Scientific Research Publishing

Engineering, 2026, 18(2), 51-75
https://www.scirp.org/journal/eng
ISSN Online: 1947-394X
ISSN Print: 1947-3931

# Definition of Specifications for Use in Pavement Course of Lithostabilized and Cement-Treated Fine Lateritic Soil in the South of Benin

**Crespin Prudence Yabi[1], Olawolé Eddy Joris Affo[2], Ghildas Raoul Sekloka[2], Mohamed Gibigaye[2]**

[1]Laboratory of Studies and Tests in Civil Engineering (L2EGC), National University of Sciences, Technologies, Engineering and Mathematics, Abomey, Benin
[2]Laboratory of Applied Energetic and Mechanic (LEMA), University of Abomey-Calavi, Abomey-Calavi, Benin
Email: yabi.crespin@unstim.bj, affojoris@gmail.com, sekloka80@yahoo.fr, mohamed.gibigaye@uac.bj

**How to cite this paper:** Yabi, C.P., Affo, O.E.J., Sekloka, G.R. and Gibigaye, M. (2026) Definition of Specifications for Use in Pavement Course of Lithostabilized and Cement-Treated Fine Lateritic Soil in the South of Benin. *Engineering*, **18**, 51-75.
https://doi.org/10.4236/eng.2026.182005

**Received:** December 20, 2025
**Accepted:** February 6, 2026
**Published:** February 9, 2026



## Abstract

Road construction is expensive for governments, especially if road materials are dwindling in the project area, as is the case in southern Benin. The solution of lithostabilizing the soil with lagoon sand cannot be implemented without specifications for monitoring its execution. This study aims to define a set of specifications for the use of litho-stabilized bar soil and cement-improved litho-stabilized clay soil in roadway pavement layers. To achieve this objective, a statistical analysis of data from previous formulations is first conducted to identify specifications of the composites suitable for use in the base course. Secondly, two additional formulations are produced for which the range of compaction water content based on Proctor points around $W_{OPM}$, is researched. These analyses revealed that the fine lateritic soil materials suitable for litho-stabilization are classified as I2 according to the GTR 2023 classification, with an average plasticity index ranging from 22 to 27 and a percentage of fines particles between 30% and 45%. For use in sub-base courses, the composite obtained should generally have a plasticity index of at least 20, a fines particles percentage of at least 30%, and a grading curve range is found in the present study. The litho-stabilized soil composite is suited for T1, T2, and T3 traffic categories (CEBTP classification). For its application, the compaction water range should be in the interval [0.90 OMC; 1.20 OMC]. As a base course, the material should be improved with a cement content of 3.5% to 4%. It is intended for traffic categories below T5 (according to NF P98-086). These results confirm the relevance of litho-stabilization on bar soil and the use of the composites derived from it for low and moderate traffic in pavement base courses.

**Keywords**

Specifications, Fine Lateritic Soil, Litho-Stabilization, Cement Improvement, Sub-Base, Base Course

## 1. Introduction

Roads are the main transportation infrastructure worldwide, especially in tropical Africa, where they account for more than 90% of transportation means [1] [2]. Their construction requires large quantities of materials. The materials commonly used for road construction in tropical areas are generally of lateritic gravel [3]-[5] and silty sand [6]. However, in Benin, these valuable materials are becoming scarce, especially in the southern region [6] [7]. Several studies have shown the abundant availability of fine lateritic soil (clayey sand), also known as *bar earth*, in southern Benin [8]-[10]. However, due to their high plasticity, fine content, and load-bearing capacity, these soils are not used in road pavement layers [11] [12]. Many efforts have focused on improving the characteristics of fine lateritic soil to enable its use as a pavement layer [6] [7] [13]-[15]. For example, Koti *et al.* [7] proposed a composite made with fine lateritic soil and Oil Palm Kernel Shell (OPKS). Most improvement proposals involved using lagoon sand [16] [17], crushed sands [18], gravel, and crushed gravel [13]. These studies concluded that this litho-stabilized composite has sufficient load-bearing capacity to be used as a pavement layer, either in its natural state or after treatment.

Despite the numerous studies conducted on fine lateritic soils, their practical application remains contingent upon the establishment of clear and precise specifications. Such specifications are essential to facilitate the approval of materials and ensure proper oversight during their implementation. Within the various guidelines utilized for road construction in tropical Africa, soils with well-defined specifications are generally lateritic gravels [19] [20]. The pavement design guide used in Senegal provides specifications specifically for litho-stabilized soils [21]. However, these standards pertain exclusively to litho-stabilized lateritic gravels and do not address fine lateritic soils. Therefore, it is imperative to define the approval and implementation specifications for the bar earth that has been litho-stabilized with either lagoon sand or crushed sand.

The objective of this study is to establish these specifications. To this end, the initial phase involves conducting statistical analyses based on data obtained from the work of Sekloka [17]. More specifically, this statistical assessment aims to identify the suitability parameters of the litho-stabilized material, determine the optimal grading envelope, and set forth the minimum performance characteristics required for use in sub-base or base course applications. Subsequently, a formulation will be developed to examine the optimal range of compaction water content for these materials.

## 2. Material and Method Framework

### 2.1. Presentation of Materials, Fine Lateritic Soil, and the Sand

In this study, the materials used are those characterized and formulated in the thesis work of Sekloka [6] [17]. To summarize, Table 1 presents the basic materials used for lithostabilization.

Table 1. Presentation of type, provenance, and designation of materials used for the study

| Type of Materials | Designation (Code) | Origin | | | |
|---|---|---|---|---|---|
| | | Locality | Municipality | coordinates | Formulation |
| Fine Lateritic soil | **FLS** | Sodohomey | Bohicon | - Lat: 7˚9'44.6004"Nord<br>- Long: 2˚4'51.59496"Est | 11 |
| Fine Lateritic soil | **FLA** | Sissekpa | Avrankou | -Lat: 6˚43'26.96"Nord<br>- Long: 2˚17'27.88 Est | 2 |
| Fine Lateritic soil | **FLV** | Savi | Ouidah | - Lat: 6˚27'42"Nord<br>- Long: 2˚04'29.50 Est | 5 |
| Fine Lateritic soil | **FLD** | Kpoha | Dogbo | - Lat: 06˚45'31.38"Nord<br>-Long: 01˚46'06.89"Est | 5 |
| Fine Lateritic soil | **FLK** | Awai | Kétou | - Lat: 07˚24'8.49"Nord<br>-Long: 02˚37'35.68"Est | 11 |
| River sand | **RSZ** | Ahlan | Zagnanado | - Lat: 7˚13'28.57404"Nord<br>- Long: 2˚28'4.84788 Est | |
| Lagoon Sand | **SLM** | Missessin | Abomey-Calavi | - Lat: 6˚31'15.92328"Nord<br>- Long: 2˚22'20.83692"Est | |
| Lagoon Sand | **LSH** | Hedomey | Abomey-Calavi | - Lat: 06˚21'57.76"Nord<br>-Long: 02˚17'59.42"Est | |
| Crushed Sand | **CSA** | Adjohoué | Lokossa | - Lat: 06˚42'34.35"Nord<br>-Long: 01˚38'38.18"Est | |
| Crushed Sand 0/5 | **CS 0/5** | Dan | Djidja | -Lat: 7˚22'6.25044"Nord<br>- Long: 2˚7'29.62992"Est | |
| **Cement CEM I 42.5** | -- | -- | -- | | |
| **Cement CEM II 32.5** | | -- | -- | - | |

### 2.2. Statistical Analysis of Data

The first step of this study involved a statistical analysis of data based on previous formulation studies of litho-stabilized fine lateritic soil. We reviewed the studies [17], which were the most comprehensive in terms of usable data and extracted the results of their formulations. In total, we collected thirty-four (34) formulations, distributed as in Figure 1 who show the overview of fine lateritic soil sampling sites.

For each formulated mixture, the properties of the used fine lateritic soil and the properties of the resulting litho-stabilized composite are focused. After creating this database in Microsoft Excel, we conducted a descriptive statistical analysis of the data to extract central tendency measures and other useful data, which are presented in the rest of this study.

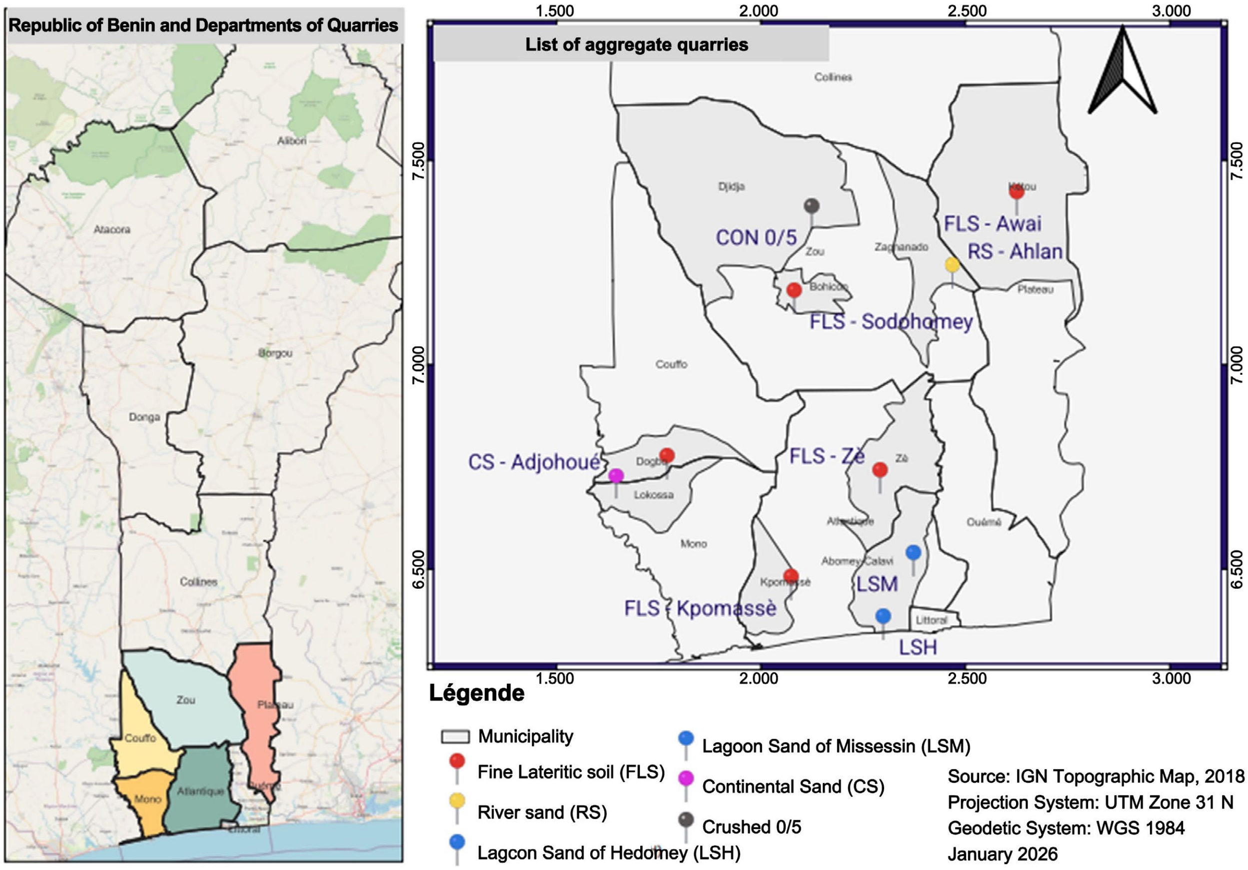


**Figure 1.** Overview of the fine lateritic soil sampling sites.

### 2.2.1. Influence of the Natural Properties of Fine Lateritic Soil on the Litho-Stabilization Process

For this step, we based our approach on the principle that the natural properties of fine lateritic soil—which allow for distinguishing different profiles of fine lateritic soil and are likely to influence the CBR value of the composite obtained after the litho-stabilization process—are the plasticity index and the percentage of fines.

In reference to the GTR 2000 and 2023 standards, the explored fine lateritic soil (clayey sand) was classified into the following categories as presented in Table 2.

**Table 2.** Properties of the fine lateritic soil used.

| Mixtures associated | Properties of the fine lateritic soil Used | | | | | Number of mixtures |
|---|---|---|---|---|---|---|
| | Class | PI | fines | CBR 95% OPM | GTR class | |
| 43RSZ + 57FLS | | | | | | |
| 36RSZ + 64FLS | | | | | | |
| 51RSZ + 49FLS | **2** | **21** | **69** | **22** | **A2** | 10 |
| 57RSZ + 43FLS | | | | | | |
| 63RSZ + 37FLS | | | | | | |

**Continued**

| | | | | | | |
|---|---|---|---|---|---|---|
| 55CS 0/5 + 45FLS | | | | | | |
| 36CS 0/5 + 64FLS | | | | | | |
| 46CS 0/5 + 54FLS | | | | | | |
| 63CS 0/5 + 37FLS | | | | | | |
| 70CS 0/5 + 30FLS | | | | | | |
| 74RSZ + 26FLS | **2** | **20** | **47** | **24** | **A2** | 1 |
| 53RSZ + 47FLK | **2** | **21** | **56** | **25** | **A2** | 10 |
| 36RSZ + 64FLK | | | | | | |
| 42RSZ + 58FLK | | | | | | |
| 48RSZ + 52FLK | | | | | | |
| 58RSZ + 42FLK | | | | | | |
| 55CS 0/5 + 45FLK | | | | | | |
| 38CS 0/5 + 62FLK | | | | | | |
| 44CS 0/5 + 56FLK | | | | | | |
| 49CS 0/5 + 51FLK | | | | | | |
| 60CS 0/5 + 40FLK | | | | | | |
| 75LSH + 25FLV | **2** | **25** | **46.8** | **15** | **A2** | 1 |
| 39CS 0/5 + 61FLA | **3** | **28** | **48.8** | **15** | **A3** | 1 |
| 58CSA + 42FLD | **3** | **27** | **41.9** | **15** | **A1** | 5 |
| 38CSA + 62TB | | | | | | |
| 44CSA + 56FLD | | | | | | |
| 49CSA + 51FLS | | | | | | |
| 53CSA + 47FLD | | | | | | |
| 42CS 0/5 + 58FLA | **5** | **26** | **35** | **21** | **B6** | 1 |
| 53RSZ + 47FLV | **5** | **24** | **32.4** | **17** | **B5** | 5 |
| 35RSZ + 65FLV | | | | | | |
| 42RSZ + 58FLV | | | | | | |
| 47RSZ + 53FLV | | | | | | |
| 59RSZ + 41FLV | | | | | | |

The dataset characteristics are described below, if the threshold values of GTR guide [22] are used:

**Class 2: PI ϵ [12; 22] and fines ≥ 35%** **Effectif = 21**

**Class 3: PI ϵ ]22; 40] and fines ≥ 35%** **Effectif = 7**

**Class 5: PI ≥ 12 and fines ≤ 35%** **Effectif = 6**

For each clay soil identified above, corresponding mixtures are associated. We extract the properties shown in Table 3 of the resulting litho-stabilized fine lateritic soil composite ($FL_{Li}$): composite plasticity index (PI), percentage of fines, proportion of corrective additive, GTR class, and CBR value at 95% OMC (Optimum Moisture Content).

Table 3. Properties of the resulting litho-stabilized composite.

| Properties of the Litho-Stabilized Composite Obtained | | | | | |
|---|---|---|---|---|---|
| Composite | PI $FL_{Li}$ | Fines $TB_{Li}$ (%) | CBR 95% OMC $FL_{Li}$ | Class GTR $FL_{Li}$ | Soil added |
| 43RSZ + 57FLS | 15 | 39.74 | 32 | B6 | Sand |
| 36RSZ + 64FLS | 16 | 45 | 30 | A2 | Sand |
| 51RSZ + 49FLS | 18 | 34.96 | 44 | B6 | Sand |
| 57RSZ + 43FLS | 15 | 30.63 | 38 | B6 | Sand |
| 63RSZ + 37FLS | 15 | 26.7 | 41 | B6 | Sand |
| 55CS 0/5 + 45FLS | 14 | 32.86 | 37 | B6 | Crushed sand |
| 36CS 0/5 + 64FLS | 15 | 45.22 | 25 | A2 | Crushed sand |
| 46CS 0/5 + 54FLS | 15 | 38.58 | 29 | A2 | Crushed sand |
| 63CS 0/5 + 37FLS | 13 | 27.9 | 51 | B6 | Crushed sand |
| 70CS 0/5 + 30FLS | 13 | 23.6 | 55 | B6 | Crushed sand |
| 74RSZ + 26FLS | 17 | 12.3 | 49 | B6 | Sand |
| 53RSZ + 47FLK | 10.3 | 24 | 35 | B5 | Sand |
| 36RSZ + 64FLK | 18 | 29 | 29 | B6 | Sand |
| 42RSZ + 58FLK | 16 | 30 | 33 | B6 | Sand |
| 48RSZ + 52FLK | 16.1 | 27 | 35 | B6 | Sand |
| 58RSZ + 42FLK | 10.4 | 21 | 39 | B5 | Sand |
| 55CS 0/5 + 45FLK | 20.4 | 31 | 43 | B6 | Crushed sand |
| 38CS 0/5 + 62FLK | 22.1 | 37 | 31 | A2 | Crushed sand |
| 44CS 0/5 + 56FLK | 21.3 | 36 | 36 | A2 | Crushed sand |
| 49CS 0/5 + 51FLK | 21.1 | 34 | 38 | B6 | Crushed sand |
| 60CS 0/5 + 40FLK | 20.5 | 30 | 55 | B6 | Crushed sand |
| 75LSH + 25FLV | 5 | 9.75 | 11 | B1 | Sand |
| 39CS 0/5 + 61FLA | 20 | 30.39 | 23 | B6 | Crushed sand |
| 58CSA + 42FLD | 9 | 19.5 | 42 | B5 | Sand |
| 38CSA + 62TB | 17 | 27.3 | 28 | B6 | Sand |
| 44CSA + 56FLD | 20 | 25.2 | 30 | B6 | Sand |
| 49CSA + 51FLS | 17 | 23.7 | 34 | B6 | Sand |
| 53CSA + 47FLD | 13 | 22.2 | 36 | B6 | Sand |
| 42CS 0/5 + 58FLA | 18 | 25.7 | 33 | B6 | Crushed sand |
| 53RSZ + 47FLV | 12 | 17.23 | 43 | B6 | Sand |
| 35RSZ + 65FLV | 21 | 22.61 | 37 | B6 | Sand |
| 42RSZ + 58FLV | 20 | 20.1 | 38 | B6 | Sand |
| 47RSZ + 53FLV | 21 | 19.26 | 41 | B6 | Sand |
| 59RSZ + 41FLV | 7 | 15.4 | 25 | B6 | Sand |

The following quantities are used for the analysis: the reduction ratio of the PI according to the soil class of the lateritic fine soil, the reduction ratio of fines according to the soil class of the lateritic fine soil, the increase ratio of the CBR according to the soil class of the lateritic fine soil, and the proportion of the additive corrector.

They are expressed as follows:

$$\text{Gain CBR} = (\text{ICBR FL}_{\text{Li}} - \text{ICBR FL})/\text{ICBR FL}$$

$$\text{Reduction PI} = (\text{PI FL}_{\text{Li}} - \text{PI FL})/\text{PI FL}$$

$$\text{Reduction fines} = (\text{Fines FL}_{\text{Li}} - \text{Fines FL})/\text{Fines FL}$$

where:

FL: is the fine lateritic soil and

$FL_{Li}$; is the stabilized litho-composite obtained.

After calculations, we obtained for each of the thirty-four (34) formulated composites, in order, the following values of variations properties during litho-stabilization as shown in Table 4:

Table 4. Observed variations during litho-stabilization.

| | Variations observed | | |
|---|---|---|---|
| Mixtures associated | Reduction of PI | Reduction of fines | Gain CBR |
| 43RSZ + 57FLS | −29% | −42% | 45% |
| 36RSZ + 64FLS | −24% | −35% | 36% |
| 51RSZ + 49FLS | −14% | −49% | 100% |
| 57RSZ + 43FLS | −29% | −56% | 73% |
| 63RSZ + 37FLS | −29% | −61% | 86% |
| 55CS 0/5 + 45FLS | −33% | −52% | 68% |
| 36CS 0/5 + 64FLS | −29% | −34% | 14% |
| 46CS 0/5 + 54FLS | −29% | −44% | 32% |
| 63CS 0/5 + 37FLS | −38% | −60% | 132% |
| 70CS 0/5 + 30FLS | −38% | −66% | 150% |
| 74RSZ + 26FLS | −15% | −74% | 104% |
| 53RSZ + 47FLK | −51% | −57% | 40% |
| 36RSZ + 64FLK | −14% | −48% | 16% |
| 42RSZ + 58FLK | −24% | −46% | 32% |
| 48RSZ + 52FLK | −23% | −52% | 40% |
| 58RSZ + 42FLK | −50% | −63% | 56% |
| 55CS 0/5 + 45FLK | −3% | −45% | 72% |
| 38CS 0/5 + 62FLK | 5% | −34% | 24% |
| 44CS 0/5 + 56FLK | 1% | −36% | 44% |
| 49CS 0/5 + 51FLK | 0% | −39% | 52% |
| 60CS 0/5 + 40FLK | −2% | −46% | 120% |

**Continued**

| | | | |
|---|---|---|---|
| 75LSH + 25FLV | **−80%** | **−79%** | **−27%** |
| 39CS 0/5 + 61FLA | −29% | −38% | 53% |
| 58CSA + 42FLD | −67% | −53% | 180% |
| 38CSA + 62TB | −37% | −35% | 87% |
| 44CSA + 56FLD | −26% | −40% | 100% |
| 49CSA + 51FLS | −37% | −43% | 127% |
| 53CSA + 47FLD | −52% | −47% | 140% |
| 42CS 0/5 + 58FLA | −31% | −27% | 57% |
| 53RSZ + 47FLV | −50% | −47% | 153% |
| 35RSZ + 65FLV | −13% | −30% | 118% |
| 42RSZ + 58FLV | −17% | −38% | 124% |
| 47RSZ + 53FLV | −13% | −41% | 141% |
| 59RSZ + 41FLV | −71% | −52% | 47% |

It is assumed that the suitability of a clayey material for litho-stabilization can be measured, in principle, based on the gain in CBR. The greater the CBR gain of the material, the better its aptitude for litho-stabilization. The nature parameters of the clayey material favor the CBR gain it exhibits at the end of the litho-stabilization process as well as its interval. For better analysis, the data have been grouped into series classes according to the value of the CBR gain.

According to Yule's rule, for a number $J$ of classes such as:

$$J = 2.5\sqrt[4]{n}\text{ ; } n \text{ is the number of observations. } (n = 34) \text{ and}$$

$$\text{Amplitude} = (\text{Obs Max} - \text{Obs min})/J$$

We have nevertheless noticed that the mixture of 75LSH + 25FLV formulation established according to the compressible stacking model (composed of 75% Laguna sand of Hedomey and 25% clayey material of Savi) shows a regression of the CBR (−27%). It is noticed that the mixtures obtained are composed of more sand than the fine lateritic soil due to the method used to formulate the mixture, which is based on the maximization of the density of the mixture. The percentage of sand is very high for the mixture.

Considering the entire dataset of evaluated CBR gain values, the average is 83.5% with a standard deviation of 44.7%. When applying Grubbs' test to the extreme value (−27, corresponding to the CBR gain associated with the 75LSH + 25FLV mixture), the calculated statistic is G = 2.48. For our sample size of 35, the critical value is Gcrit = 2.3. Since G > Gcrit, the value −27 is identified as a statistically significant outlier according to Grubbs' test.

Indeed, the very low plasticity index value (PI = 5) of the lateritic soil used indicates that we are dealing with a soil of low plasticity and therefore a sandy soil, generally characterized by weak cohesion. This lack of cohesion between the grains of the lateritic soil was further accentuated in the mixture due to the abundance of lagoon sand (75%).

The resulting litho-stabilized composite was both too loose and lacking cohesion, and therefore unable to develop adequate bearing capacity.

This constitutes an outlier value that we have chosen to exclude for the first part of this study. Thus n = 33 and we obtain the following grouping presented in Table 5:

**Table 5.** Classification of data series based on CBR gain.

| Classes | Variations observed | Fine lateritic soil used properties | | | | |
|---|---|---|---|---|---|---|
| | Average Gain CBR (%) | Average addition FL (%) | Average PI FL | Average CBR | Average Fines FL (%) | Headcount |
| **[13.6; 46.9]** | 32.33% | 42.20 | 21.00 | 30.50 | 61.20 | 10 |
| **[46.9; 80.2]** | 59.81% | 51.75 | 22.88 | 34.50 | 52.78 | 8 |
| **[80.2; 113.5]** | 95.44% | 54.00 | 23.20 | 38.40 | 53.76 | 5 |
| **[113.5; 146.7]** | 128.69% | 49.86 | 24.00 | 41.71 | 43.71 | 7 |
| **[146.7; 180.0]** | 160.98% | 60.33 | 24.00 | 46.67 | 47.77 | 3 |

The scatter plots created with each formulation allowed us to identify, in the progression, the type of correlation that exists between the soil PI of the subbase and the CBR gain variable on one hand, and then the percentage of fines in the subbase soil and the CBR gain variable on the other. Based on the interpretations made, we also identified the threshold values for the PI properties and the fines content of the subbase soil that effectively and sufficiently promote this CBR gain.

#### 2.2.2. Identification of the Ideal Granulometric Band of the Stabilized Litho Composite

For this step, the goal is to find a granulometric band within which usable litho-stabilized composites can be integrated as a foundation layer. For use as a pavement subbase, road materials are primarily selected based on their ICBR value at 95% of the OMC. Three (3) families of litho-stabilized soil-based materials are defined:

Family 1: CBR greater than 35;

Family 2: CBR greather than 30 and less than 35

Family 3: CBR greather than 25 and less than 30

Considering Families 1 and 3, it is observed that several values are not centered around the mean. Thus, for the continuation, these values were removed from the analysis to retain only reliable data per class. Additionally, by filtering our data based on the limiting PI and fines percentage criteria for general use in foundation layers according to CEBTP, the composites retained within this set of three families and suitable for use as foundation layers are presented in Table 6.

We subsequently overlaid the granulometric curves of the litho-stabilized mixtures with the best mechanical performance and the permitted Ip and fines values.

As a result of this analysis, we were able to identify the traffic types for which the use of the composite is feasible.

**Table 6.** Properties of composites usable as foundational/sub-base layer materials.

| CBR | Addition (%) | PI | Fines (%) | Traffic |
|---|---|---|---|---|
| 41 | 63 | 15 | 26.7 | T1 à T5 |
| 42 | 58 | 9 | 19.5 | T1 à T5 |
| 43 | 53 | 12 | 17.23 | T1 à T5 |
| 39 | 58 | 10.4 | 21 | T1 à T5 |
| 36 | 53 | 13 | 22.20 | T1 à T5 |
| 38 | 42 | 20 | 20.1 | T1 à T5 |
| 34 | 49 | 17 | 23.70 | T1 à T3 |
| 35 | 53 | 10.3 | 24.00 | T1 à T3 |
| 35 | 48 | 16.1 | 27.00 | T1 à T3 |
| 33 | 42 | 16 | 30 | T1 à T3 |
| 33 | 42 | 18 | 25.70 | T1 à T3 |
| 29 | 36 | 18 | 29.00 | T1 |
| 30 | 44 | 20 | 25.2 | T1 |
| 28 | 38 | 17 | 27.3 | T1 |

#### 2.2.3. Identification of the Corrector to Achieve the Best Mechanical Performance

Based on a study where litho-stabilization was applied with the same subbase soil but using two different additives, for example, the mixtures RSZ + FLK and CS + FLK we seek to observe, for nearly equal proportions of lagoon sand filler against crushed sand, which one yields the best mechanical performance.

#### 2.2.4. Identification of the Optimal Water Content Range for Compaction

To determine the water content range for applying the material, the various Proctor curves of the mixes developed in the previous studies allowed us to identify the moisture content values that achieve 95% of the maximum dry density of the Proctor test. To set a first reference range, these Proctor moisture content values were expressed as a ratio relative to OMC. We selected the studies for processing based on the precision of the Proctor gradations of their mixes. Table 7 shows the recorded Proctor data and Figure 2 defines the range of water content at 95% around the OMC.

**Table 7.** Proctor test results for the mixtures.

| OMC | $\gamma_{dmax}$ | 0.95 $\gamma_{dmax}$ | $W_{inf}$ | $W_{sup}$ | $W_{inf}$/OMC | $W_{sup}$/OMC | Mixture associated |
|---|---|---|---|---|---|---|---|
| 10.6 | 1.99 | 1.89 | 7.8 | 13 | 0.74 | 1.23 | 64FLS + 36RSZ |
| 10.6 | 1.99 | 1.89 | 7.5 | 14 | 0.71 | 1.32 | 57FLS + 43RSZ |
| 10.6 | 2.01 | 1.91 | 7.5 | 13.5 | 0.71 | 1.27 | 49FLS + 51RSZ |

**Continued**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8.5 | 2.02 | 1.92 | 4.5 | 11.5 | 0.53 | 1.35 | 43FLS + 57RSZ |
| 8.5 | 2.05 | 1.95 | 5 | 11 | 0.59 | 1.29 | 37FLS + 63RSZ |
| 10.6 | 1.96 | 1.86 | 7 | 15 | 0.66 | 1.42 | 64TB + 36CS 0/5 |
| 10.6 | 2.02 | 1.92 | 7.8 | 13 | 0.74 | 1.23 | 54TB + 46CS 0/5 |
| 10.6 | 2 | 1.9 | 7.5 | 13 | 0.71 | 1.23 | 45FLS + 55 CS 0/5 |
| 9.2 | 2.02 | 1.92 | 6 | 12.2 | 0.65 | 1.33 | 37FLS + 63CS 0/5 |
| 9.2 | 2.06 | 1.96 | 6 | 12 | 0.65 | 1.30 | 30FLS + 70CS 0/5 |
| 9.1 | 2.06 | 1.96 | 5 | 12.5 | 0.55 | 1.37 | 64FLV + 35 RSZ |
| 9.9 | 2.05 | 1.95 | 5 | 13 | 0.51 | 1.31 | 58FLV + 42RSZ |
| 10.1 | 2.04 | 1.95 | 6 | 13.8 | 0.59 | 1.37 | 53FLV + 47RSZ |
| 8.8 | 2.06 | 1.96 | 4 | 11.5 | 0.45 | 1.31 | 47FLV + 53RSZ |
| 11 | 2 | 1.9 | 10 | 11.5 | 0.91 | 1.05 | 41FLV + 59RSZ |
| 9.8 | 1.97 | 1.87 | 6.5 | 13 | 0.66 | 1.33 | 62FLD + 38CSA |
| 11 | 1.99 | 1.89 | 5 | 15 | 0.45 | 1.36 | 56FLD + 44CSA |
| 9.5 | 2 | 1.9 | 8 | 10.5 | 0.84 | 1.11 | 51FLD + 49CSA |
| 10.1 | 2 | 1.9 | 9.1 | 11 | 0.90 | 1.09 | 47FLD + 53CSA |
| 10 | 2.01 | 1.95 | 7.2 | 13 | 0.72 | 1.30 | 42FLD + 58CSA |

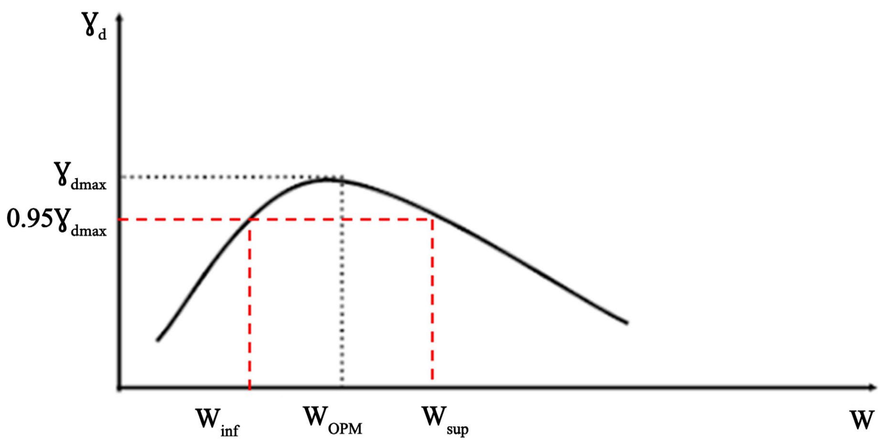


Figure 2. Limit of the water content at 95% around the OMC.

$W_{inf}$ is the water content value read from the Proctor curve before reaching OMC, corresponding to 95% of the maximum dry density $\gamma_{dmax}$.

$W_{sup}$ is the water content value read from the Proctor curve after reaching OMC, corresponding to 95% of $\gamma_{dmax}$.

$W_{inf}$/OMC is the ratio that indicates what proportion of OMC must be reached to achieve 95% of $\gamma_{dmax}$.

$W_{sup}/W_{OPM}$ is the ratio that indicates what proportion of OMC must be reached to achieve 95% of $\gamma_{dmax}$.

Based on the average values observed for the $W_{inf}$/OMC and $W_{sup}$/OMC ratios, we identified the proportion of OMC required to reach 95% of $\gamma_{dmax}$.

Then, a parametric study was conducted by varying the compaction water content around OMC, bounded by the reference range, using a mix of Ouidah fine lateritic soil and crushed Dan sand, followed by a mix with Athiémé lagoon sand that we formulated.

### 2.3. Determination of Compaction Water Content

Two mix designs of litho-stabilized bar soil were prepared, one with the lagoon sand and the other with the crushed sand, to confirm the interpretations. Tests were carried out according to relevant standards Proctor test around 95% of OMC. Before formulating the lithostabilyzed mixtures, the identifications tests are done on constituent material from Ouidah fine lateritic soil (FLO), lagoon sand of Athiémé (LSA), and crushed sand 0/5 of Dan (CSD). The different results are grouped in Table 8.

**Table 8.** Summary of properties of fine lateritic soil of Ouidah and lagoon.

| *Material characteristics* | *Parameter* | *Fine lateritic soil of Ouidah* | *Lagoon sand of Athieme* | *Crushed sand of Dan* |
|---|---|---|---|---|
| **Granulometric analysis** | Dmax | 1.6 mm | | |
| | Passing sieve 0.080 mm | 46.5% | 3.3% | 16.5% |
| | Passing sieve 0.063 mm | 46% | 3.3% | 15.8% |
| **Proctor** | Maximum dry density | 2.28 t/m$^3$ | - | - |
| | $W_{OPM}$ | 15.5% | - | - |
| **Atterberg limits** | $W_L$ | 42 | - | - |
| | $W_P$ | 20 | - | - |
| | PI | 22 | - | - |
| **Bleu value** | VBS | 3.7 | 0.15 | 0.15 |
| **CBR test** | CBR à 95%OPM | 18 | - | - |

We evaluated the proportion of ballast soil and corrective material required to constitute each mixture.

- **Mixture formulation**

To formulate the mixture, the Fuller-Thompson grading curve method presented by Sekloka *et al.* [6] in their work is used.

To design our mixture, it is important to define the optimal proportions of each material that allow for a good granular arrangement and consequently proper compaction. The MEC represents a formulation method based on a solid theoretical framework, aiming to maximize the compactness of the material. However, in our present case, this method would not be relevant to apply since it leads to composites with an excessive proportion of corrective material compared to the lateritic soil. We will therefore proceed with the Talbot method.

$$\frac{P}{100} = \left(\frac{d}{D}\right)^n$$

where:

$P$ = percentage of particles passing through a sieve of mesh size $d$;

$D$ = maximum aggregate size.

If $D$ is fixed, two parameters remain: on the one hand the exponent $n$, and on the other hand the percentage of particles passing through a sieve of mesh size $d$, for example $d$ = 80 μm. In other words, one can fix $D$ and the filler percentage, and then $n$ is determined. Conversely, one can fix $n$. If $n$ = 0.5, we obtain the Fuller curves, which are commonly used for asphalt mixtures. On the contrary, the Talbot curves ($0.11 \le n \le 0.33$), found in certain specifications, correspond to different values of $D$ and $n$, with the percentage of fines varying from one curve to another.

For the mixture with crushed sand, $D$ = 5 mm and $d$ = 0.063 mm

For the mixture fine lateritic soil + crushed sand the reference proportions are: 26%FLO + 74%CS 0/5.

For the mixture fine lateritic soil + lagoon sand the reference proportions are: 27%FLO + 73% LSA.

To respect the context of valorizing the fine lateritic soil, we performed iterations by varying these proportions in the direction where the amount of fine lateritic soil is greater than that of the sand, while always limiting the fines percentage to 30%.

We obtain retained proportions of 55% FLO + 45% CS 0/5 and 55% FLO + 45% LSA. Table 9 presents the identification results of litho-stabilized mixtures.

**Table 9.** Identification results of litho-stabilized mixtures.

| Material characteristics | Scalar | 55FLO + 45LSA | 55FLO + 45CS 0/5 |
|---|---|---|---|
| **Granulometric analysis** | Dmax | 8 mm | 6.3 mm |
| | Passing sieve 0.080 mm | 29.1% | 28.9% |
| | Passing sieve 0.063 mm | 29% | 26% |
| **Proctor** | Maximum dry density | 2.641 t/m³ | 2.56 t/m³ |
| | $W_{OPM}$ | 7.8% | 9.1% |
| **Atterberg limits** | $W_L$ | 35 | 35 |
| | $W_P$ | 17 | 20 |
| | PI | 18 | 15 |
| **Bleu value** | VBS | 0.9 | 0.2 |
| **CBR test** | CBR à 95%OPM | 12 | 28 |

We deduce that the composites formed are Class I2 according to the GTR 2023 classification.

Based on previous studies, we found that litho-stabilized fine lateritic soil could not be used systematically as a base layer. Indeed, it is necessary to subject the material to cement reinforcement in an optimum proportion. In general, the Guide for Soil Treatment (GTS) remains the reference document providing specifications for the use of improved materials. It thus constitutes the applicable specification reference for the litho-stabilized ballast soil reinforced with cement.

We therefore focused primarily on identifying the traffic (uses/applications) for which the cement-reinforced material could be used.

## 3. Results and Discussion

### 3.1. Definition of the Property of Fine Lateritic Soil Suitable for Litho-Stabilization

From the series classes according to the criterion "Gain CBR" previously found, we built the data histogram to assess how the CBR gain properties evolve—PI FL on the one hand and fines FL gain on the other.

- **Analysis of variation of Plasticity Index (PI) per class of gain in CBR**

Figure 3 presents the histogram of the mean Plasticity Index values for different classes of CBR gain. From the data histogram, it is observed that the higher the Plasticity Index, the greater the CBR gain of the ballast soil after litho-stabilization. The estimated correlation coefficient between the CBR gain and the IP of ballast soils is 0.90. This indicates a strong correlation between the two properties. The Plasticity Index thus has a significant influence on the CBR value observed in the litho-stabilized composite at the end of the litho-stabilization process. The histogram shown in Figure 3 illustrates the evolution of the CBR gain according to the plasticity index of the lateritic soil used.

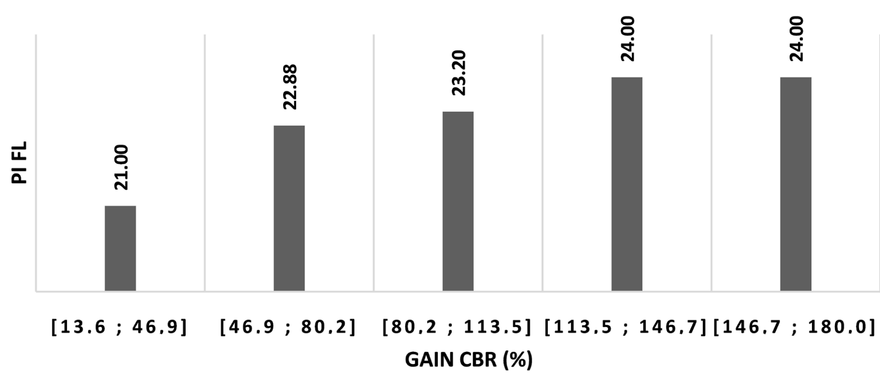


Figure 3. Histogram of Plasticity Index of fine lateritic soil per class of gain of CBR after litho-stabilization.

- **Analysis of variation of fine percentage of Fine lateritic soil per class of gain in CBR**

Figure 4 shows that the lower the fines percentage, the greater the CBR gain. The correlation coefficient between the two properties is as significant as it is because it is −0.85.

Before concluding, let us analyze the behavior of mixtures in the extreme classes: those with the highest CBR gain rates and those with the lowest rates. The confidence interval is defined as the interval of values centered around the mean.

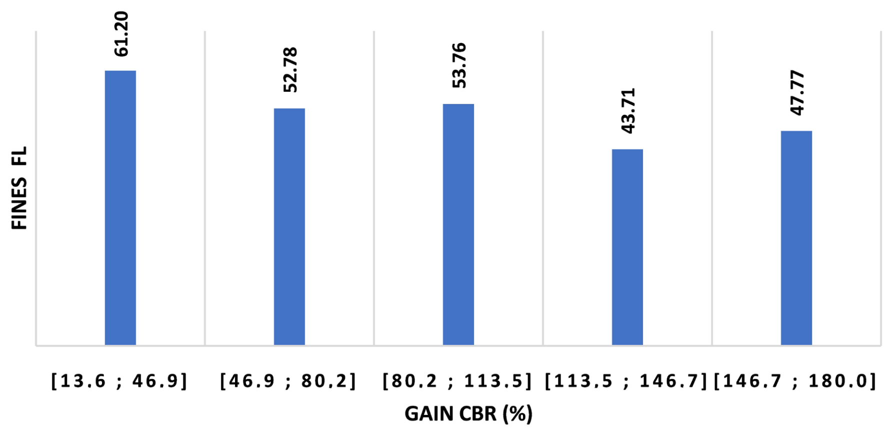


**Figure 4.** Histogram of fines percentage of fine lateritic soil per class of gain of CBR after litho-stabilization.

The class [13.6; 46.9] has a standard deviation of 11% and the ]146.7; 180] has 17%.

This study value range is therefore [21.1%; 43.5%] or ]146.7%; 180%] U ]113.5%; 146.7%]

- **First range of plasticity index [21.1%; 43.5%]**

For data class [21.1%; 43.5%], Table 10 and Table 11 show the fines percentage, the gain in CBR and the plasticity Index for the lithostablized mixture. When considering the class [21.1%; 43.5%], it is observed that the Plasticity Index (PI) of the FL used has an average value of 21 (constant value). In parallel, for the class [113.5%; 178%], the PI has an average value of 23.6.

Regarding the fine percentages, the class [21.1%; 43.5%] has an average value of 60.33, while the class [114%; 178%] has an average value of 45.26. Furthermore, it is noted that to achieve a significant CBR gain, TB materials with a low PI (21) and a high fines percentage require a substantial addition of a corrective (beyond 55%).

Considering the valorization context of ballast soil, these ballast soil profiles therefore do not meet this additional constraint.

**Table 10.** Data class ]21.1%; 43.5%].

| Fines (%) | Gain | Addition (%) | PI |
|---|---|---|---|
| 56 | 24% | 38 | 21 |
| 69 | 32% | 46 | 21 |
| 56 | 32% | 42 | 21 |
| 69 | 36% | 36 | 21 |
| 56 | 40% | 53 | 21 |
| 56 | 40% | 48 | 21 |

- **Third and fourth range of plasticity index [113.5%; 180%]**

**Table 11.** Data class ]146.7%; 180% ] U ]113.5%; 146.7%].

| Fines (%) | Gain | Addition (%) | PI |
|---|---|---|---|
| 32.4 | 118% | 35 | 24 |
| 56 | 120% | 60 | 21 |
| 32.4 | 124% | 42 | 24 |
| 41.9 | 127% | 49 | 27 |
| 69 | 132% | 63 | 21 |
| 41.9 | 140% | 53 | 27 |
| 32.4 | 141% | 47 | 24 |
| 69 | 150% | 70 | 21 |
| 32.4 | 153% | 53 | 24 |

Earlier in our analysis, we noted that the mixture of 75LSH + 25FLV formulation case (PI = 25; fines = 46.8 and CBR gain = −27%) is an exception to the rule. This is due to the high proportion of sand in the mixture. This is due to the large proportion of additive corrector used in this case (75%), resulting from the use of MEC as the formulation method. The litho-stabilized ballast soil composite developed in this study was both too clayey (due to the high plasticity) and had poor water retention capacity, without cohesion between grains (due to the high sand content), leading to increased instability under load.

When considering the formulation of the composite in the TIKO study (PI = 28 and Fines = 48.8), a CBR = 23 is noted with an additional proportion of 39%. The PI value of 28 thus appears to be a threshold plasticity index from which the composite, even when proportions are correct, will have an acceptable CBR gain (here 53%) but still insufficient (not reaching 25).

## 3.2. Specifications of Litho-Stabilized Fine Lateritic Soil

After superposing the granulometric curves of the different composites with sufficient CBR values and acceptable IP and fines percentage, we observe the band within which all the mixtures fit. Figures 5-8 shows the granulometric curve range. The different results of the particle size analysis are summarized in Table 12.

**Table 12.** Grain size analysis results of mixtures suitable for use in foundation layers.

| Tamis | Og 2 | Og 3 | Ker 3 | Og 4 | Adji 1 | Adji 2 | Adji 3 | Tiko 1 | Adji 5 | Adj 2 | Og 2 | Adj 3 | Adj 6 | Ogou1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **14** | | | | | | | | | | | | | | |
| **12.5** | | | | | | | | | | | | | | |
| **10** | 100.0 | 100.0 | 100 | 100.0 | | | | | | | 100 | | | 100 |
| **8** | 99.0 | 99.0 | 99.64 | 100.0 | | | | | | | 99 | | | 99 |
| **6.3** | 99.0 | 99.0 | 98.92 | 99.0 | | | | | | | 99 | | | 99 |
| **5** | 98.0 | 98.0 | 98.45 | 98.0 | 100 | 100 | 100 | 100 | 100 | 100.00 | 98 | 100.00 | 100 | 99.00 |

Continued

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **4** | 98.0 | 98.0 | 97.87 | 98.0 | 100 | 100 | 100 | | 100 | 100.00 | 98 | 100.00 | 100 | 99.00 |
| **3.15** | | | | | 100 | 99.7 | 99.5 | | 100 | 100.00 | | 100.00 | 100 | |
| **2.5** | | | 96.08 | | 100 | 98.8 | 98.9 | | 100 | 100.00 | | 100.00 | 100 | |
| **2** | 95.0 | 94.0 | 94.54 | 98.0 | 99.7 | 98 | 97.9 | 79.2 | 99.4 | 99.50 | 94 | 99.30 | 99.4 | 94.00 |
| **1.63** | | | | | | | | | | | | | | |
| **1.25** | | | 87.26 | | 98.6 | 94.4 | 93.1 | 68.2 | 98.3 | 98.40 | | 96.50 | 98.3 | |
| **1** | 85.0 | 82.0 | 81.69 | 96.0 | 97.6 | 90.4 | 88.6 | | 97.1 | 97.50 | 81 | 93.10 | 97.1 | 84.00 |
| **0.8** | | | | | | | | | | | | | | |
| **0.63** | 68.0 | 62.0 | 63.5 | 82.0 | 91.7 | 77.7 | 72.8 | | 90.9 | 92.00 | 60 | 83.50 | 90.9 | 66.00 |
| **0.5** | | | 52.73 | | 84.5 | 72.1 | 64.5 | | 82.9 | 86.30 | | 76.10 | 82.9 | |
| **0.4** | 48.0 | 39.0 | 42.57 | 53.0 | 70.3 | 60.9 | 56.4 | 48.1 | 66.3 | 75.00 | 36 | 67.60 | 66.3 | 47.00 |
| **0.315** | 41.0 | 32.0 | | 44.0 | 51.3 | 51 | 46.5 | 42.3 | 46 | 57.70 | 29 | 57.30 | 46 | 46.00 |
| **0.25** | | | 32.63 | | 40.6 | 40.1 | 37.2 | | 35.4 | 47.10 | | 47.80 | 35.4 | |
| **0.2** | 31.0 | 24.0 | 30.33 | 37.0 | | 33.75 | 31.6 | | 31.6 | | 21 | | | 40.00 |
| **0.16** | | | 28.94 | | 31.7 | 27.4 | 26 | 35.6 | 27.8 | 34.80 | | 36.30 | 34.8 | |
| **0.125** | 31.0 | 24.0 | 27.62 | 34.0 | 28.9 | 23.4 | 23.1 | | 25.7 | 32.30 | 21 | 30.90 | 32.3 | 30.00 |
| **0.1** | 30.0 | 24.0 | 27 | 27.0 | | | | | | | 21 | | | 30.00 |
| **0.08** | 30.0 | 24.0 | 26.78 | 27.0 | 23.7 | 20.1 | 19.3 | 25.7 | 22.2 | 27.30 | 21 | 25.20 | 27.3 | 29.00 |
| **0.063** | | | 26.7 | | 22.9 | 19 | 18.9 | | 22.1 | 26.50 | | 24.20 | 26.5 | |

The following curve overlay is obtained.

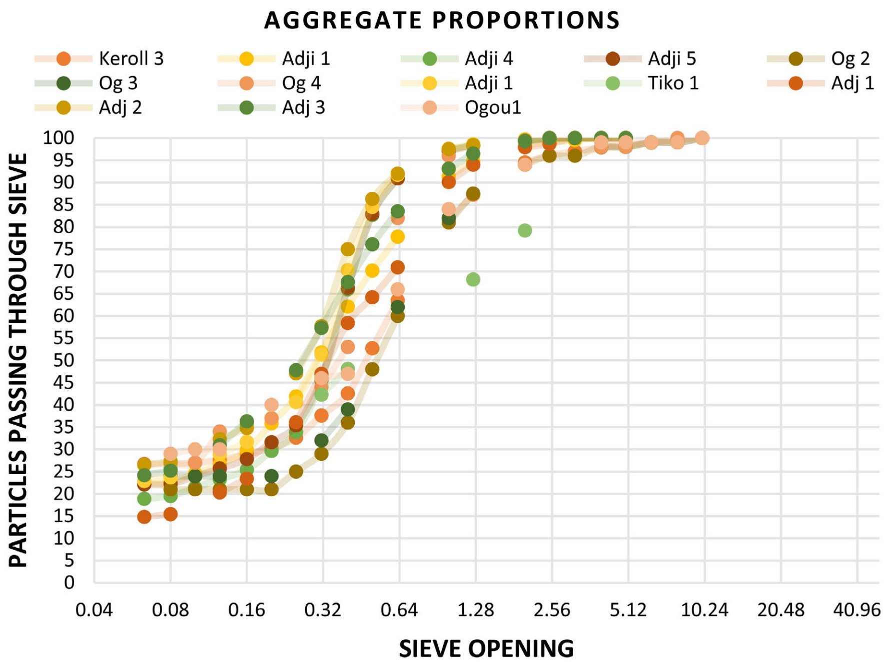


**Figure 5.** TBLi grading envelope suitable for use in foundation layers.

More specifically, the grading envelopes for the three class.

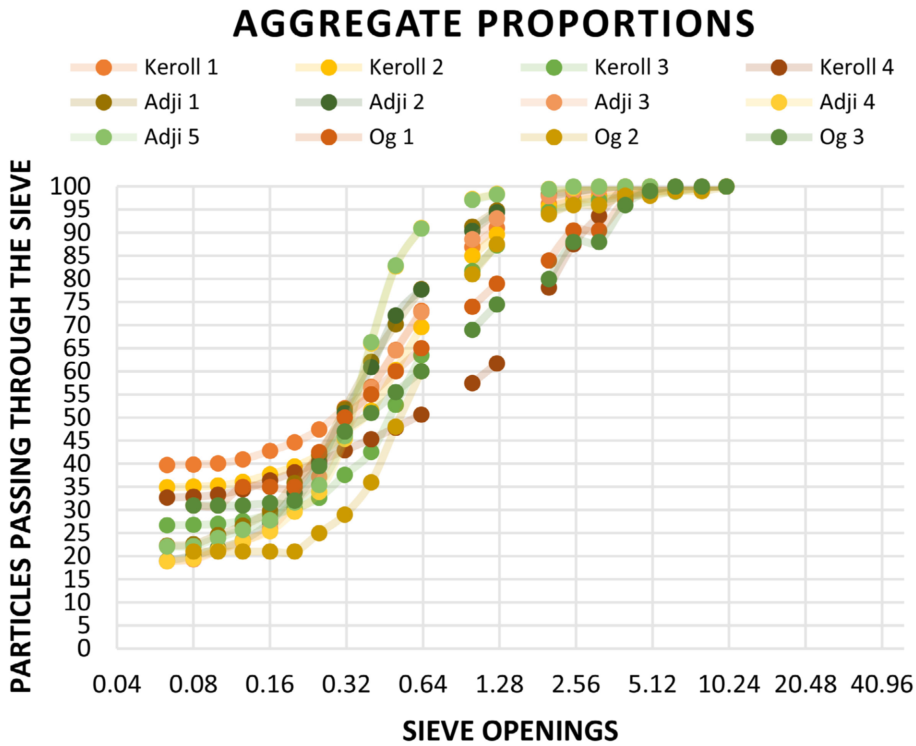


**Figure 6.** TBLi grading envelope suitable for T1 to T5.

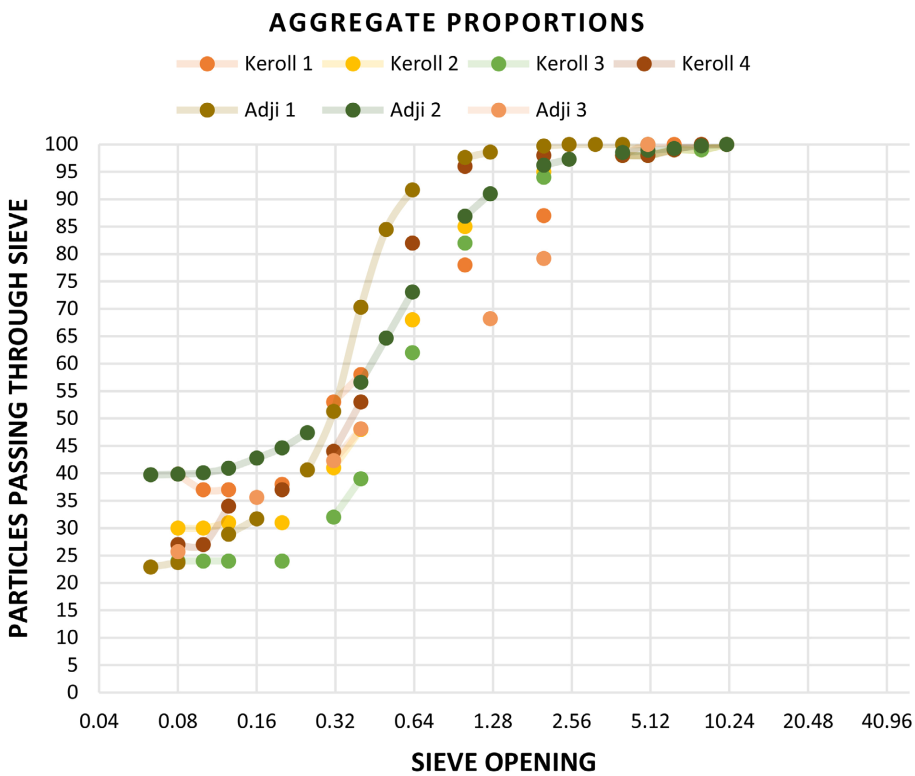


**Figure 7.** TBLi grading envelope suitable for T1 to T3 traffic.

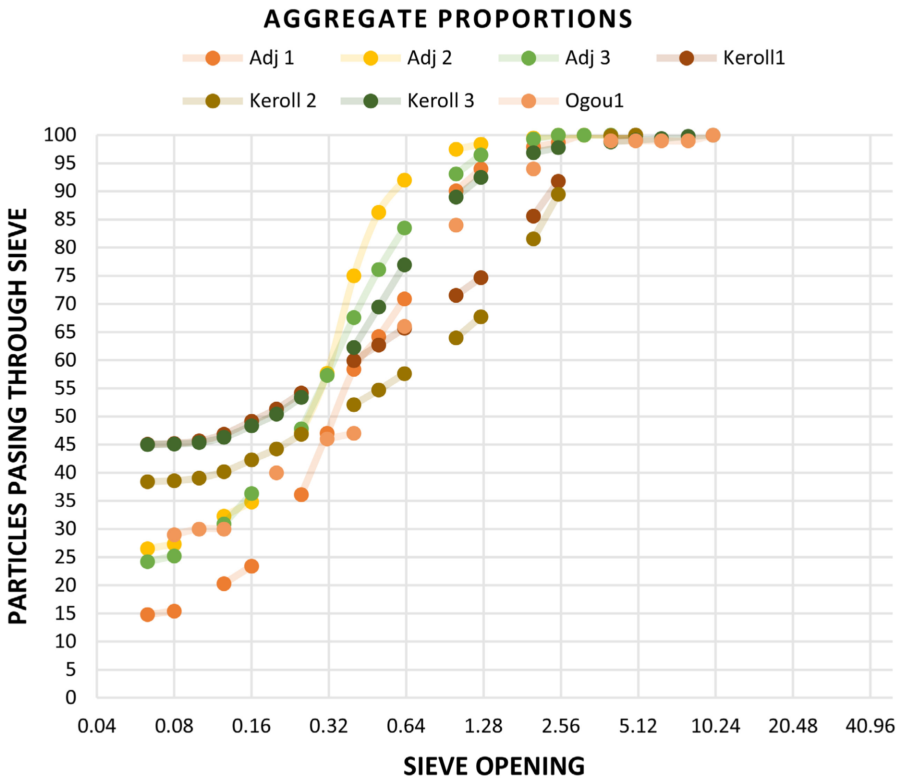


**Figure 8.** TBLi grading envelope suitable for T1trafic.

When reconsidering the valorization framework for fine lateritic soil, it becomes clear that mixtures with sufficient CBR values and a replacement proportion below 50% are those intended for traffic in T1 to T3, and those intended for traffic in T1 only. Consequently, the composite is usable for T1 to T3 traffic as a foundation layer of the pavement (corresponding respectively to the bands defined by Figure 7 and Figure 8).

Table 13 provides a comparison of the CBR value of litho-stabilized composites according to the corrective material used.

**Table 13.** Comparison of CBR for litho-stabilized composite depending on the additive used.

| Addition of Crushed sand | CBR Composite | Addition SL | CBR Composite |
|---|---|---|---|
| 38% | 31 | 36% | 29 |
| 44% | 36 | 42% | 33 |
| 49% | 38 | 48% | 35 |
| 55% | 43 | 53% | 35 |
| 60% | 55 | 58% | 39 |

It is observed that for nearly equal proportions of stabilizer, the CBR values at 95% of the Proctor optimum exhibited by the mixtures prepared with crushed sand are higher than those with lagoon sand. It appears that crushed sand is the best choice as a corrective (the best mechanical performances are achieved with it, with a CBR up to 55) because its skeleton is more reinforced. This finding is verified for the reference mixes that we formulated.

### 3.3. Identification of the Destination Traffic Classes for the Cement-Improved Litho-Stabilized Ballast Soil Composite

In reviewing the various formulation studies conducted, we found that only the studies by BIAOU H. and ASSANHOUN adequately evaluated the modulus value of the obtained composite. These modulus values were respectively obtained at 60 days and 90 days. To retrieve the values at 360 days for classifying the material, we used the following relation:

$$E_{90}/E_{360} = R_{t90}/R_{t360} = 0.93$$

Then the following one, in accordance with the NF P98-086 standard.

$$E_{60}/E_{360} = 0.82$$

$$R_{t60}/R_{t360} = 0.78$$

The collected data for the formulations are compiled in Table 14:

Table 14. Couple ($E$, $R_t$) formulations.

| Mixture | $R_t$ (MPa) | $E$ (MPa) | $R_{t360}$ (bars) | $E_{360}$ (MPa) |
|---|---|---|---|---|
| 26FLS + 74RSZ | 0.338 | 3732 | 0.433 | 4551 |
| 42FLS + 58CSA | 0.260 | 2591 | 0.279 | 2786 |

We integrate these two distinct points into the graph $E = f(R_t)$ as shown in Figure 9.

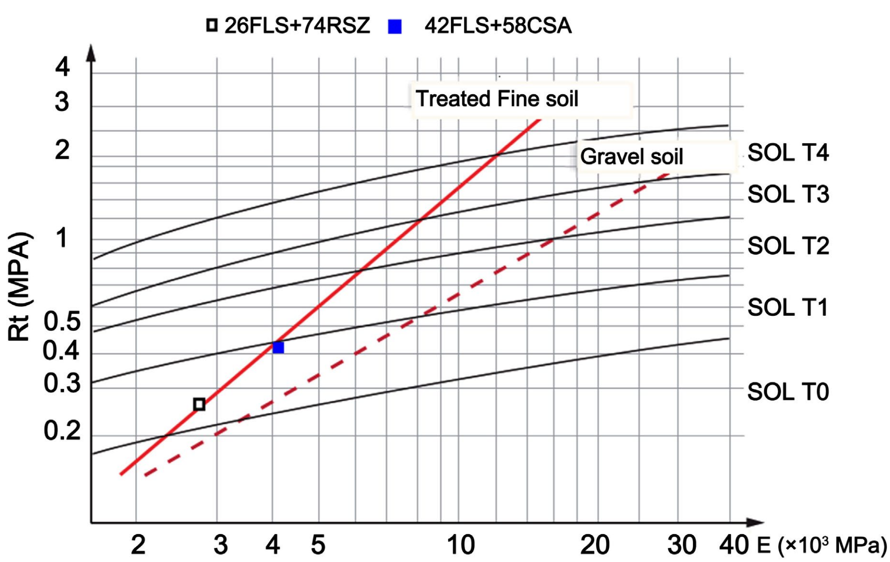


Figure 9. Couple ($E$, $R_t$) of mixtures 42FLS + 58CSA and 74RSZ + 26FLS.

From these two observations, we conclude that the cement-improved litho-stabilized ballast soil is a treated soil of class T1. It is therefore usable as a pavement base layer for traffic below T5 as defined by the LCPC guide. Indeed, some previous studies have based traffic designation for litho-stabilized soil on the CBR value. This criterion is not well suited for classifying soils treated with hydraulic binders, as it neglects stiffness and will-strength, which are important criteria for treated materials.

### 3.4. Definition of the Implementation Specifications for the Litho-Stabilized Composite

The ballast soil is highly water sensitive. Its implementation thus requires careful control of its compaction moisture content. Ideally, the material should be brought to its Optimum Water Content (OMC) and reach at least 95% of the maximum dry density. In the rest of our study, we seek the optimal compaction moisture range for the litho-stabilized material that preserves its properties.

- **Compaction moisture content range**

Consider the data used to evaluate the compaction moisture range. We focus on the ratios $W_{inf}$/OMC and $W_{sup}$/OMC. Table 15. Summarize the results obtained for different mixtures.

Table 15. Values of $W_{inf}$/OMC and $W_{sup}$/OMC.

| Mixtures | $W_{inf}$/OMC | $W_{sup}$/OMC |
|---|---|---|
| 64FLS + 36RSZ | 0.74 | 1.23 |
| 57FLS + 43RSZ | 0.71 | 1.32 |
| 49FLS + 51RSZ | 0.71 | 1.27 |
| 43FLS + 57RSZ | 0.53 | 1.35 |
| 37FLS + 63RSZ | 0.59 | 1.29 |
| 64TB + 36CS 0/5 | 0.66 | 1.42 |
| 54TB + 46CS 0/5 | 0.74 | 1.23 |
| 45FLS + 55 CS 0/5 | 0.71 | 1.23 |
| 37FLS + 63CS 0/5 | 0.65 | 1.33 |
| 30FLS + 70CS 0/5 | 0.65 | 1.30 |
| 64FLV + 35 RSZ | 0.55 | 1.37 |
| 58FLV + 42RSZ | 0.51 | 1.31 |
| 53FLV + 47RSZ | 0.59 | 1.37 |
| 47FLV + 53RSZ | 0.45 | 1.31 |
| 41FLV + 59RSZ | .91 | 1.05 |
| 62FLD + 38CSA | 0.66 | 1.33 |
| 56FLD + 44CSA | 0.45 | 1.36 |
| 51FLD + 49CSA | 0.84 | 1.11 |
| 47FLD + 53CSA | 0.90 | 1.09 |
| 42FLD + 58CSA | 0.72 | 1.30 |

When considering the mixtures prepared with lagoon sand, on average, the material must reach 0.66 OMC to achieve 0.95 $\gamma_{dmax}$ in the lower bound, and 1.27 OMC to achieve 0.95 $\gamma_{dmax}$ in the upper bound.

$$W_{compactage} \text{ € } [0.66 \text{ OMC}; 1.27 \text{ OMC}]$$

When considering mixtures prepared with crushed sand, on average, the material must reach 0.68 WOPM to achieve 0.95 $\gamma_{dmax}$ in the lower bound, and 1.30 OMC to achieve 0.95 $\gamma_{dmax}$ in the upper bound.

$$W_{compactage} \text{ € } [0.68 \text{ OMC}; 1.30 \text{ OMC}]$$

Additionally, when considering all these data (Table 7), the 95th percentile in the lower bound corresponds to a moisture content of 9.1% in the lower bound, 0.90 OMC for the associated mix, and corresponds to 13.5% in the upper bound, 1.27 OMC for the associated mix.

$$W_{compactage} \text{ € } [0.90 \text{ OMC}; 1.27 \text{ OMC}]$$

For the composite 55FLO + 45LSA, the optimal water content OMC is 7.8%. Thus the composite is humidified around this optimal value and we obtained the Proctor curve shown in Figure 10.

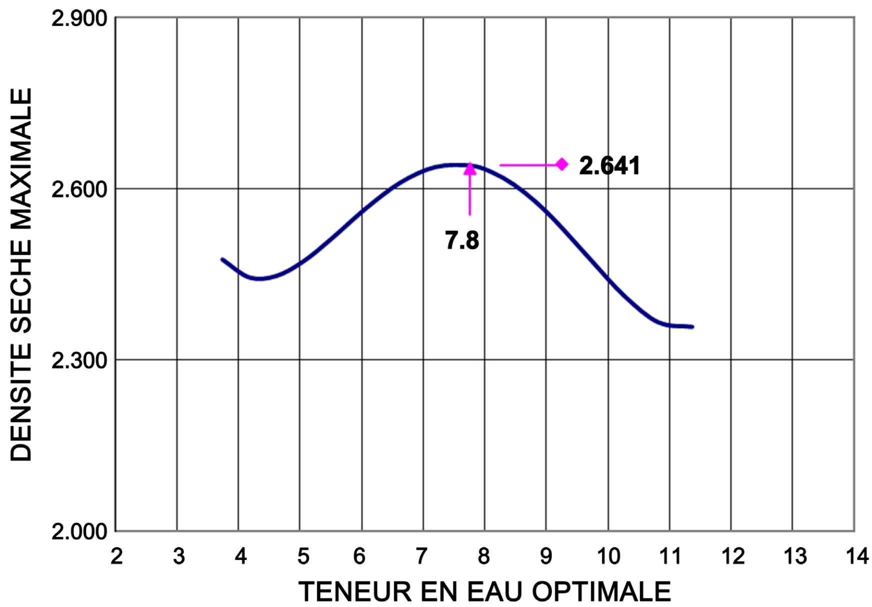


**Figure 10.** Proctor mixture FLO + LSA results.

Maximum dry density of the material: 26.41 kN/m$^3$. In the foundation, aim for at least 95% of this value, *i.e.*, 25.09 kN/m$^3$. According to the results at 7.6% moisture, 95% of the OMC is not reached at 8.9% moisture, dry density measured is 24.37 kN/m$^3$. A 0.2% change in moisture leads to about a 2 kN/m$^3$ increase. To reach 25.09 kN/m$^3$, the maximum moisture content must be raised to 8.7%. Recommended compaction moisture content range:

Proposed range: [OMC; 1.15 OMC].

By comparison, the bounds from previous mixes for this composite would be

[0.66 OMC; 1.27 OMC], about [5.15%; 9.91%].

Visual observation: at 5% moisture, the mix does not compact and remains powdery.

Considering the 95th percentile and observations from previous mixes, it would be appropriate to constrain the range to roughly [0.90 OMC; 1.20 OMC], to allow a margin compatible with results from other studies and tests on samples conducted under different conditions studies.

Indeed, the proposed water content range [0.90 OMC; 1.20 OMC] affects not only the dry density but also the mechanical strength (CBR) of the composite. On the dry side (0.90 OMC), although the density is slightly lower, particle contacts are stronger, which enhances internal friction and results in higher bearing capacity. Conversely, on the wet side (1.20 OMC), the excess water acts as a lubricant between soil particles, reducing cohesion and shear strength. In fine lateritic soil, this condition typically results in a marked reduction in CBR, since the bearing capacity is undermined by the loss of structural stability. To obtain both adequate dry density and satisfactory CBR values, compaction should be performed close to the optimum moisture content or slightly on the dry side. Proper control of particle size distribution is required to balance cohesion and internal friction, and stabilization measures may be considered when dealing with highly clayey soils.

## 4. Conclusions

To address the issue of road material shortages in Benin, several studies have focused on the fine lateritic soil, presented as the most readily available resource. To fully exploit this material, the technique of litho-stabilization has been applied by various authors due to its main characteristic: water sensitivity. Based on the compilation of these formulations, our study aimed to define a set of specifications for the use of composite litho-stabilized and cement-enhanced litho-stabilized as sub-base layers in road construction.

Following our analysis, we observed firstly that raw fine lateritic soils with better aptitude for litho-stabilization—resulting in composites with significant CBR gains—exhibit the following properties:

- Plasticity index PI between 22 and 27.
- Fine particle content between 30% and 45%.

These characteristics correspond to materials classified as I2 according to GTR 2023 and, in the Beninese context, are like the fine lateritic soil found in the Lokossa region. The MEC method should be excluded as a formulation approach, as it no longer aligns intending to valorize fine lateritic soil; this method typically maximizes the sand proportion in the composite to achieve high compaction.

Regarding the litho-stabilized composite, it initially appears that crushed sand is the appropriate corrective material to use for litho-stabilization, enabling optimal mechanical performance. For its use as a foundation layer, the resulting composite should generally meet the following criteria:

- Plasticity index PI below 20.

- Fine particle content below 30%.
- Particle size distribution curve fitting within the range identified earlier in this study (**Figures 5-8**);
- Various analyses indicate that the resulting composite is generally suitable for traffic classes T1 to T3 as defined by CEBTP (based on sufficient mechanical properties).
- From an implementation standpoint, the composite maintains its mechanical performance within a compaction moisture content range of [0.90 OMC; 1.20 OMC].
- For its use as a base layer, the material should undergo cement treatment in the range of 3.5% to 4% (based on laboratory study results). It falls under mechanical class T1, typically intended for traffic levels below T5 as defined in the LCPC guide.
- At the end of this work, the following perspectives emerge:
- The need to construct an experimental test section to evaluate the material's performance under real conditions.
- Conduct an environmental impact study of the material.
- Map the deposits of "terre de barre" available across Benin and make this information accessible online.
- Organize the "terre de barre" sector (supply + implementation).

## Conflicts of Interest

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

## References

[1] BOAD (2015) Etude sur l'entretien routier dans les pays de l'union économique et monétaire ouest africaine (UEMOA): Bilan des 50 dernières années et perspectives.

[2] Yabi, C.P. (2018) Modélisation d'une plaque en sous revêtement d'une route sur sol élastique et inerte soumise à des charges dynamiques. Université d'Abomey Calavi.

[3] Hyoumbi, W.T., Pizette, P., Wouatong, A.S.L. and Abriak, N. (2018) Mineralogical, Chemical, Geotechnical and Mechanical Investigations of Bafang Lateritic Fine Soils Formed on Basalts (West-Cameroon) for Road Embankment Purpose. *Earth Science Research*, **7**, 42. https://doi.org/10.5539/esr.v7n2p42

[4] Hyoumbi, W.T., Armand, W., Ludovic, S., Pizette, P., Abriak, E. and Medjo, R.E. (2017) Assessment of Laterite Suitable for Road Construction in Bafang Area (West-Cameroon) Based on Physical Properties, Geo-Environmental Factors and GIS Software. *Journal of Multidisciplinary Engineering Science and Technology* (*JMEST*), **4**, 2458-9403.

[5] Foko Tamba, C., Kengni, L. and Tematio, P. (2023) Geotechnical Suitability of Soils in Road Construction for Sustainable Development in Tropical Africa: Case of Lateritic Graveled Soils of Bandjoun (West, Cameroon). *Advances in Civil Engineering*, **2023**, Article ID: 6662521. https://doi.org/10.1155/2023/6662521

[6] Sekloka, H.G.R., Yabi, C.P., Cloots, R. and Gibigaye, M. (2022) Elaboration of a Road Material Based on Clayey Soil and Crushed Sand. *Fluid Dynamics & Materials Processing*, **18**, 1595-1605. https://doi.org/10.32604/fdmp.2022.022434

[7] Koti, J., Yabi, C.P., Gibigaye, M., Millien, A. and Petit, C. (2022) Analysis of Lateritic

Soil Reinforced with Palm Kernel Shells for Use as a Sub-Base Layer for Low-Traffic Roads. *Fluid Dynamics & Materials Processing*, **18**, 1469-1482. https://doi.org/10.32604/fdmp.2022.021902

[8] Azontonde, A. (1993) Dégradation et restauration des terres de barre (sols ferrallitiques faiblement désaturés argilo-sableux) au Bénin. *Cahiers ORSTOM Série Pédologie*, **28**, 217-226.

[9] Gbaguidi, V.S., Kiki, Y.T., Zankpe, M. and Vedogbeton, N. (2018) Identification of the Strata of Lateritic Soils and Alterites in Benin. *International Journal of Advanced Research*, **6**, 282-293.

[10] Slansky, M. (1962) Contribution à l'étude géologique du bassin sédimentaire côtier du Dahomey et du Togo, Vol. 11. Bureau de recherches géologiques et minières.

[11] Shirur, N.B. and Hiremath, S.G. (2014) Establishing Relationship between CBR Value and Physical Properties of Soil. *IOSR Journal of Mechanical and Civil Engineering*, **11**, 26-30. https://doi.org/10.9790/1684-11512630

[12] Zumrawi, M. (2012) Prediction of CBR from Index Properties of Cohesive Soils. In: Chang, S.Y., Al Bahar, S.K. and Zhao, J.Y., Eds., *Advances in Civil Engineering and Building Materials*, CRC Press, 561-565. https://doi.org/10.1201/b13165-118

[13] Houanou, K.A., Danvi, K.R., Dossou, K.S. and Olodo, E. (2025) Determination of the Geotechnical Parameters of Tohouè Silty Sand (Semè-Kpodji) for Its Use in Road Construction in Southern Benin. *Open Journal of Applied Sciences*, **15**, 2051-2073. https://doi.org/10.4236/ojapps.2025.157135

[14] Kiki, S.Y.T. (2017) Caractérisation minéralogique, thermique et m croscopique des sols fins en technique routière. Ph.D. Thesis, Université de Bordeaux.

[15] Kollaros, G. and Athanasopoulou, A. (2017) Sand as a Soil Stabilizer. *Bulletin of the Geological Society of Greece*, **50**, 770-777. https://doi.org/10.12681/bgsg.11783

[16] Ndiaye, M., Magnan, J.P., Cissé, I.K. and Cissé, L. (2013) Étude de l'amélioration de latérites du Sénégal par ajout de sable. *Bulletin des Laboratoires des Ponts et Chaussees*, No. 280-281, 123-137.

[17] Sekloka, H.R.G. (2023) Developpement de materiaux composites durables à base de terre argileuse en vue de leur utilisation en couches d'assises de chaussées routières. University of Abomey Calavi.

[18] Traore, Y.B., Lompo, P.E., Savadogo, N. and Yonli, H.F. (2025) Experimental Study on the Use of Crushed Granite Sand for Lithostabilization of Lateritic Soils in Road Construction. *World Journal of Advanced Research and Reviews*, **28**, 1242-1252. https://doi.org/10.30574/wjarr.2025.28.2.3798

[19] PIARC (2019) REVUE du guide pratique de dimmensionement des chaussées pour les pays tropicaux.

[20] CEBTP (1984) Guide Pratique de Dimensinnement des chaussées pour les pays tropicaux.

[21] AGEROUTE, IFFSTAR, EGIS and SENELABO (2015) Catalogue de structures de chaussées neuves et Guide de dimensionnement des chaussées au Sénégal.

[22] IDDRIM (2023) Guide des terrassements des remblais et des couches de forme—Fascicule 1—Principe généraux, CEREMA. Les références.