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Characterization and Geotechnical Classification of Soils and Lateritic Gravelly Materials along the Songololo-Lufu Road Axis (Kongo Central Province, DR Congo)

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Abstract

This study aims to characterize from a geotechnical point of view, the soils as well as the lateritic gravels along the Songololo-Lufu road route in the Kongo Central Province in the Democratic Republic of Congo (DRC). Ten soil samples and eight lateritic gravel samples were analysed and tested in the laboratory. For each sample, identification parameters were determined such as particle size analysis, natural water content, Atterberg limits (plasticity index and consistency index), but also compaction and lift parameters such as optimal water content, maximum dry density and CBR lift index. All materials and soils have been classified according to the Congolese Road Standard (NRC) and according to the American HRB classification. The test results show us that clay soils almost always contain between 70% and 90% fine fraction; the grained fraction represents less than 30% in clay samples. For lateritic gravels soils, the percentage of fine elements varies between 35% and 15%; in sand around 20%; the gravelly fraction represents a little more than 50% of the soil. The majority of soil facies encountered define a plasticity index lower than 15. As for the consistency index, we obtained values greater than 1, both for clayey soils and for gravelly soils. The classification according to NRC defined for these soils the types Ae1 and Ae2 for the clayey facies and the types GL1 and GL2 for the gravelly soils, while that of the HRB identified the classes and subclasses A-6 and A-7-6 for clayey soils, and subclass A-2-6 for gravelly soils. The optimal water content values obtained range between 10.2% and

23.10%; the maximum dry densities are between 1.66 and 2.07 t/m^3 and the CBR index is between 6 and 26. As for the lateritic gravels materials of the Songololo region, the percentage of fine elements generally remains between 12% and 31%; the plasticity index is between 8 and 18; the optimal dry density is around 2 t/m^3; the optimal water content is between 9.8% and 14.5% and the CBR index is between 27 and 82. The Songololo-Lufu lateritic gravels are characteristic of laterites in the savannah region, with a high gravel fraction at the expense of the fine fraction, but low parameters such as the liquid limit and plasticity index.

Keywords

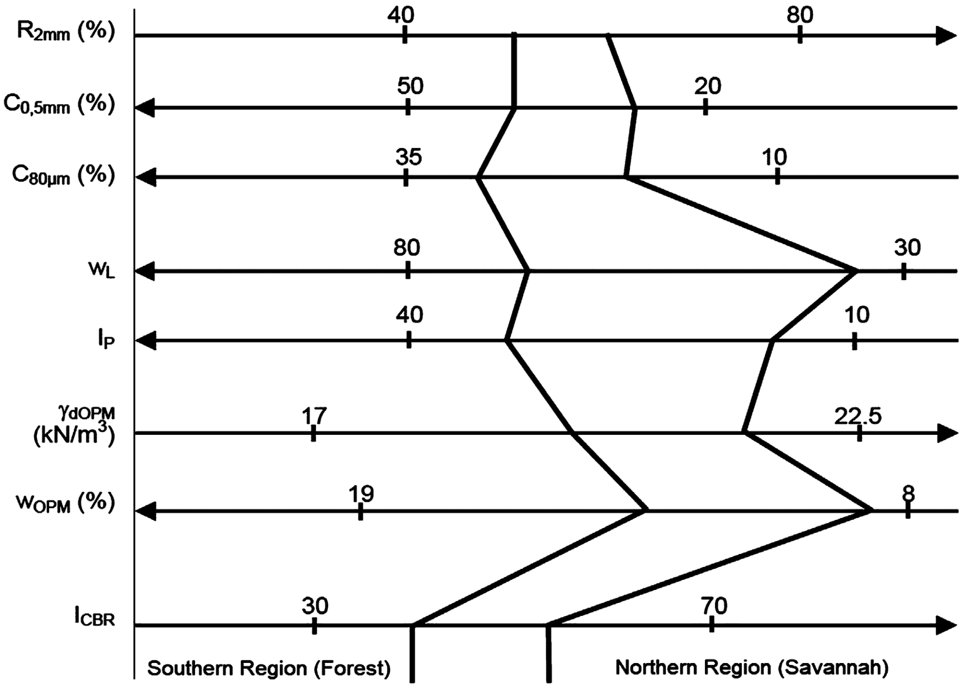
Songololo-Lufu, Lateritic Gravels, Classification, Geotechnical, NRC

1. Introduction

Laterites have been studied extensively in Africa, but also characterized for their use in road construction. Bohi's studies (2008); Issiakou et al. (2015); Hassaballah et al. (2019); Ahouetohou (2021) and Darman et al. (2022) illustrate some of them in several different geographical contexts. The Pavement Sizing Guide for Tropical Countries defines the geotechnical characteristics of lateritic soils and materials (CEBTP, 1984). Since then, this guide continues to serve as a reference for characterizing both natural and improved road materials. In addition, for lateritic materials from the Democratic Republic of Congo, the Zairian Road Design, cited in Bohi (2008), has established a characterization diagram for lateritic materials in the DRC (**Figure 1**). Said materials are defined according to their geotechnical parameters, and thus distinguish laterites from forest regions from laterites from savannah regions. The parameters that come into play depend on the identification tests, in particular the results from the particle size analysis, the Atterberg limits, the compaction tests, as well as the equivalent CBR bearing index (Bohi, 2008).

The laterites of the Songololo region in the Kongo-Central province crop out over a vast area, and have always been used by the local population as gravel. As part of the immense road construction project between the cities of Songololo and Lufu, this study could contribute to the characterization of said materials according to the CEBTP guide, and according to the Zairian Road Design (currently Congolese Road Standard), with the aim of updating the general knowledge already acquired on the use of these materials.

The objective of this study is to characterize the lateritic soils and materials of the Songololo region according to the CEBTP standards and the Congolese Road Standard (formerly Zairian Road Design). The approach undertaken therefore amounts to characterizing the soil in place by defining some geotechnical parameters. As for lateritic materials, the different geotechnical parameters studied should inform us about the usability of these materials in road construction, while



Empirical relationship: ICBR = 0.44 [(R2mm – 30) - (C80µm – 10) – (IP – 10)] + 47.5

Figure 1. Geotechnical identification diagram of lateritic gravels proposed by studies in the DRC (Bohi, 2008).

comparing the parameters obtained with the average values of some laterites already studied in Africa.

2. Study Area

This study concerns national road number 15, which is between 5˚44' and 5˚50' of South Latitude and 14˚02' and 14˚05' of East Longitude (**Figure 2**). This runs along the territory of Songololo (PK0 + 000) from national road number 1, passes through the city of Lufu to the border post between the Democratic Republic of Congo and the Republic of Angola (PK18 + 700) over a total length of 18.810 km.

The nature of the soil along this road axis is mainly clayey then crosses a vast expanse of lateritic gravel (which can be sufficiently exploited as road material). However, the soil facies is heterogeneous in places, passing towards clayey sands at some points.

The local geological context is highlighted by the presence of mixed carbonate and purely carbonate silico-clastic facies (Tuema et al., 2021). Along the said road axis, unfortunately no rock outcrops are present. Tack (1973) defines the presence of a granite formation gnessified during the West-Congolian folding, and which outcrops along the Lufu River, natural border between the Democratic Republic of Congo, and the Republic of Angola on this part. However, the study area is strongly characterized by a strong presence of soils laterites, markers of the superficial alteration of the underlying base.

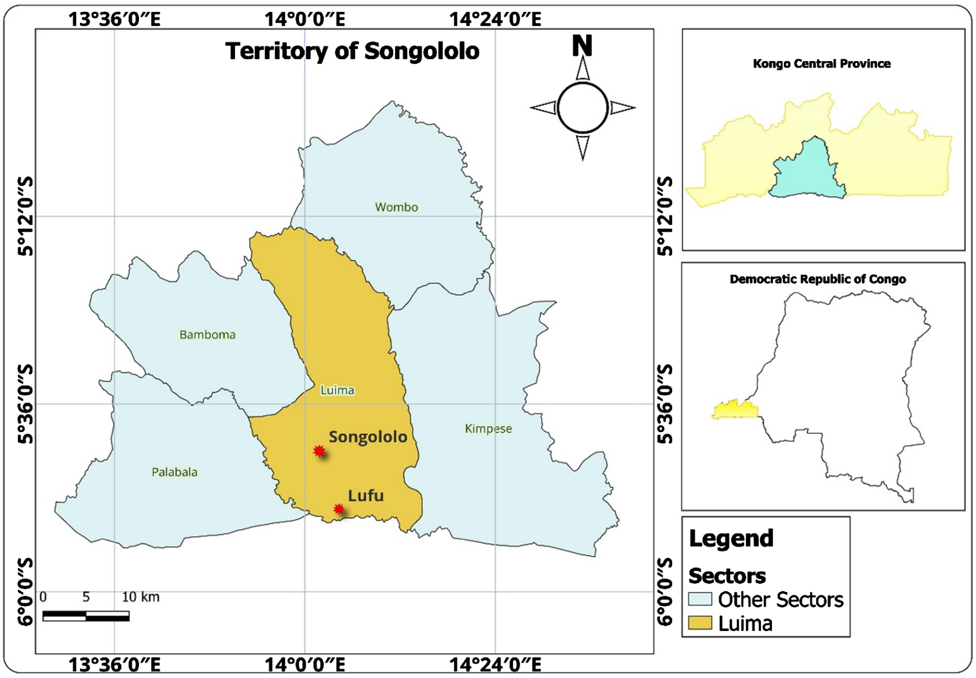


Figure 2. Location of the road axis.

3. Methodology

We proceeded by taking soil samples along the road route; during which an inventory of the different embankment borrow sites was made, with the aim of their characterization, classification and specification. The geotechnical identification, load-bearing and compaction tests were carried out at the National Public Works Laboratory (LNTP) as well as at the laboratory of the Faculty of Polytechnic of the University of Kinshasa. The classification of soils and lateritic materials was established according to the Congolese Road Standard (NRC) and according to the American classification of the Highway Research Board (HRB).

3.1. Sampling

Out of a total of 19 soil samples taken alternatively, either on the left right-of-way of the road (G) or on the right-hand right-of-way of the road (D). The soil samples taken in the field were analysed in the laboratory. Each sample was identified from the point of view of texture, colour, etc. Samples showing lithological variability (or a change in facies) along the route were therefore given priority for laboratory analysis. Ten of the 19 samples were selected on the basis of differences in soil texture.

The formations encountered mainly showed a lateritic clayey and gravelly nature. The sampling step along the Songololo-Lufu road, which is National Road number 15 (RN15) is shown in Figure 3 below. The road is perpendicular to National Road number 1 (RN1), it is currently unused, except at the junction crossing a dirt road, which can be used from the RN1.

In addition to samples taken from both sides of the road route, eight other additional sites around which laterites crop out, sometimes in the form of ironclads or ferruginous nodules, were inspected as main borrowing sites (**Table 1**). These materials will therefore be studied with the aim of using them as road embankments, hence the determination of their geotechnical parameters.

3.2. Analyses and Processes

The identification tests that we have carried out are the Granulometric analysis and the Atterberg Limits. The particle size analysis was carried out by sieving, according to standard NF P 94-056 (1996). The sieving was carried out dry. The particle size curves were plotted according to the opening of the sieves, the cumulative refusals in grams, the cumulative refusals in percentage, and finally the

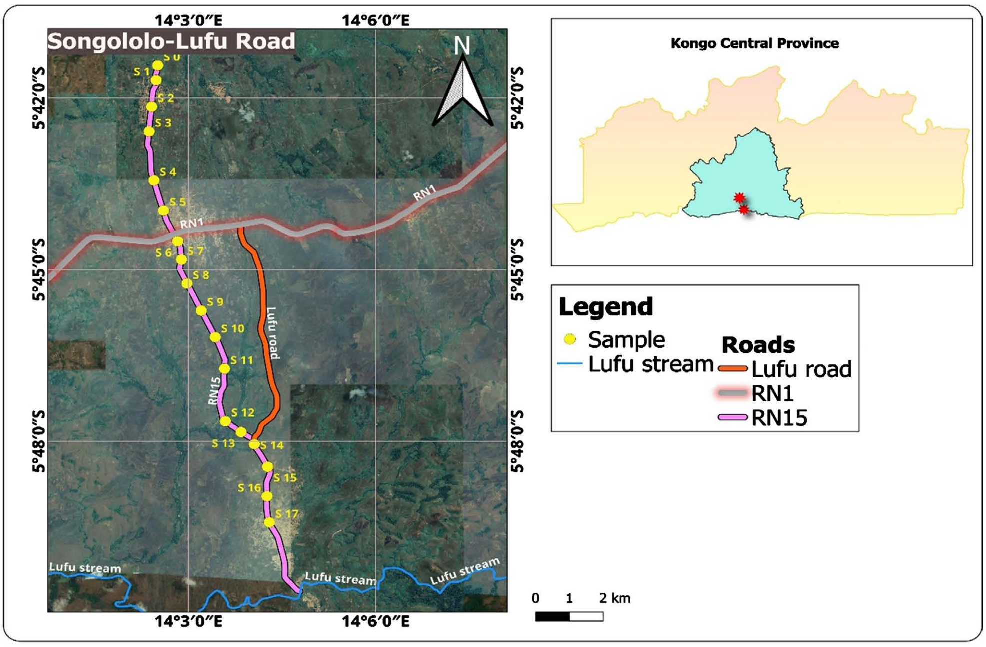


Figure 3. Sampling of platform soils on the Songololo-Lufu road.

Table 1. Lateritic gravel stone-pit sites along the Songololo-Lufu axis.

N° Survey	Point Kilometre (PK)	Sampling depth in meters	Description of the outcrop
S 00	2 + 400 D	0.20 - 2.00	Lateritic gravelly with ferruginous nodules with the presence of lateritic armor blocks.
S 01	2 + 700 D	1.20 - 2.00	
S 02	5 + 650 G	0.20 - 1.60	Lateritic gravel contains quartz elements and lateritic crusts.
S 03	7 + 500 G	0.20 - 3.50	Lateritic gravel with ferruginous nodules
S 04	7 + 500 D	0.20 - 2.00	
S 05	13 + 300 D	0.70 - 1.00	Lateritic gravel with ferruginous nodules with the presence of lateritic armor blocks.
S 06	13 + 300 G	0.50 - 2.00	
S 07	5 + 600 D	0.20 - 2.60	Lateritic gravels

sieves or passers-by in percentage.

The Atterberg limits were obtained according to standard NF P 94-051 (1993). Each soil sample was mixed with a quantity of water. The dough obtained is placed in a cup of approximately 100 mm in diameter of the Casagrande apparatus. After tracing a standardized groove on the smoothed dough, after a series of impacts with the cup. At the end of the experiment, we observe the contact of two lips of the groove. The liquidity limit is that water content in percentage (%) which corresponds to a conventional closure at 25 shocks.

For the plasticity limits, we mixed the samples concerned with varying quantities of water, then we proceeded to shape a roll of 3 mm in diameter and around a hundred millimetres in length. The plasticity limit being this water content expressed as a percentage of the weight of the dry material, of the soil spindle which breaks into small pieces when its diameter reaches 3 mm.

The Atterberg limits were also defined to observe the consistency of the soils. We started from the classification of Tchouani Nana & Callaud (2004) to identify the stages of soil consistency (State) for the selected samples. The two authors cited represent these different value intervals (**Table 2** and **Table 3**).

The compaction tests were carried out after making the Proctor Molds according to standard NF P 94-093 (1999). The mass of the lady being 2.48 kg, the fall height of 305 mm, three layers and 25 blows per layer for the Proctor Normal. For the Modified Proctor we used a lady weighing 4.535 kg, a drop height of 457 mm, 5 layers and 55 blows per layer. We thus obtained a Proctor curve, giving the dry density as a function of the water content.

These geotechnical load-bearing tests and those of compaction were carried out in order to define the CBR (Californian Bearing Ratio) load-bearing index according to standard NF P94-078 (1997). For the lift class, the value of the CBR at 95% of the dry density of the Optimum Proctor Modified (OPM) was taken

Table 2. Classification of soil clay according to the plasticity index according to Tchouani Nana & Callaud (2004).

Plasticity Index (Ip)	Soil condition
0 - 5	Non-plastic
5 - 15	bit plastic
15 - 40	Plastic
>40	Very plastic

Table 3. State of the soil according to the consistency index according to Tchouani Nana & Callaud (2004).

Consistency Index (Ic)	Soil condition
Ic > 1	Solid
0 < Ic < 1	Plastic
Ic < 0	Liquid

into account.

We took as a reference the "Pavement Sizing Guides for Tropical Countries" (CEBTP, 1984) to compare the results obtained with the average values for lateritic gravels materials, taking into account their possible use as road materials.

3.3. Classifications

The soil classifications were established according to the Zairian Road Design (1982a, 1982b), which defines the Congolese Road Standard (NRC). This essentially characterizes the nature of the materials according to their particle size and their plasticity. **Table 4** and **Table 5** illustrate the classification principle for

Table 4. Geotechnical classification criterion for gravels soils (with % of fines less than 40% passing to 0.08 mm and % of refusal at 2 mm greater than 50% of the refusal at 0.08 mm; according to the Zairian Road Design, 1982).

Group	Class	Subclass	Classification criteria	Genesis
GRAVELOUS SOILS	GL	GL1	$F < 20\%$ F. $Ip < 300$	Lateritic Gravels
		GL2	$20\% < F < 30\%$ F. $Ip < 600$ or $F < 20\%$ $300 <$ F. $Ip < 600$	
		GL3	$F > 30\%$ or F. $Ip > 600$	
	G	G1	$F < 15\%$ F. $Ip < 180$	Alluvial and Eluvionaries gravels
		G2	$F > 15\%$ F. $Ip < 500$ or $F < 15\%$ $180 <$ F. $Ip < 500$	
		G3	F. $Ip > 500$	
	Ge	Ge1	cf. G1	Gravel of eruptive origin
		Ge2	cf. G2	
		Ge3	cf. G3	

With: F (percentage of the fine fraction) and Ip (Plasticity Index).

Table 5. Geotechnical classification criterion for fine soils [with % of fines (increasing to 0.08 mm) greater than 40%; according to the Zairian Road Design, 1982).

Group	Class	Subclass	Classification criteria	Genesis
FINES SOILS	A	A1	F. $Ip < 1300$ and F. Ip. $G < 800$	Alteration clays of the crystalline and crystallophyll base, schisto-sandstone rocks, and sedimentary formations of the graben
		A2	$1300 <$ F. $Ip < 2500$ and F. Ip. $G < 1500$ or F. $Ip < 1300$ and $800 <$ F. Ip. $G < 1500$	
		A3	F. $Ip > 2500$ F. Ip. $G > 1500$	
	Ae	Ae1	cf. A1	Cretaceous and Quaternary sedimentary clays and alteration clays of eruptive formations
		Ae2	cf. A2	
		Ae3	cf. A3	

With: F (percentage of the fine fraction), Ip (Plasticity Index) and G (Swelling).

fine and gravels soils.

Said classification was also made according to the American classification of the Highway Research Board (HRB): which, in addition to the conditions of the first, also focuses on their conditions of use or reuse in embankment. This classification uses a simplified particle size analysis (2 mm, 0.40 mm and 80 µ sieve) as well as the liquid limit and the plasticity index (Quoted in Konate, 2008).

Sieving with an 80µ sieve makes it possible to categorize fine soils (from A4 to A7) from coarse soils (A1, A2 and A3) depending on whether the sieve is greater or less than 35%. In grainy soils we distinguish groups A1 (pebbles, gravel and sand) and A3 (fine sand), which are devoid of plasticity, or almost, from group A2 which includes fractions of gravel, silty or clayey sand. Group A2 is divided into four subgroups (from A2-4 to A2-7) following the same criteria as fine soils (Quoted in Konate, 2008). **Table 6** details these different classes.

4. Results

Particle size analysis

The results obtained by the particle size analysis allowed us to deduce the

Table 6. Geotechnical soil classification criterion according to the HRB standard; cited in Konate, 2008.

General Classification	**Granular materials** (Less than 35% of those passing the 80 µ sieve)							**Silt-clay materials** (More than 35% of those passing the 80 µ sieve)			
Group	A - 1		A - 3	A - 2				A - 4	A - 5	A - 6	A - 7
Subgroup	A - 1 - a	A - 1 - b		A - 2 - 4	A - 2 - 5	A - 2 - 6	A - 2 - 7				A - 7 - 5 A - 7 - 6
Particle size analysis.											
Percentage of passing the sieve:											
No 10	50 max	-	-	-	-	-	-	-	-	-	-
No 40	30 max	50 max	51 min	-	-	-	-	-	-	-	-
No 200	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of the fraction passing the No. 40 sieve:											
Liquidity limit	-		-	40 max	41 min	40 max	41 min	40 max	41 max	40 max	41 min
Plasticity index (1)	6 max		N.P. (3)	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Group index (2)	0		0	0		4 max		8 max	12 max	16 max	20 max
Type of materials	Stone fragments, gravel and sand		Fine sand	Gravel and sand with silt or clay				Loamy soils		Clay soils	
General value as a foundation	Excellent to good							Average to poor			

(1) The plasticity index of subgroup A - 7 - 5 is equal to or less than the liquidity limit minus 30. The plasticity index of subgroup A - 7 - 6 is greater than the liquidity limit minus 30; (2) The Ig group index must be placed in parentheses following the group symbol, for example: A – 2 - 6 (3), A - 2 - 4 (3) …; (3) N.P.: Non-plastic.

following characteristic curves depending on the type of soil. Figure 4 describes the clayey facies; Figure 5, the clay-gravels facies and Figure 6, the lateritic gravels facies.

Atterberg limits

Ten samples were tested to determine the Atterberg limits. Figure 7 and Figure 8 describe the state of plasticity and consistency of soils. The choice of samples was based particularly on the variation in lithological facies of the soils encountered and on their representativeness in the field.

The optimal dry density (γopm) and optimal water content (wopm) were defined after Proctor test. Figure 9 and Figure 10 describe the ranges of values obtained. The CBR bearing index was deduced for all soil samples, and the results are shown in Figure 11.

Summary table and classifications

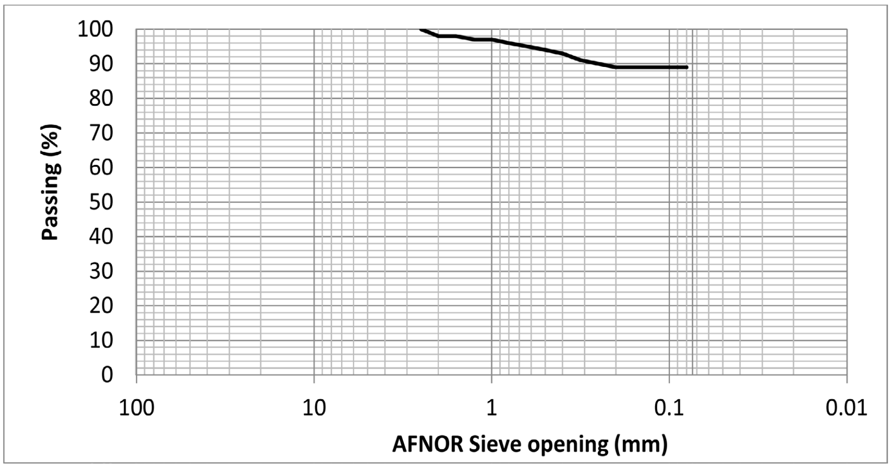


Figure 4. Illustrative curve for clay soils (with nearly 90% of the clay fraction and less than 10% of the grainy or gravels fraction).

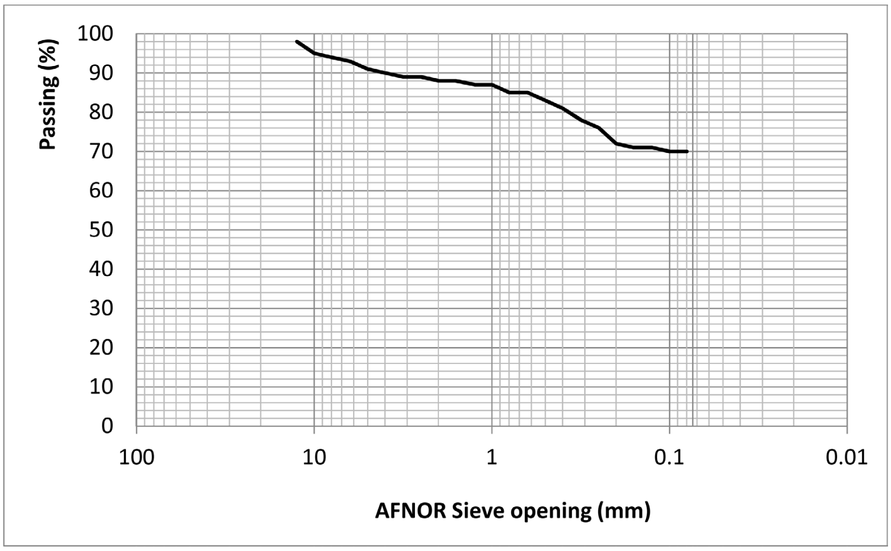


Figure 5. Illustrative curve for clay-gravels soils (with 70% of the clay fraction and 30% of the grainy or gravels fraction).

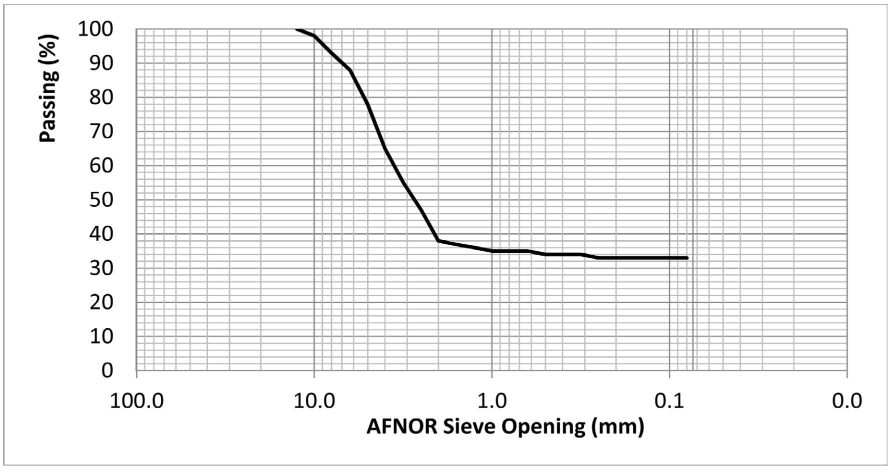


Figure 6. Illustrative curve of lateritic gravels (with more than 50% of the gravels fraction and around 30% of the fine fraction).

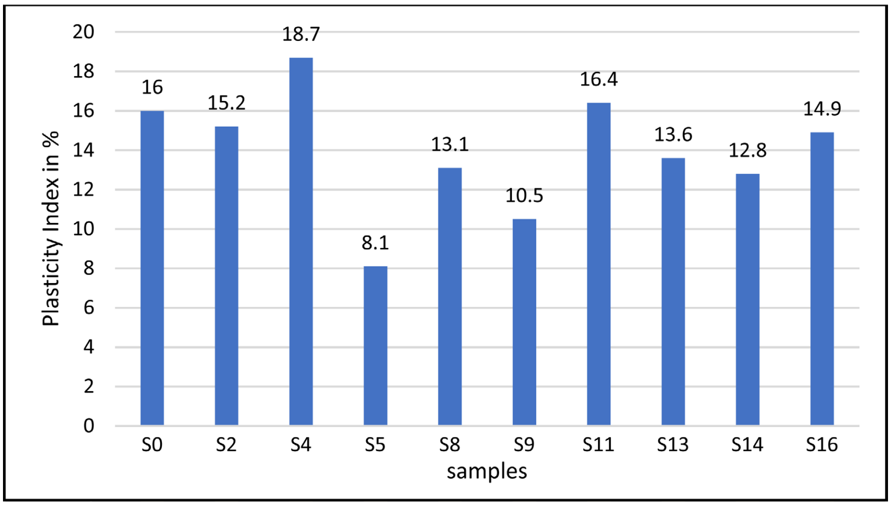


Figure 7. Plasticity index values for the soil facies encountered.

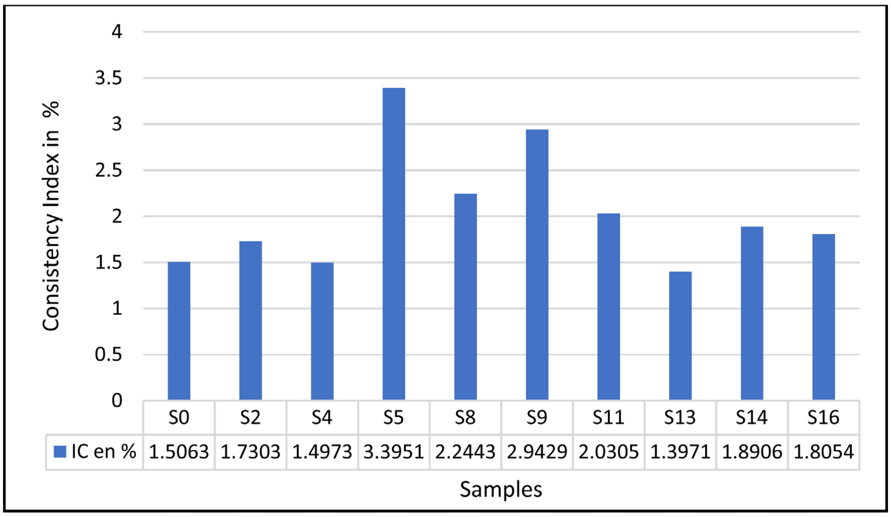


Figure 8. Consistency index values for the facies of the soils encountered Compaction and load-bearing tests.

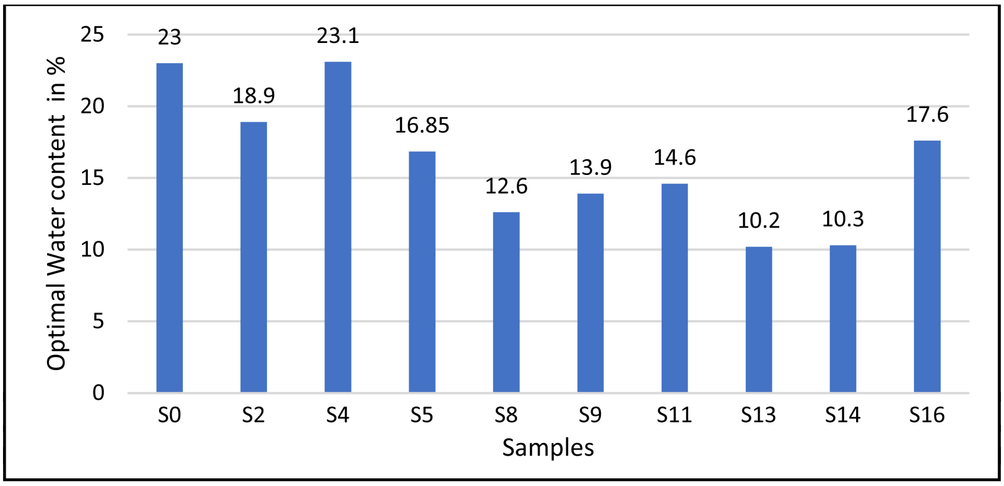


Figure 9. Optimal water content values for the soil facies encountered.

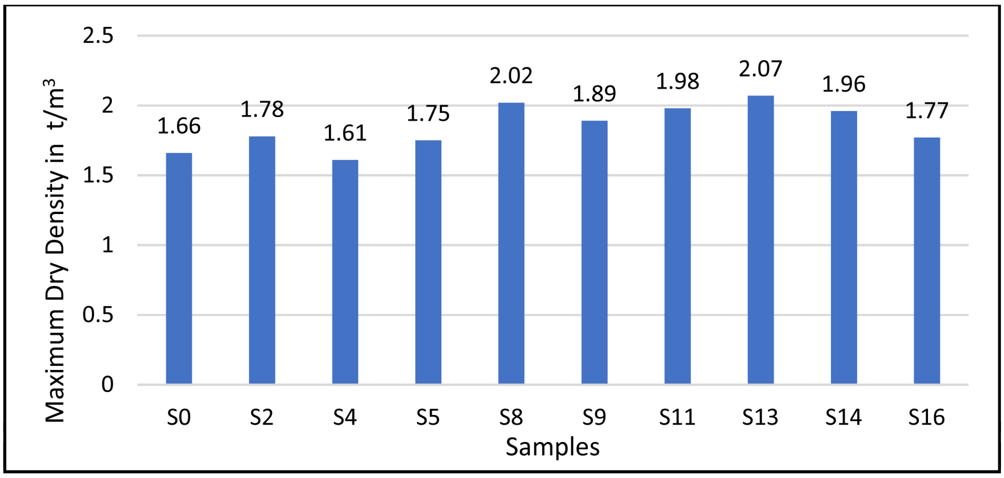


Figure 10. Maximum dry density values for the soil facies encountered.

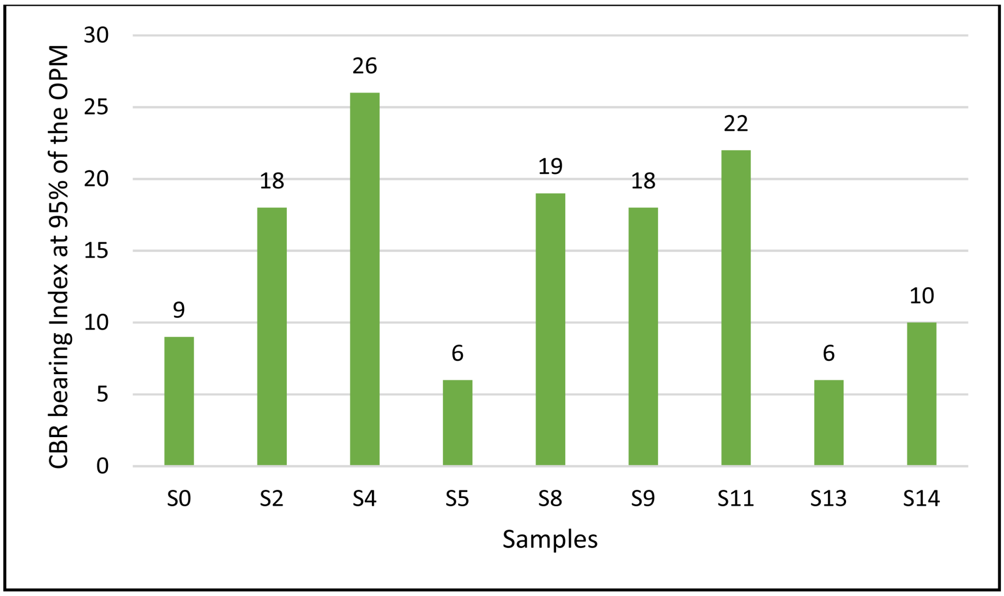


Figure 11. CBR bearing index values along the road route.

Table 7 below describes all the parameters studied for the soils of Songololo, as well as the classifications formulated according to the HRB and NRC (Zairian Road Design) standards. Table 8, for its part, summarizes the different results obtained during the geotechnical tests carried out on the lateritic gravelly materials studied, which materials must be used as backfill.

5. Discussions

With a 58,385 km network of priority roads, including 2,801 km of asphalt roads (4.8%) and 55,584 km of earth roads (95.6%) (Bukome & Kingoma, 2002), it is necessarily imperative to study and characterise the geological materials closest to the main roads, with the aim of better understanding their possible use in future projects. Laterites, because of their geographical distribution in the west, north and south of the Democratic Republic of Congo (Van Ganse, 1957), are of vital interest among the road materials to be studied.

Table 7. Summary of platform soil surveys on the Songololo-Lufu road.

PK	0 + 700	2 + 700	4 + 700	5 + 700	8 + 700	9 + 000	11 + 400	13 + 000	14 + 700	16 + 700
Survey	S0	S2	S4	S5	S8	S9	S11	S13	S14	S16
Sample	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Depth (m)	0.12 - 0.31	0.05 - 0.29	0.10 - 0.30	0.15 - 0.30	0.00 - 0.30	0.25 - 0.48	0.00 - 0.27	0.10 - 0.30	0.16 - 0.43	0.20 - 0.41
Nature of materials	Clay	Clay	Clay	Clay	Lateritic Gravel	Lateritic Gravel	Gritty clay	Gritty clay	Clay	Clay
Identification										
Natural W%	17.3	13.6	15.8	7.3	9.4	5.7	11.5	8.7	16.8	11.7
Ø maximal (mm)	2.5	2.5	2	8	16	10	12.5	20	1.6	5
Fines (%)	89	86	86	70	33	17	59	70	87	78
Liquidity limit	41.9	39.9	43.7	34.8	38.8	36.6	44.8	27.7	41	38.6
Plastic Index	16.5	15.2	18.6	8.1	13.1	10.5	16.4	13.6	12.8	14.9
Compaction										
W opt. (%)	22.6	18.9	23.1	16.9	12.6	13.9	14.6	10.2	10.3	17.6
γd max. (t/m^3)	1.66	1.78	1.61	1.75	2.02	1.89	1.98	2.07	1.96	1.77
Lift										
γd a 95% OPM (t/m^3)	1.58	1.69	1.53	1.66	1.92	1.72	1.88	1.96	1.86	1.68
CBR at 95% OPM 4 days of immersion.	9	18	26	6	19	18	22	6	10	7
Classifications										
NRC	Ae2	Ae1	Ae2	Ae1	GL3	GL1	Ae1	Ae1	Ae1	Ae1
HRB	A-7-6(11)	A-6(10)	A-7-6(12)	A-7-6(6)	A-2-6(1)	A-2-6(0)	A-7-6(8)	A-6(8)	A-7-6(11)	A-6(10)

Table 8. Geotechnical characteristics of lateritic gravels materials along the Songololo-Lufu axis.

PK	2 + 400 D	2 + 700 D	5 + 650 G	7 + 500 G	7 + 500 D	13 + 300 D	13 + 300 G	5 + 600 D
Survey	S00	S01	S02	S03	S04	S05	S06	S07
Depth (m)	0.20 - 2.00	1.20 - 2.00	0.20 - 1.60	0.20 - 3.50	0.20 - 2.00	0.70 - 1.00	0.50 - 2.00	0.20 - 2.60
Identification								
Natural W%	13.3	11.5	7.9	8.1	10.7	13.4	12	4.6
Ø maximal (mm)	12.5	25	25	25	31.5	25	25	31.5
Fines (%)	33	29	8	11	14	23	29	25
Liquidity limit	40.6	40.0	36.6	33.5	45.5	36.9	42.3	39.6
Plasticity Index	16.2	16.4	14.9	7.8	17.8	9.8	16.1	10.5
Compaction								
W opt. (%)	13.8	14.5	11.8	9.8	13.3	11.5	12	12.4
γd max. (t/m^3)	2.00	1.96	2.12	2.13	2.20	2.14	2.06	2.09
Lift								
γd a 95% OPM (t/m^3)	1.90	1.86	2.01	2.02	2.09	2.03	1.86	1.99
CBR at 95% OPM 4 days of immersion.	72	26	35	72	82	27	30	43
Classifications								
NRC	GL2	GL2	GL1	GL1	GL1	GL2	GL2	GL2
HRB	A-2-6(1)	A-2-6(1)	A-2-6(1)	A-2-4(0)	A-2-7(0)	A-2-4(0)	A-2-7(0)	A-2-6(0)

For the results of the Granulometric Analysis, the clay fraction almost always includes between 70% to 90% soil on all the clay facies samples analysed; the grainy fraction represents less than 10% in clay samples and between 10% and 30% in gravelly clays. For lateritic gravelly soils, the percentage of fine elements varies between 35% and 15%; in sand around 20%; the gravelly fraction represents 40% to 50% of the soil. The last kilometres of the axis studied are represented by predominantly clayey soil. The proportion of fine elements is between 60 and 87%; sandy particles between 15% and 20%; the gravelly fraction around 10% of the soil.

The uniformity coefficient as well as the curvature coefficient of the different soils analysed cannot be obtained because the different curves do not go below 20%.

After obtaining the Atterberg limits, we can see that the majority of soil facies encountered define a plasticity index for soils that are not very plastic (with a plasticity index less than 15. However, the predominantly clayey facies are more plastic (represented by the first samples), and the plasticity index decreases towards less plastic soils for soils comprising a granular or gravel fraction.

All soil facies encountered have a consistency index greater than 1, both for clayey soils and for grainy and gravelly soils. The consistency index varying from

1.5 to more than 3, this indicates a solid state of soil, less subject to plastic deformation.

After Proctor test, the values of the optimal water content (wopm) obtained oscillate between 10.2% and 23.10%; which demonstrates a significant absorption capacity of these soils because the usual values vary from 5% to 12% (Issiakou et al., 2015). Optimal dry densities (γopm) are between 1.66 and 2.07 t/m^3.

For the CBR test, we started from the principle that the platform soil must have a CBR index of at least 5 (CEBTP, 1984). By analysing the frequency of values obtained along the road route, we have fluctuating values between 6 and 26. The lowest values observed around clays at more than 80% of the fine fraction, and the highest values observed around more gravelly soil profiles.

The classification according to the Congolese Road Standard (NRC) established by the Zairian Road Design (1982) defines for these soils the types Ae1 and Ae2 for clayey soils and the types GL1 and GL2 for gravelly soils. Ae types characterize clays of sedimentary origin but also some clays of surface alteration. GL Types, for their part, are specifically characteristic of lateritic gravels, and highlight a significant proportion of the fine fraction of the soil, generally greater than or equal to 20%.

The classification according to HRB (Highway Research Board) defines for platform soil, classes and subclasses A-6 and A-7-6 for clayey soils, as well as subclass A-2-6 for gravels soils.

Geotechnical studies of the platform soil show us that the road rests mainly on clay soil for more than ten kilometres. However, these soil facies encountered present heterogeneous values of the parameters studied from one point to another. To correct these specific aspects of the issue, the use of a subgrade layer of lateritic gravel is recommended as a remedy all along the road route. This latter material has several significant advantages through this study: the parameters studied so far establish satisfactory results at platform ground level, but also, it can be exploited on site, thus minimizing the cost of transport and treatment.

For roads built in tropical environments, CEBTP (1984) recommends a CBR index greater than or equal to 10 when using lateritic gravel as backfill or subgrade; the percentage of fine elements must not exceed 35%, with a plasticity index less than 20, for roads which could be used by heavy machinery. The minimum dry density required is 1.8 to 2 t/m^3 depending on traffic.

For the lateritic gravelly materials of the Songololo region, the percentage of fine elements generally remains between 12 and 31%; the plasticity index is between 8 and 18; the optimal dry density is around 2 t/m^3; the optimal water content is between 9.8% and 14.5% and the CBR index is between 27 and 82.

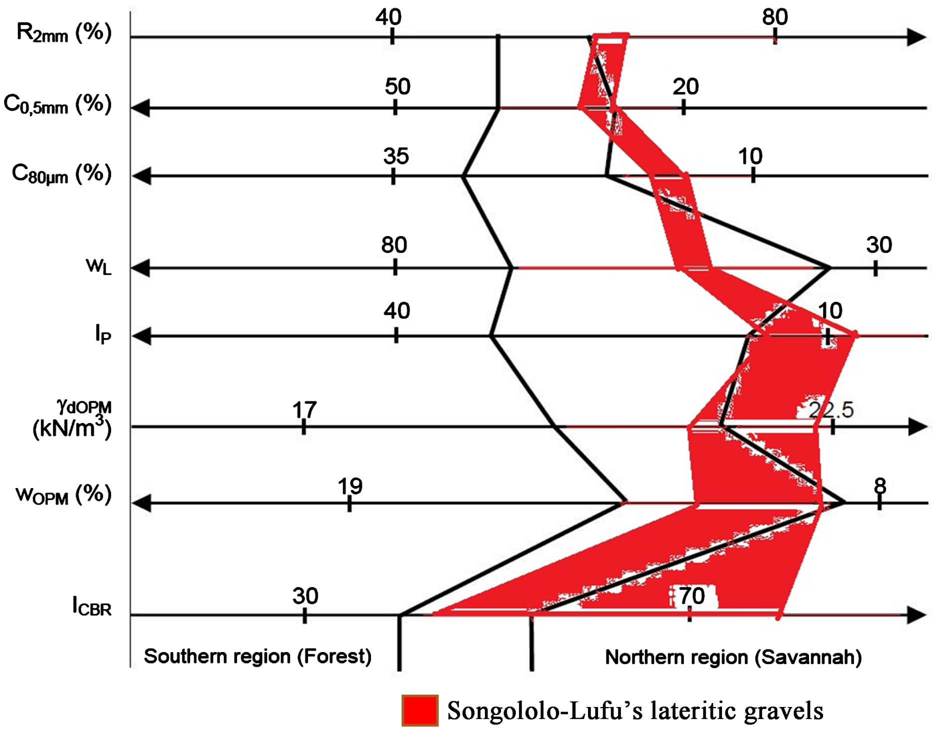
Analysis of the subgrade soil enables us to identify it as falling into classes S2 and S4 on the basis of their CBR of between 6 and 26 (CEBTP, 1984). The laterites studied here can therefore be used as a surfacing layer, base layer or sub-base layer for class T1 and T2 traffic, i.e. daily traffic of up to 1000 vehicles, 30% of which are heavy goods vehicles (CEBTP, 1984).

Songololo laterites can also be used as a base or sub-base course for class T3 and T4 traffic; this refers to daily traffic of between 1000 and 6000 vehicles, assuming that 30% of the vehicles are heavy goods vehicles (CEBTP, 1984).

A diagram was established (**Figure 12**) for the laterites of the Democratic Republic of Congo, geographically distributing the laterites of forest regions from those of savannah regions (quoted by Bohi, 2008). Said classification relates to the percentage of refusals at the 2 mm sieve, the percentage of passing the 0.5 mm and 80 μ sieve, the liquidity limit, the plasticity index, the optimal dry density, the water content optimal and the CBR index.

The lateritic gravels of Songololo would be found between the intermediate range and that characteristic of the laterites of the savannah region, characterized by a significant gravelly fraction to the detriment of the fine fraction, but low parameters such as the liquidity limit or the index of plasticity.

Lateritic soils have been the subject of numerous studies for their use in the construction of roads and tracks in Africa (Lawane et al., 2011). If we must cite only a few examples: the Agneby laterites in Ivory Coast are characterized by a fine fraction of between 20% and 26%, an average maximum dry density of between 2.1 to 2.2 t/m^3, a plasticity index varying from 20 to 25 and an average CBR index between 23 and 25 (Bohi, 2008). The Dosso laterites in Niger show a range of values around 17.24% of the fine fraction, a density average maximum dryness of 1.79; the average CBR index being 22, with an average plasticity index of 12.98. In addition, average CBR index values are 25 for the laterites from



Empirical relationship: $ICBR = 0.44\ [(R2mm - 30) - (C80\mu m - 10) - (IP - 10)] + 47.5$

Figure 12. Geotechnical identification diagram of lateritic gravel proposed by the Democratic Congo studies (taken from Bohi, 2008).

Kélo-Pala in Chad (Hassaballah et al., 2019); these values are more important at the height of 58 for the laterites from Avlamé in Benin (Ahouetohou, 2021) and the different granular fractions vary from one region to another; they vary between 8.4% and 42.1% for the laterites of Mbé in Cameroon (Darman et al., 2022) and on average from 5% to 30% for the laterites of Burkina Faso (Bohi, 2008).

Figure 13, however, shows us the evolution of the values of the CBR index in some laterites studied in Africa, in particular for their use as road aggregate for the foundation layer.

These CBR index values differ enormously from one region to another, which could suggest that this can be influenced by several other parameters, particularly linked to the conditions of their formations or their placement on the surface. However, these materials have always been used in the road sector, and the CBR index of most of these laterites have always shown more than appreciable use values.

6. Conclusion

The properties of lateritic soils are complex and cannot be described in a completely coherent manner. Laterites with the same geotechnical characteristics can differ greatly in their chemical composition and vice versa. No correlation can therefore be made at this stage to characterize the laterites studied in the different regions of Africa. However, one aspect is observed which remains no less significant in the characterization of these materials: they constitute an excellent subgrade for roads and can be sufficiently exploited in construction. However, these materials require improvement when used for the upper layers of the roadway, and the lateritic gravels of Songololo-Lufu are no exception.

Thus, to carry out this road project, the soil in place, essentially clayey and lateritic in nature, showed us acceptable geotechnical characteristics for the

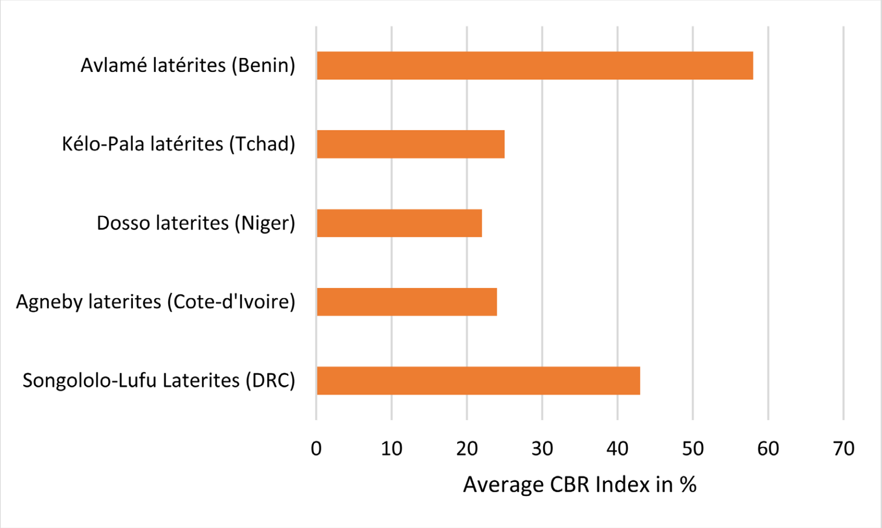


Figure 13. Average CBR Index values of some laterites studied in Africa.

development of the subgrade. The soil compactness index identifies it as semi-solid soil. Lateritic gravel can therefore be used as a foundation layer; the standards characterizing them have defined sufficient parameters for its use.

The state of the DRC's priority roads has not really improved in recent years, despite a number of projects launched to interconnect the various provinces. A number of constraints are often cited in connection with the enormous task of road projects in the provinces, notably the availability, use and delivery of crushed road aggregates or bitumen. Laterites, which are nevertheless available, both in quantity and quality, are therefore an indispensable palliative for the proper maintenance of priority roads in this immense country-continent.

Conflicts of Interest

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

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