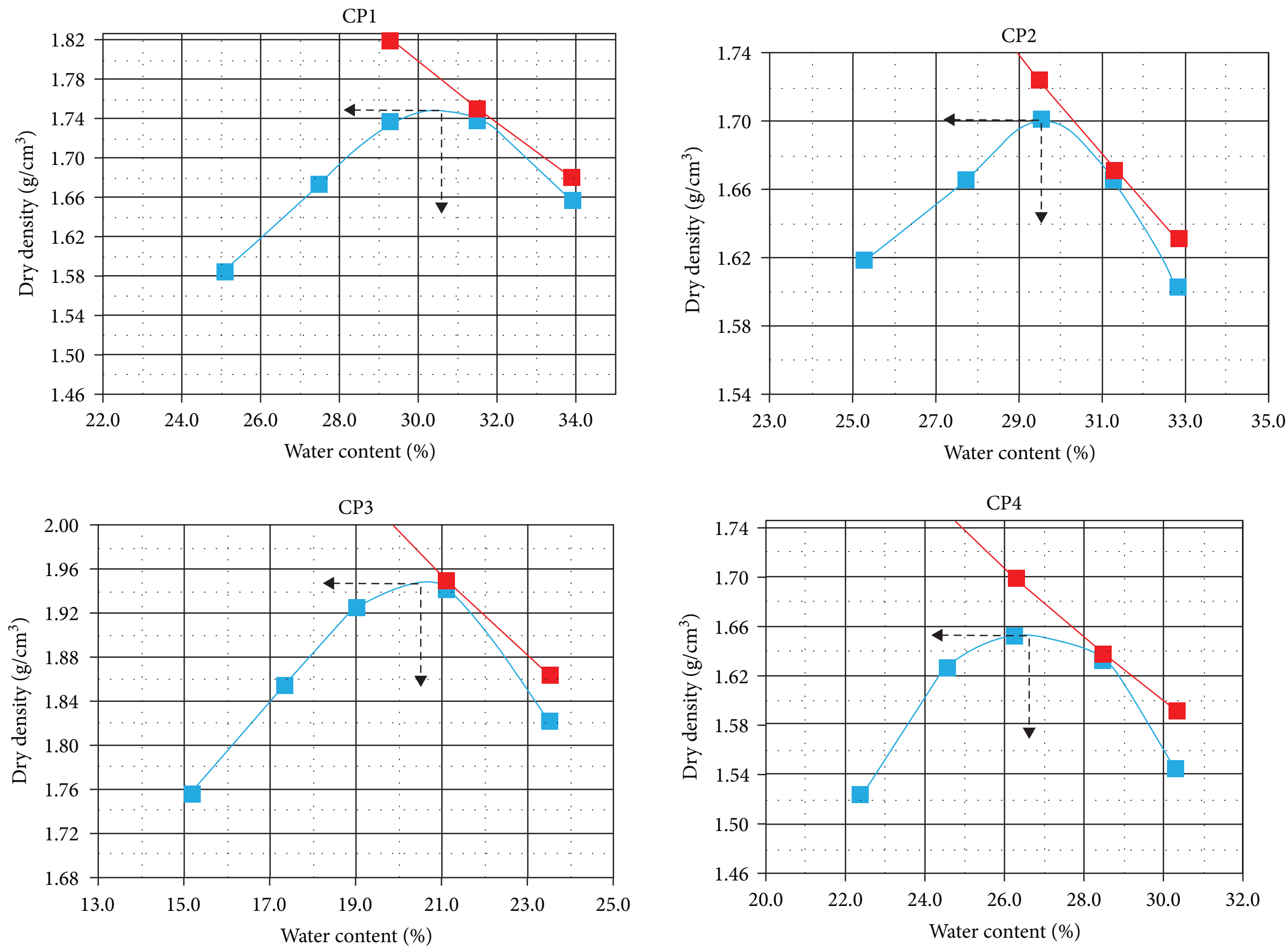

Figure 5: Modified Proctor curves of samples.

of the material, followed by fines (18.6%), and the lowest fraction is fine sands (1.0%). The size fraction of pebbles is at a proportion of 15.5% and that of coarse sand is 6.0% (Figure 4).

4.1.2. Sample CP2. Sample CP2 consists mainly of pebbles, gravels, coarse sands, fine sands, and fines. The grading curve of this sample shows that the dominant fraction is gravel, which represents 72.7% of the material, followed by pebbles (12.5%), and the lowest fraction is fine sands (0.6%). The size fraction of fines has a proportion of 7.7% and that of coarse sand is 5.7% (Figure 4).

4.1.3. Sample CP3. The highest fraction in sample CP3 is gravel, with a proportion of 89.2%, followed by pebbles (5.7%), and the lowest fraction is fine sand (0.4%). The size fraction of fines at a proportion of 0.6% and that of coarse sand is 3.9% (Figure 4).

4.1.4. Sample CP4. The analysis of the particle size curve of sample CP4 shows that the dominant fraction is gravels, which represent 55% of the material, followed by fines (23.1%), and the lowest fraction is fine sands (1%). The grain size fraction of pebbles is 14.5%, and that of coarse sand is 6.1% (Figure 4).

The lateritic graveled soils of Bandjoun are consisted of the following:

(i) Gravel has an average proportion of 68.80% and a standard deviation of 15.62.

(ii) Pebbles have an average proportion of 12.05% and a standard deviation of 4.41.

(iii) Coarse sand has an average proportion of 4.55% and a standard deviation of 2.77.

(iv) Fine sands have a mean proportion of 12.05% and a standard deviation of 0.03.

(v) The fines have a mean proportion of 12.5% and a standard deviation of 10.30.

4.2. Compaction and Bearing Capacity Parameters. From the Proctor curves, it can be seen that the MDD values vary between 1.637 (CP4) and 1.942 g/cm³ (CP3), with optimum moisture contents (OMC) of 26.7% and 20.5%, respectively (Figure 5). The highest dry density (MDD = 1.942 g/cm³) is obtained with the lowest OMC (21.1%). The mean value for

Table 2: Summary of the different mechanical characterization results.

Parameters	Proctor test		CBR (95%)
	MDD (g/cm³)	OMC (%)	
Samples			
CP1	1.74	31.50	41.40
CP2	1.70	29.50	26.00
CP3	1.94	21.10	83.30
CP4	1.64	28.50	29.40
Max	1.94	31.50	83.30
Min	1.64	27.60	26.00
Average	1.75	27.60	45.02
Deviation	0.13	4.54	26.36

CBR = California bearing ratio, MDD = maximum dry density, OMC = maximum water content.

these four samples is 1.755 g/cm^3 with a standard deviation of 0.13 (Table 2).

As for the OMC, the values vary from 21.1% to 31.5% (Figure 5). The average value for these four samples is 27.65%, with a standard deviation of 4.54 (Table 2).

The dry density variation curves by CBR index (Figure 6) were plotted from the values obtained from different manipulations. The CBR indices by immersion at 95% of the Proctor optimum are determined from the dry density variation curves following these indices (Figure 6). The results obtained indicate that the CBR indices of the samples studied vary from 26% (CP2) to 83.3% (CP3). The average CBR value of these soils is 45.02%, with a standard deviation of 26.36 (Table 2).

4.3. Proposal for Optimal Use of These Soils in Road Construction. In road construction, soils remain the most widely used material, whether used as road fill or as support materials. Therefore, the quality of the structure is closely linked to the properties and characteristics of the soils used. In this section, the geotechnical suitability of LGSB for use in road construction is assessed.

4.3.1. Use of Paved Roads.

(*1*) *Use in Subgrade*. The soils from the Bandjoun quarries have CBR values of between 26.0% and 83.3%. The low proportion of fines sufficiently demonstrates the ability of these soils to resist water. This is not the case for sample CP4, which has an average percentage of fines (23.1%) and a low-bearing capacity (29.40%). The LGSB can be used as a subgrade, as their bearing capacity is well above the values retained [32]. These values are respectively 10% and 15% in Cameroon, Côte d'Ivoire, and Senegal.

(*2*) *Use as a Subbase Layer*. According to the recommendations of CEBTP [32], the studied soils more or less conform to the conditions for subbase layers. Indeed, this soil has a percentage of fines ≤35% and a plasticity index lower than 20%. If we add to this the granulometric criteria, the granulometric curve of samples CP1 and CP2 are more or less within the prescription limits, whereas samples CP3 and CP4 are only partially encrusted (Figure 7) and consequently, the materials close to these sampling points cannot be used as subbase layers. However, the CEBTP recommendations, as presented above, are applied differently in tropical countries because local realities require it. Indeed, the geotechnical characteristics of soils are influenced by local parameters such as rainfall and slope. In Côte d'Ivoire, for example, the soil must have a percentage of fines less than or equal to 20, a plasticity index less than or equal to 20, and a CBR index greater than 30, for a medium traffic road, greater than 25 for low traffic roads and 35 for high traffic roads. In Brazil, lateritic gravels used as a subbase must have a plasticity index lower than 15, an LL lower than 40, a fine content between 5% and 30%, and a CBR index higher than 60 or 80 [33]. In Cameroon, for soil to be eligible for use as a subbase, it must have a bearing capacity of 30% or more, although a CBR of 25% can be tolerated for Tl traffic [8]. Considering the rules of use in Cameroon, the soils studied can all be used as subbases for T1 to T3 traffic since their CBR (average CBR = 45%) is higher than 30%. However, their characteristics need to be optimized for use in subbases for heavy traffic (T4 and T5), as their dry density at the modified Proctor optimum (1.75 g/cm^3) is less than 2 g/cm^3. Moreover, these low dry-density values are attributable to the low proportion of fine particles in these materials.

(*3*) *Use as a Base Layer*. For use as a base layer, the soil must, according to the specifications in CEBTP [32], have an optimum dry density greater than or equal to 2 g/cm^3, a CBR value greater than or equal to 80% (a minimum value of 60 is allowed for T1 traffic), a plasticity index less than or equal to 15%, a linear swelling less than or equal to 1% and a percentage of fines less than 20%. In addition, the grading curves must fit into the reference grading range as prescribed by CEBTP [32]. The sieve curves of samples CP1, CP2, and CP4 are the ones that more or less keep the shape (Figure 8), but sample CP3 only partially fits into these spindles because of the very low fine content (well below 5%). Taking into account local realities, each country adopts its own rules, but without deviating from the CEBTP specifications. For example, in Cameroon, Côte d'Ivoire, and South Africa, the selection criteria are generally as follows: CBR index ≥ 60%, percentage of fines ≤ 25%, and linear swelling ≤ 0.3% [33].

In all the samples studied, the MDD is less than 2 g/cm^3, and the CBR bearing index is less than 80% for samples CP1, CP2, and CP4. As a result, the samples studied are not suitable for use in base courses; even though the average particle

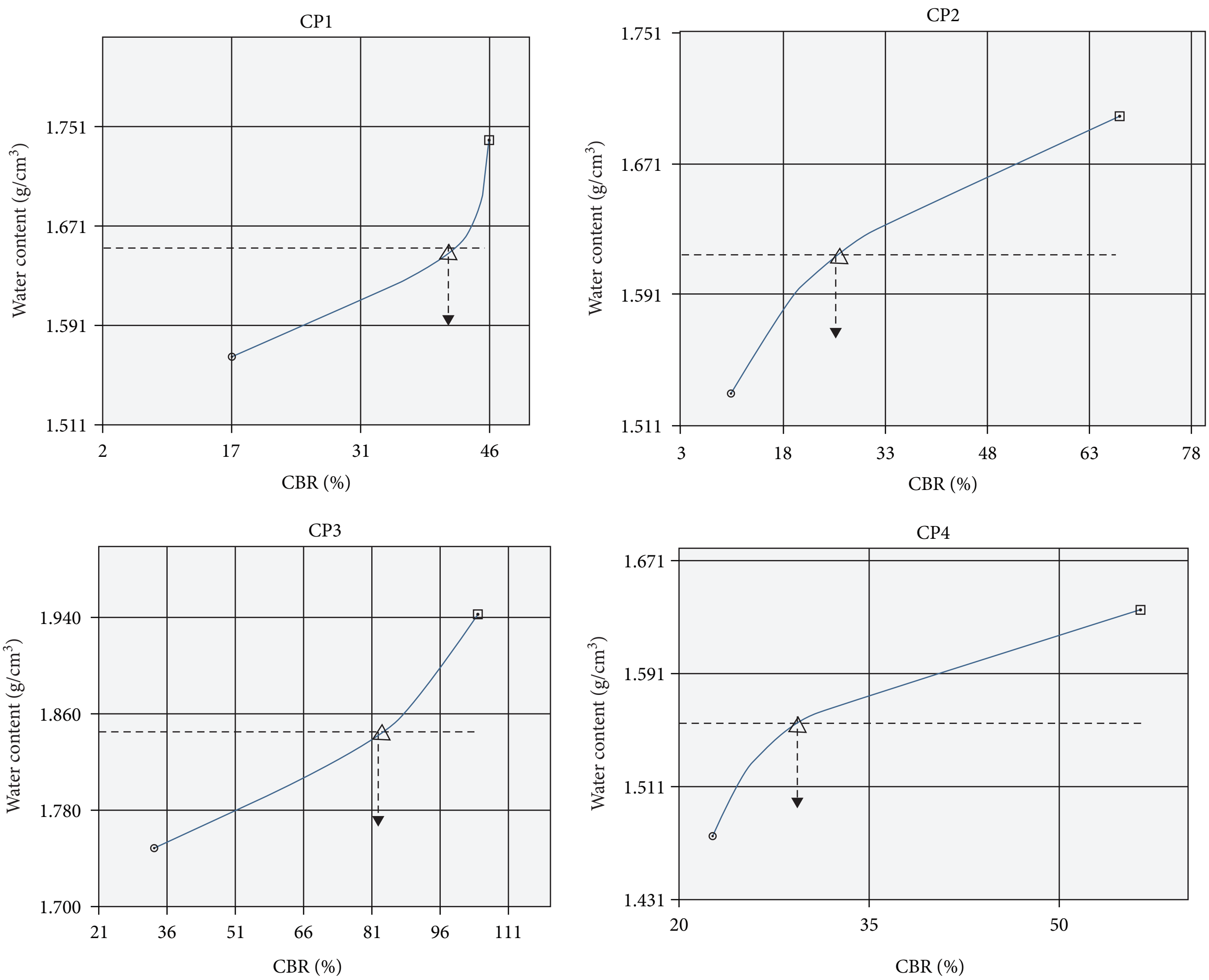

Figure 6: CBR curves of the samples.

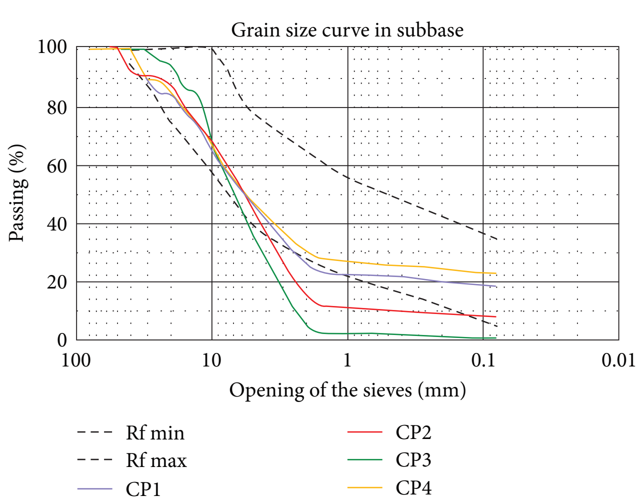

Figure 7: Position of the grading curves of lateritic graveled soils of Bandjoun in the grading range of the subbase [32].

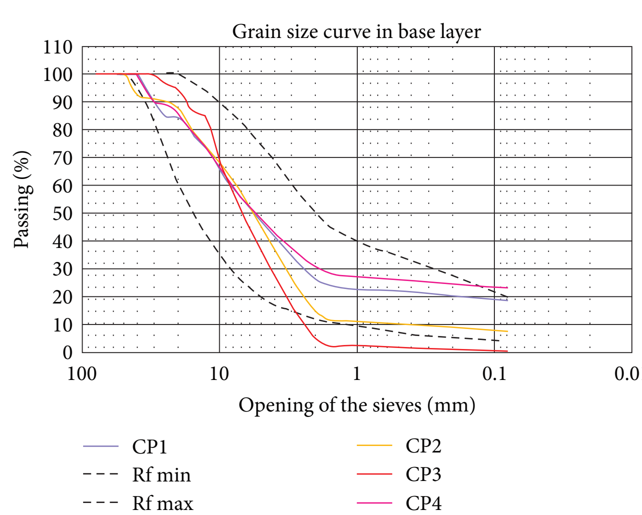

Figure 8: Position of the grading curves of lateritic graveled soils of Bandjoun in the grading range of the base layer [32].

size curve of samples CP1, CP2, and CP4 fits perfectly within the limits of the CEBTP prescription, these materials do not have the CBR-bearing capacity required for use in base courses. Nevertheless, the soils close to the CP3 sample point can be used as a base course for low traffic (T1), but grading corrections must be made.

4.3.2. Uses for Surfacing Earth Roads. The use of lateritic graveled soils for the surfacing of earth roads follows the same prescriptions as for asphalt roads, and the wearing course is provided by the base course. For the construction of unpaved roads, the emphasis is on the characteristics of the material to be used in the base course; this is to limit the phenomena of "gravel loss" and "corrugated sheets." These two phenomena are typical signs of degradation of earth roads when the choice of material has not been judiciously made.

(*1*) *Gravel Loss Phenomenon*. One of the best-known characteristics of earth roads is the "gravel loss." This is a phenomenon characterized by the release of dust and material caused by vehicle traffic. This loss of material is the main cause of the reduction in pavement thickness. This loss is estimated at 25 t/year/km for the traffic of 100 vehicles/day [7]. It is simply expressed in centimeters per year and reaches 2–4 cm for the traffic of 150–500 vehicles/day [34]. Factors that contribute to the development of material loss on unpaved roads, according to Jones et al. [35], include traffic, vehicle load, rainfall, road geometry, maintenance frequency, and, most importantly, the type of material used. Thus, the loss of material leads to a decrease in the life of the road by decreasing the base layer. This phenomenon increases the need for resurfacing and the cost of operating vehicles. To limit this phenomenon on unpaved roads, an assessment of the relationship between the type of traffic and the type of material to be used should be made before any maintenance or reprofiling work. LGSB are enriched with coarse elements (gravel and pebbles) whose proportions are well above 70%. Depending on the fines (silt + clay), a distinction is made between materials enriched with fines (CP4 and CP1), those with medium fines (CP2), and those with low fines (CP3). Therefore, the use of these materials for unpaved roads would probably limit the gravel loss phenomenon.

(*2*) *Corrugated Sheet Phenomenon*. Abrasion due to the passage of vehicles in the dry season on earth roads manifests itself in the form of a phenomenon called "corrugated sheet." This deformation of the longitudinal profile takes the form of a pseudo-sine wave with a wavelength of around 0.60–1.00 m. These corrugations usually extend over the entire width of the road but sometimes only over a part of it [7]. The amplitude is even more pronounced in dry climates and when maintenance is neglected [32]. A corrugated sheet is formed whenever a lack of surface cohesion allows the material to be torn off due to the frequent tangential forces applied by passing vehicles and when these tears occur uniformly and not in the form of potholes. The torn-off materials harden over time, and there is no alternative but to strip them [32]. The cohesion failure can be caused by a discontinuity in the grain size of the material. In general, the grain size curve of laterites

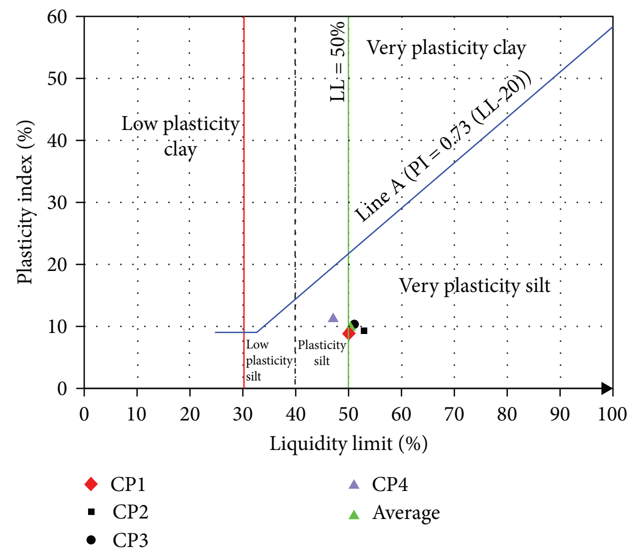

Figure 9: Position of Bandjoun lateritic graveled soils in the Cassagrande fine soil plasticity and classification diagram.

subject to "corrugated sheet" shows marked discontinuities. According to Fenzy [36], corrugated sheeting can occur in almost any material regardless of grain size but with varying strain rates and amplitudes. Several methods have been developed to limit the corrugated sheet phenomenon. The prevention of this phenomenon consists of selecting the appropriate type of material and then proceeding to improve or correct the physical or mechanical characteristics. Of the samples studied, only soils close to sample CP3 can be used as a base layer for unpaved pavements, but improvement of the mechanical parameters is necessary.

4.4. Geotechnical Classification. The numeric results obtained from the Atterberg limits (plasticity and LLs) conducted the positioning of LGSB in the Cassagrande plasticity diagram (Figure 9).

The results of the geotechnical analyses carried out on the LGSB show several similarities. Samples CP1, CP2, CP3, and CP4 have an average percentage of fines of about 12.5%. They are indeed lateritic gravels. The liquidity and plasticity limits of the studied samples allow them to be found below line A of the Cassagrande plasticity diagram (Figure 9), more precisely in the domain of very plastic silts (Lt) for samples CP2 and CP3, in the domain of plastic silts (LP) for sample CP4. Sample CP1 is located between the two zones. Therefore, with more than 50% of the elements greater than 0.08 mm in diameter having a diameter greater than 2 mm and more than 12% of elements with a diameter less than 0.08 mm, these materials are silty gravels (GL), according to the classification and silty gravels (GL) according to the classification of the Laboratoire Central des Ponts et Chaussées [37].

Based on the Highway Research Board (HRB) classification, LGSB have less than 35% of material passing the 0.08 mm sieve: they are group A-2 and subgroup A-2-7 gravelly soils. In addition, they have very good GI, plasticity indices above 10 and LLs above 40%. According to the

HRB classification, these characteristics allow them to be called "silty or clayey gravels and sands."

In the classification of the guide de Terrassement Routier, LGSB are classified in class B because the percentage of fines is less than 35%. Their sieve size at 0.08 mm is between 12% and 35%; subclass B6 is appropriate for them even if their plasticity indices are below 12%. Depending on the hydric state, these soils have consistency indices higher than 1.3; thus, they are in the B6ts subclass. Thus, LGSB belong to the class of sandy and graveled soils with fines and the subclass of clayey to very clayey sands and gravels (B6). It is a granular material containing variable fractions of sand and clay.

4.5. Tonnage and Ecological Implications of Soil Use in Road Construction. With an average nodular level of 116.5 cm, a total borrow area of 7,282.5 m^2, and an average specific gravity value of 2.17 t/m^3, the tonnage of Bandjoun lateritic graveled soils was estimated at 18,389 t. Thus, the use of these soils in subgrade and foundation, as revealed by the geotechnical studies, will save 14–132 kW h in electricity and 77,050–16,0904 kW h in fossil fuels. The global warming index shows that the use of 18,389 t of Bandjoun lateritic graveled soil in road construction can reduce 31,629–62,706 kg of carbon emissions.

5. Discussions

The specific gravity (γs) of LGSB varies from 1.90 to 2.25. These γs values are lower than those obtained on lateritic graveled soils by Nzabakurikiza et al. [38], Paige-Green et al. [39], and Tene Fongang et al. [40]. These materials thus show poor performance in terms of specific gravity ($\gamma s < 2.75$), according to Nwaiwu et al. [11] and Onana et al. [13]. These low γs values can be explained by the high aluminosilicate content of these soils [41, 42]. On the other hand, the γs values of the studied materials are similar to those obtained on lateritic gravels from Senegal [43].

The methylene blue (VBS) values of LGSB range from 4.00 to 4.50/100 g. These VBS values are higher than those obtained on the lateritic graveled Boumpial (1.3 g/100 g) by Oyelami and Van Rooy [44]. The LGSB are clayey silty, according to Duplain et al. [45].

The LGSB consist of pebbles (12.05%), gravels (68.80%), coarse sands (4.55%), fine sands (12.05%), and fines (12.5%). These materials are poor in fines, i.e., 12.5%, which is lower than (33.49% and 76.41%) found at Bamoungoum by Lyon Associates [41], and 25.6% and 32.9% found at Banka by Kamtchueng et al. [9], but higher than those obtained by Djuickouo [46] (12%) at Dschang. Thus, on the whole, these lateritic gravels are enriched in coarse elements (gravels and pebbles) whose proportions are largely above 70% of the materials. They are true lateritic graveled. This enrichment in coarse elements can be explained by the steep slopes where the alterations are constantly eroded. Furthermore, the grading curves of the studied samples are more or less within the prescription limits for the subbase and base layers [32]. However, the CP3 and CP4 samples are only partially embedded, and therefore, the materials close to these sample points cannot be used in subbase and base layers from a grading point of view.

The average value of the LL of the LGSB (LL = 50.25%) is similar to that obtained in the humid savannah zone of Central Cameroon (51%) [47] and Eastern Cameroon (52%) [48]. This LL value is higher than those obtained in West Africa (23%–55%) [49, 50] and in Banka in West Cameroon by Kamtchueng et al. [9]. On the other hand, this LL value is lower than that obtained in Bamougoum in West Cameroon (55%–75%) by Lyon Associates [41] and in Mfou in Central Cameroon by Jones et al. [35]. The low proportion of LGSB fines would explain this low LL value.

The average PI value of LGSB (10.1%) is lower than that obtained on lateritic graveled in Central Cameroon (26%) [35], that obtained at Boumpial (18%) [11], that obtained at Akonolinga (18%) [48]. This PI value is similar to those obtained in West Africa (11%) by Millogo et al. [49]. However, this average PI value is lower than the maximum required (20%) for subbase and base course materials (15%) of high-traffic roads [32]. According to the Casagrande plasticity diagram, LGSB are plastic silty materials with high plasticity.

The MDD value is 1.75 g/cm^3. This value is almost similar to that obtained on lateritic materials from Bamougoun in West Cameroon (1.48–1.85 g/cm^3) [41]. Lateritic gravels must have an MDD greater than or equal to 1.80 and 2.00 g/cm^3 to be used as subbase and base layers, respectively [32]. Thus, LGSB do not have an acceptable MDD value for subbase and base layers.

LGSB have an average CBR value of 95% of 26%–83.30%. The CBR value (45%) of these soils is higher than those obtained on the lateritic soils of Banaka by Hermann et al. [15] and Bamougoum by Gidigasu [4]. The average CBR value is above 30%, the minimum acceptable for use as a subbase layer for low-traffic pavements [32]. In summary, LGSB can be used naturally in pavement layers, especially in subgrade layers for all traffic classes, and in subbase layers for light traffic from T1 to T3. However, because of their MDD of less than 2 g/cm^3, optimization of their geotechnical properties will allow their use in subbases for heavy traffic (T4 and T5) as well as in subbases.

On an ecological level, it is emphasized that the use of Bandjoun lateritic gravel soils in road construction has significant ecological implications. Geotechnical studies show that using these soils in subbase and foundation can save between 14 and 132 kW h of electricity, as well as between 77,050 and 160,904 kW h of fossil fuels. This reduction in energy consumption contributes to a decrease in greenhouse gas emissions, which is beneficial for combating climate change.

Additionally, by using a total of 18,389 tonnes of Bandjoun lateritic gravel soils, it is estimated that carbon emissions can be reduced from 31,629 to 62,706 kg. This demonstrates the positive impact of this practice on greenhouse gas emissions.

These results highlight the environmental benefits of using Bandjoun lateritic gravel soils in road construction, both in terms of energy savings and carbon emission reduction. These favorable ecological implications underscore the importance of adopting sustainable practices in the construction industry to preserve our environment.

5.1. New Elements of Research Compared to Other Similar Studies in the Region. The main novelty of this study, compared to previous work conducted, respectively, on lateritic gravel soils in Bafang and the northern part of Mount Bangou by Foko Tambo et al. [16] and Hyoumbi et al. [51], is the specific evaluation of the geotechnical properties of lateritic gravel soils for road construction, as well as the assessment of their ecological impact and their potential for use as a low-cost and environmentally friendly road construction material. Similarly, the lateritic gravel soils in Bandjoun have high CBR bearing ratios, low fines content, and high gravel content compared to the lateritic gravel soils in Bafang in Western Cameroon [51] and the lateritic gravel materials in the northern part of Mount Bangou [16]. This is likely due to the difference in the geo-environmental formation of these lateritic graveled materials.

6. Conclusion

The geotechnical suitability of LGSB was evaluated to assess their limits in terms of their use in road construction. The fieldwork revealed that the LGSB are contained in the graveled mineral horizon. Nodules of a millimeter to multicentimeter size predominate in this graveled mineral horizon. The materials studied belong to the category of granular soils. They are silty or clayey gravels and sands of group A-2 and subgroup A-2-7 according to the HRB classification and silty gravels (GL) according to the classification of the Central Laboratory of Bridges and pavements. As for the classification of the Road Terrassement Guide, the soils studied are in the class of sandy and gravel soils with fines and the subclass of clayey to very clayey sands and gravels (B6). The studies showed that LGSB can be used naturally in pavement layers, especially as a subgrade for all traffic classes and as a subbase layer for low traffic, according to the specifications of the Practical Guide to Pavement Design in Tropical Countries. However, because of their MDD of less than 2 g/cm^3, optimization by litho-stabilization will allow them to be used as a subbase layer for heavy traffic, as well as a base layer for light traffic. Beyond Cameroon, the utilization of lateritic soils in road construction presents a compelling alternative for mitigating the environmental impacts associated with rock aggregate production, while simultaneously offering ecological and economic benefits.

Data Availability

Data are available on request from the authors.

Additional Points

Highlights. The study focuses on the evaluation of geotechnical parameters and ecological implications of lateritic graveled soils in Bandjoun for road construction. These soils have Californian bearing ratio indices ranging from 26% to 83.3%, a plasticity index of 10.11%, and a fines content of 12.05%. They are classified as silty or clayey gravels and sands of subgroup A-2-7 according to the Highway Research Board classification. The soils have favorable properties for use in pavement layers, subgrade, and subbase in road construction. The tonnage of these soils is estimated at 18,389 t. The use of these soils can reduce carbon emissions associated with the manufacture of rock aggregates. Lateritic soils are a more environmentally friendly alternative to rock aggregates for road construction.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

Carlos Foko Tamba has done the data collection, conceptualization, writing, editing, and revision; Lucas Kengni has done the formal analysis and orientations; and Paul Tematio has done the formal analysis and orientations.

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