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Research Article

Influence of the Treatment of Bingerville Clayey Sands with a Batard Binder Mixture (Lime-cement) for Use in Road Engineering

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Abstract

In tropical countries, clay soils used in construction have unfavorable geotechnical properties and degrade prematurely due to their low bearing capacity and sensitivity to water, such as those of Bingerville, in southern Cote d'Ivoire, where these soils are the raw material for infrastructures projects. The use of improvement techniques such as treatment with hydraulic binders can improve the geotechnical properties of these soils by increasing their physical and mechanical strength in many countries where these materials are abundant, thereby reducing material transportation costs and environmental pollution. This study characterizes the clay soils of Bingerville in their natural state for their identification and suitability for treatment before subjecting them to lime and cement mixtures. The results of this study showed that the clay soils of Bingerville are clayey sands. After analysis, they are suitable for mixed treatment (lime-cement) in order to increase their geotechnical properties for their use in road techniques. Laboratory tests identified an optimal mixture of 3% lime and 6% cement. The experimental results made it possible to obtain, on clayey soils in the initial state, the total organic matter content (TOC), equal to 0.15%, a very low value, less than 1%, showing that these soils can support any load without deforming under the influence of water, therefore suitable for binder treatments. The plasticity index (PI) equal to 23.7%, a value greater than 12%, suggests that these clayey soils are subject to mixed Batard treatment (lime-cement). After treatment of Bingerville clay soils with lime and cement mixtures, dry densities increased from 1.83 to 2.03, with the 95% California Bearing Ratio (CBR) of the Modified Optimum Proctor (MOP) at 4 days of immersion increasing significantly from 14 to 94. These results are consistent with the recommendations for their use as treated local soils in low to medium traffic road projects.

Keywords

Clayey Sands, Soil Treatment, Bingerville, Lime, Cement, Batard

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1. Introduction

Land use planning policies drive the development of infrastructure (roads, buildings, etc.), which leads to the use of locally available construction materials. However, in many tropical regions such as Bingerville, a growing city, the soils encountered are predominantly clayey, with low load-bearing capacity, coupled with a lack of understanding of their mechanical behavior [1].

These unsuitable soils cannot be directly used in their natural state in pavement layers without prior treatment. To address these physical and mechanical deficiencies, soil treatment by adding hydraulic binders, particularly lime and/or cement, is a widely used technique in infrastructure construction. This study primarily aims to characterize the clayey soils of Bingerville in their natural state and then after treatment with Batard mixtures (lime and/or cement) for their use in road construction.

Laboratory tests will be conducted on the natural clay soils of Bingerville to identify their nature and suitability for treatment with binders. After treatment of these Bingerville soils with binders, the physical and mechanical behavior will be characterized for their use in road construction.

2. Materials and Methods

2.1. Materials

2.1.1. Raw Material and Acquisition Equipment

The raw materials used are the reworked clay soils of Bingerville in southern Cote d'Ivoire. These clay soils were located using the GPS receiver indicated in Table 1.

This northern zone of the so-called high plateau lagoon fault between 40 and 110 meters above sea level, par excellence, is where fine soils are located, in this case clay soils [2]. The reworked clay soils were sampled, according to [3] standards, previously located by the LBTP, onshore, in the sedimentary basin, southern part of Cote d'Ivoire, in the R1 geotechnical region particularly in Bingerville [4]. The reworked clayey sands of Bingerville were sampled in several borrow deposits on the urban outskirts. A single focal point around which three other sampling points gravitate within a radius of 3 meters with depths ranging from 2-3 meters with this location. Figure 1 shows the sampling sites of the reworked clay soils.

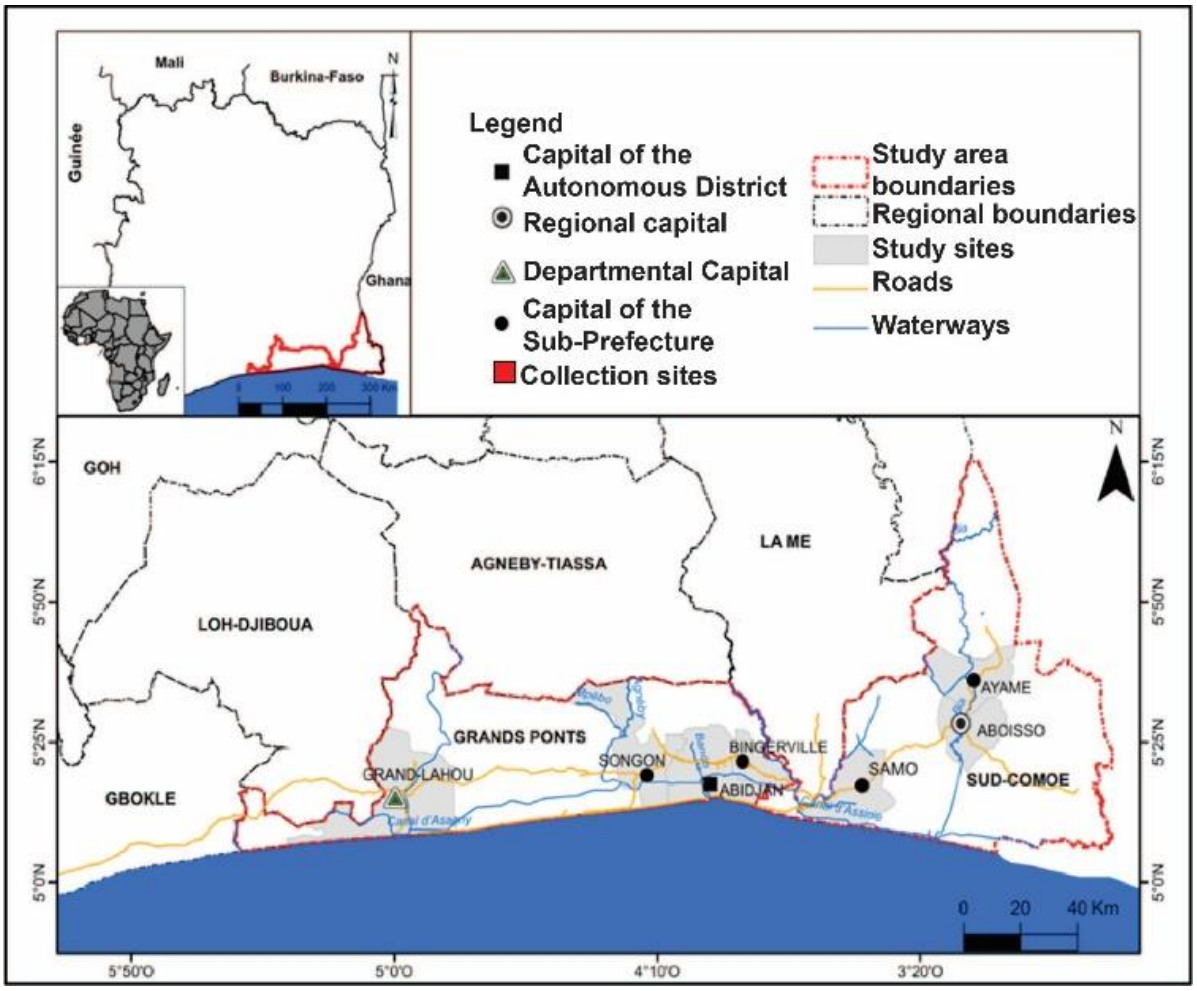

Figure 1. *Location of the sampling sites for the reworked clay soils in the study.*

Table 1. *Location of raw material sampling sites in geographic coordinates.*

Longitude	Latitude
3°53'42"32 W *	5°21'32"38 N

Two types of hydraulic binders are known for soil treatment: commercial quicklime manufactured in Saint-Astier (France) according to standard [5]. The technical data sheet for the lime used shows that it consists of 64.5% CaO and 35.5% $Ca(OH)_2$, as well as insoluble residues. Its absolute density ranges from 2200 kg/m^3 to 2500 kg/m^3, and Portland cement referenced CPJ-CEM II from Cote d'Ivoire, with a true class of 32.5 MPa. The composition of its clinker is 67% CaO, 22% SiO_2, 5% Al_2O_3, 3% Fe_2O_3, and 3% admixture [6].

2.1.2. Equipment for Acquiring Raw Materials in the Field

This equipment consists of a GPS receiver, shovels, picks, augers, and a set of plastic bags for conditioning the clay soils sampled in Bingerville from ambient field temperature to laboratory temperature of around 25 ℃.

2.1.3. Data Acquisition and Laboratory Processing Equipment

Figure 2 shows the laboratory equipment that can be used for data acquisition before and after soil treatment: A branded drying oven (FRIOCELL) for drying the soil (A), a Sartorius BL1500S electronic balance for weighing samples ready for sieving (B), a 16-sieves AFNOR-type vibrating column sieve shaker reserved for sieving samples (C) and a CBR mold (D).

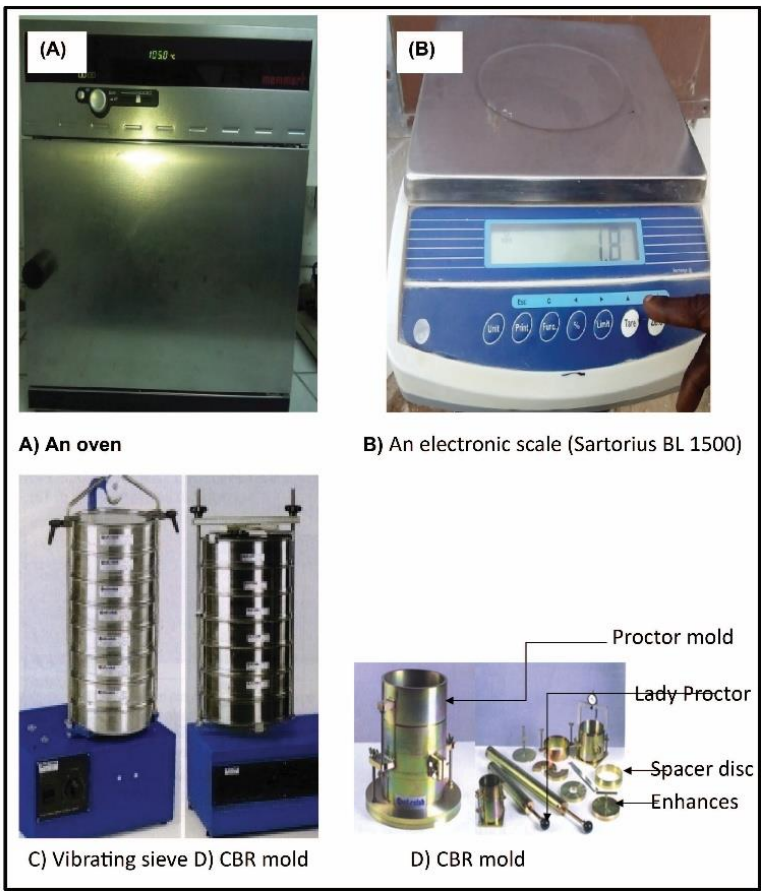

Figure 2. *Laboratory Equipment.*

2.2. Methodological Approach

2.2.1. Identification of Clay Soils

This identification of clay soils was carried out through dry particle size analysis in accordance with French Standard [7] according to [8]. The distribution of soil grains by size indicates the identity of soil types according to Table 2.

Table 2. Soil Designations According to Soil Type Proportions [9].

Proportion of Soil Types	Terminology	Examples
>35%	gives the name of the soil	Gravel, sand, silt, etc
20% to 35%	gives the adjective	Gravelly, sandy, etc
10% to 20%	A little	With traces of clay, silt, etc
<10%	defines the trace	

2.2.2. Rock-eval Device

Figure 3 characterizes the total organic matter (TOM) content of the raw material by pyrolysis, which reveals the susceptibility of a soil to support any load (traffic) according to this classification indicated in Table 3.

Figure 3. Rock Eval Device.

Table 3. Classification of organic matter and suitability of a soil for use without deformation in Road Techniques [10].

TOM (% weight)	Classe	Soil suitability
< 0.5	Poor	Fit
0.5-1	Average	Fit
1-2	Good	Fit
2-4	Very good	Unfit
> 4	Excellent	Unfit

2.2.3. Oedometric Device

This test is carried out according to the [11] norm standard. It allows the volumetric swelling of clay soils to be characterized and identifies their potential to be treated with hydraulic binders according to the standard prescribed in Table 4.

Figure 4. Oedometric device and soil specimen after compressibility testing.

Table 4. Soil Potential for Treatment [12].

Treatment Type	Suitability for Treatment	Volumetric Swelling Cg (%)
Treatment with LHR or Cement	Directly Suitable	$Cg \leq 5$
"Accelerated" Test	Doubtful: Potentially	$5 < Cg \leq 10$
7 days - 40 ℃	Unsuitable: Insufficient	$Cg > 10$

2.2.4. Atterberg Limits

The Atterberg limits were established according to [13] norms. They provide insight into the water behavior of soils and allow for the optimal choice of treatment materials with hydraulic binders (cement and/or lime). A Plasticity Index (PI) above 12% suggests that these soils can be treated, and better still, with an appropriate mixed treatment using lime and cement [14-16].

2.2.5. Specimen Design

The implementation of lime and/or cement mixtures for reworked soils is carried out in accordance with French Standard norms [17] as shown in Figure 5.

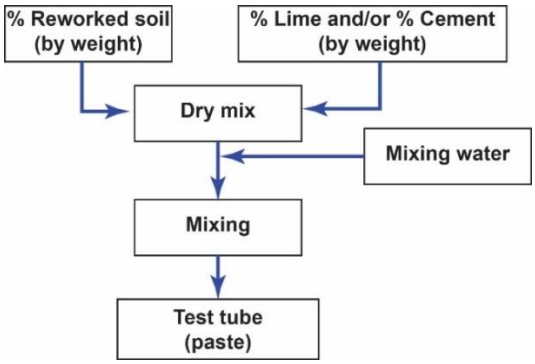

Figure 5. *Steps in formulating compaction specimens [18].*

The lime content is set at 0, 1, 2 and 3%. Cement content is then added at 0, 2, 4, and 6%. The 0% lime and cement content corresponds to the natural states of the raw material. The variation in the lime content defines the range with which the cement content and the proportion of clay soil are combined to form the specimen unit.

Modified Proctor tests are applied to the prepared specimens, and high dry densities with low water contents are selected, optimal for performing CBR tests after treatment with hydraulic binder mixtures. The range with the highest CBR at 95% of the MOP after 4 days of immersion in water, which is associated with a dosage number, will be retained.

3. Results and Analyses

3.1. Bingerville Clay Soils in Their Natural State

3.1.1. Identification of Bingerville Clay Soils

The particle size analysis of Bingerville clay soils in their natural state is given in Figure 6 showing the distribution of the different grains contained in Bingerville clay soils.

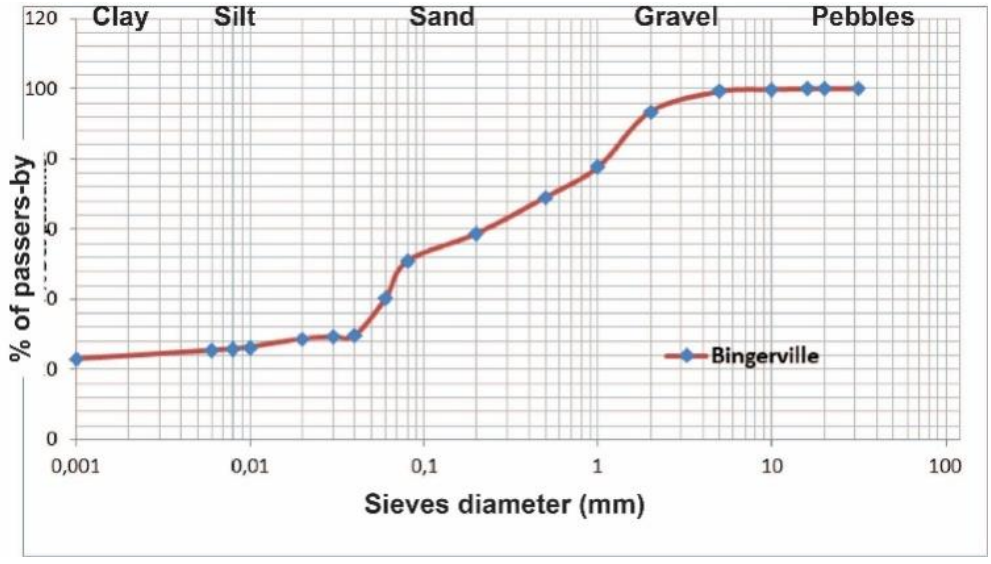

Figure 6. *Grain size distribution curve of Bingerville clay soils.*

Table 5 shows the grain size composition of Bingerville clay soils.

These Bingerville clay soils contain (24%), silt (26%), sand (44%) with traces of gravel (4%). The Bingerville clay soils are identified as clayey sands based on the grain distribution.

Table 5. Grain size composition of Bingerville clay soils.

Fractions	Soils	Particle composition of grains (%) by diameter
Coarse	Gravel (2mm < Φ < 20mm)	6
	Sand (80µm < Φ < 2mm)	44
Fine	Silt ((2µm < Φ < 80 µm)	26
	Clay (< 2 µm)	24

3.1.2. Bearing Capacity of Bingerville Clay Soils

Figure 7 presents the modified Proctor curve of Bingerville clay soils in their natural state. Dry density varies with soil water content and peaks at the Modified Proctor optimum. The optimum water content for Bingerville clayey sands is given in Table 6.

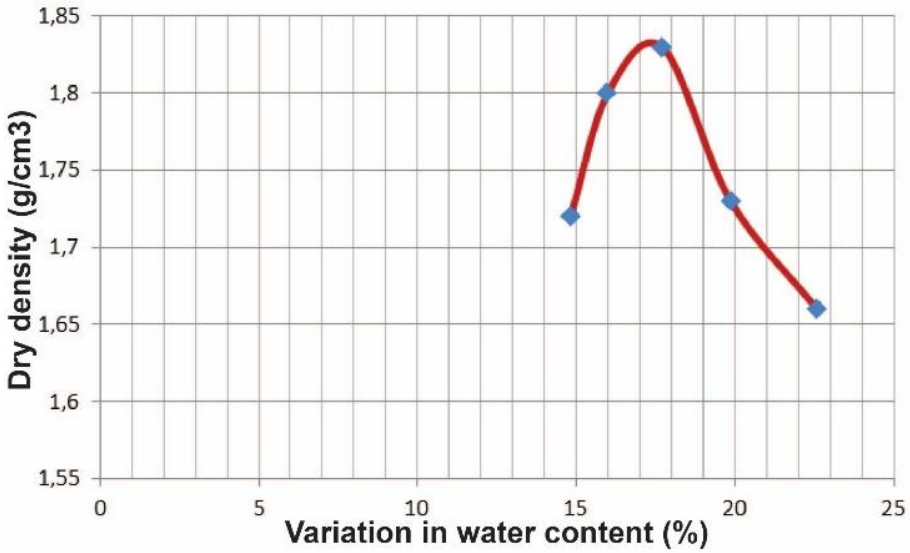

Figure 7. Modified Proctor Curve of Bingerville clay soils.

Table 6. Proctor Optimum Values for different soils.

	Dry density (g/cm^3)	Optimal water content (%)
Clayey sands	1.83	16.58

Bingerville clay3ey sands have high water content values, which is 16.58% for a dry density of 1.83. This value remains below 2, which explains their high fine fraction rates, which is 50%.

The CBR bearing capacity results of Bingerville clayey soils in their natural state are presented in Figure 8.

The CBR bearing capacity values vary depending on the degree of compaction. Table 7 gives the CBR values at 95% of the MOP after 4 days of immersion.

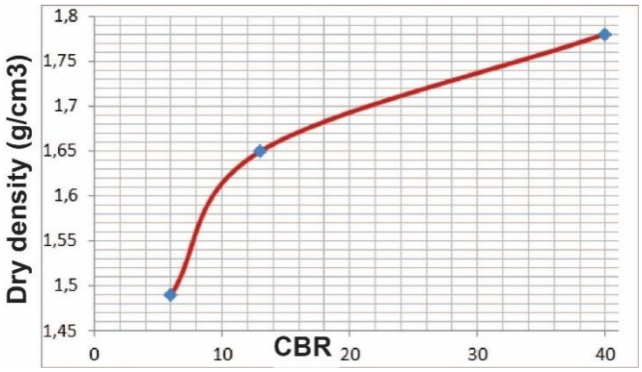

Figure 8. CBR curves of Bingerville clayey sands in their natural state.

In Table 7, the Bingerville clayey sands have a CBR at 95% of the MOP after 4 days of immersion in water of 14, a value less than 30. These soils are classified as category S3 halo-morphic soils that cannot be used in road pavement structures in their natural state. This could be explained by their grain size distribution, which is dominated by the proportion of the fine fraction (50%). In reality, the desired property for the construction of a durable road is the ability of the materials to support loads, i.e., their load-bearing index.

Table 7. *CBR values at 95% of the MOP after 4 days of immersion in water for Bingerville clayey sands.*

	CBR at 95%	Equivalent layer	Road type
Clayey sands	14	Platform	Not defined

The volumetric swelling coefficient of this clayey sand is 1.2 kN/m^2 (10^{-3}). The total organic carbon content of this Bingerville clayey sands, which is 0.15%.

The Bingerville clayey sands contain little swelling clay, with a Volumetric Swelling Coefficient (1.2 ±0.1), a value less than 5, and a total organic carbon of 0.15%. This is a very low value, being less than 1%, which makes the Bingerville clayey sands suitable for treatment with hydraulic binders.

3.2. Plasticity Index and Treatment Suitability of the Bingerville Clayey Sands

3.2.1. Plasticity Index

The water parameters of the Bingerville clayey sands are shown in Table 8.

The analysis of Table 8 shows that the Bingerville clayey sands have a Plasticity Index (PI) of 23.7%, greater than 12%. These are therefore plastic clayey sands, and are subject to treatment with mixed hydraulic binders of lime and cement mixtures according to this recommendation.

Table 8. *Water Parameters of the Bingerville clayey sands.*

Parameters	Percentages (%)
Liquid Limit (WL)	60.6
Plastic Limit (WP)	36.9
Plasticity Index (PI)	23.7

3.2.2. Treatment of Bingerville Clayey Sands with Lime-cement Mixtures

After treatment with lime and cement mixtures on Bingerville clayey sands, the Proctor results for high dry densities with low optimal water content yielded (Figures 9 and 10):

Range 1 (lime content set at 1%) for a dosage number 1 corresponding to 1% lime and 2% cement. The dry density increases from 1.83 g/cm^3 with an optimal water content of 16.58% in its natural state to 2.03 g/cm^3 with an optimal water content of 15.2%.

Range 2 (lime content set at 2%). It is dosage number 6, i.e., 2% lime and 6% cement, that increases the dry density in its natural state from 1.83 g/cm^3 with the optimal water content of 16.58% to 1.92 g/cm^3 with an optimal water content of 14.4%.

Range 3 (lime content set at 3%). Dosage number 9 (3% lime and 6% cement) gives an interesting result; this increases the dry density from 1.83 g/cm^3 with 16.58%, the optimal water content in its natural state, to a dry density of 1.95 g/cm^3 with a low optimal water content of 14.3%.

In short, we retain the results of dosages 1, 6, and 9, which correspond to Bingerville 1 (B1), Bingerville 6 (B6), and Bingerville 9 (B9). These three interesting results for the Proctor will undergo CBR or bearing capacity tests.

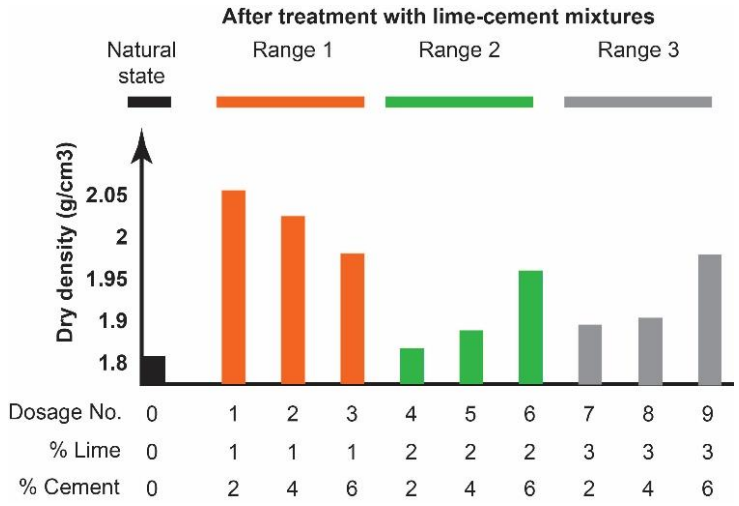

Figure 9. *Change in dry density as a function of lime-cement mixtures of Bingerville clayey sands.*

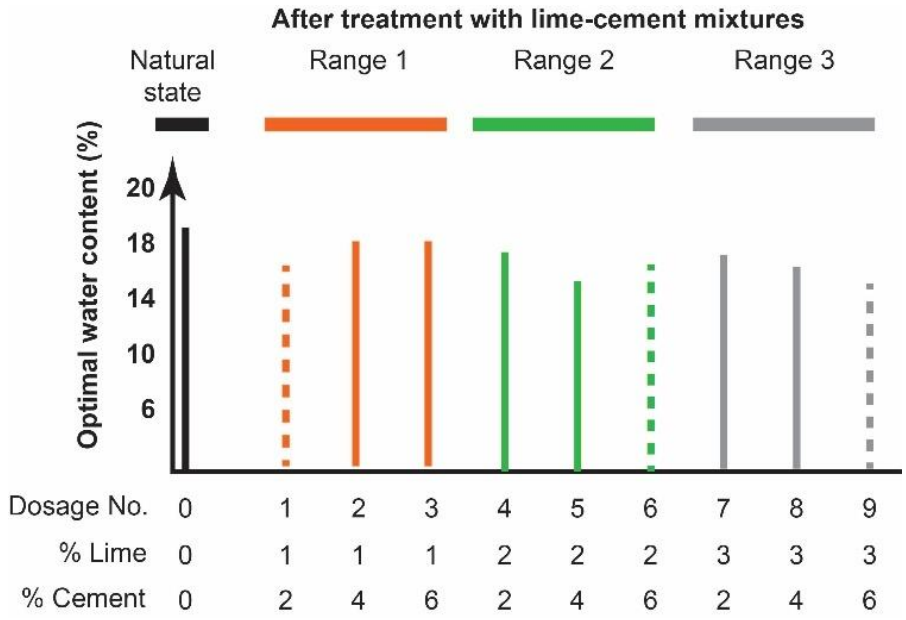

Figure 10. *Change in optimal water content as a function of lime-cement mixtures of Bingerville clayey sands.*

In Table 9, we note a significant change in the dry density of Bingerville clayey sands when treated with lime and cement mixtures, which increases from 1.83 g/cm^3 in the natural state before treatment to 2.03 g/cm^3 after treatment with lime-cement mixtures of Bingerville clayey sands. For range 1, it is dosage number 1, i.e. mixtures of 1% lime and 2% cement, which give convincing results reaching 2.03 g/cm^3 with average optimal water contents of 15.2%. Range 2 is dominated by dosage number 6, i.e., mixtures of 2% lime and 6% cement corresponding to dry densities of 1.92 g/cm^3 with optimal average water contents of 14.4%, and range 3 is dominated by number 9, which corresponds to mixtures of 3% lime and 6% cement for dry densities of 1.95 g/cm^3 and optimal average water contents of 14.3%.

Table 9. *Values for the evolution of dry densities as a function of water content for dosage numbers in lime-cement mixtures of Bingerville clayey sands.*

No. Dosage	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
% Lime	1	1	1	2	2	2	3	3	3
% Cement	2	4	6	2	4	6	3	3	3
Optimal Water Content (%)	15.2	17.6	18.0	16.2	14.8	14.4	14.4	14.4	14.3
Dry density (g/cm^3)	2.03	2	1.95	1.8	1.85	1.92	1.86	1.65	1.95
Range		1			2			3	

3.2.3. Optimization of the Bearing Capacity of Bingerville Clayey Sands After Treatment with Lime and Cement Mixtures

The Figure 11 shows the evolution of CBR at 95% MOP of clayey sands treated with lime and cement mixtures compared to these soils in their natural state. The results show that with B1, the CBR at 95% MOP increases from 13 to 35. For B6, this result increases from 13 to 50, and for B9, this result increases from 13 to 94. An increase is observed with the addition of lime and cement mixtures on the Bingerville clayey sands.

In their natural state, these soils do not meet the selection criteria for use in pavement structures. These soils become suitable, after dosage with lime and cement mixtures, for use in pavement bases for class T1 and T2 traffics.

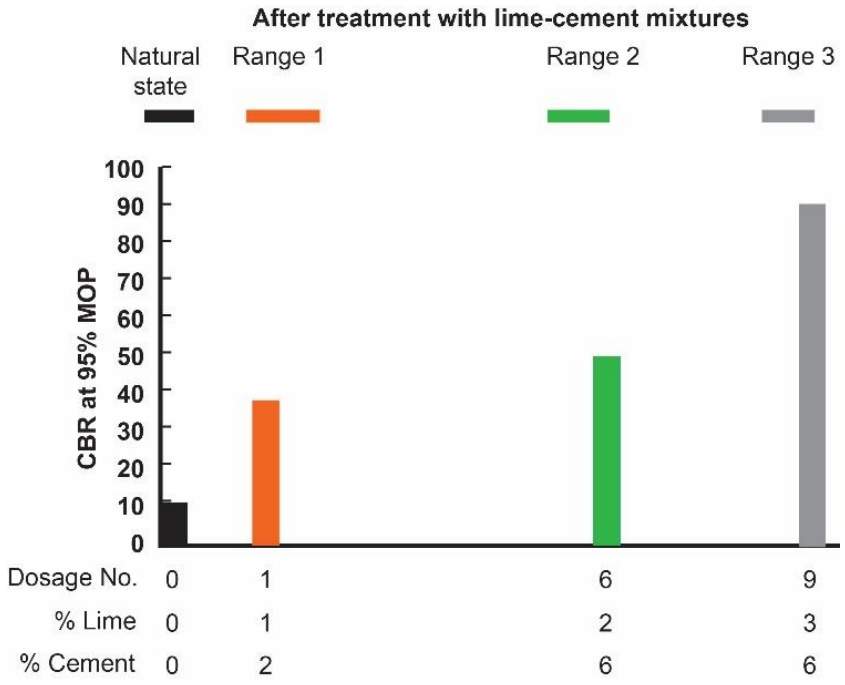

Figure 11. *Influence of the lime-cement mixture on the CBR at 95% of the MOP of Bingerville clayey sands.*

According to Table 10, the values of the evolution of the CBR index at 95% of the MOP after 4 days of immersion in water, for the Bingerville clayey sands treated with lime and cement mixtures with variable rates of lime and cement (lime and cement dosage number) identified as Bingerville B1, B6 and B9 show the very rapid increase in these CBR bearing indices depending on the treatment. This increase in the bearing capacities of the clayey sands treated with lime and cement mixtures (increase in CBR at 95% of the MOP at 4 days of immersion in water) is justified by the reduction in the volume of voids in these soils which is due to the good distribution of soil particles with fine particles of lime and cement.

The various lime-cement mixture treatments of clayey sands with the highest CBR indices 95% of the MOP after 4 days of immersion are: B1 (35), B6 (50), and B9 (94). These CBR indices, at 95% of the MOP after 4 days of immersion in water, could be used as a road base layer for light traffic classes T1 and T2.

Table 10. *Values of the CBR evolution at 95% of the MOP as a function of the lime-cement mixture numbers of Bingerville clayey sands.*

No. Dosage	1	6	9
Lime%	1	2	3
Cement%	2	2	6
CBR at 95% of the MOP	35	50	64

4. Discussion

The Bingerville clayey sands, initially unsuitable for road structures, become, after mixing with lime and cement, materials that meet the physical requirements for light to medium traffic pavements. The lime-cement mixture therefore proves economically and ecologically relevant. It makes it possible to exploit local resources, reduce the use of imported materials, and limit the carbon footprint of road projects.

Regarding the CBR bearing capacity at 95% of the MOP at 4 days of immersion in water, clayey sands treated with lime and cement mixtures varying from (35-94) and dry densities (□d) ranging from 1.94 to 2.03 g/cm^3. The addition of the lime and cement mixture to clayey sands improves the geotechnical properties, mainly the CBR bearing capacity at four days of immersion in water. This is confirmed by [19-22]. These authors report that the improvement in the mechanical properties of clayey soils is due to the hydration reactions of the cement producing C-S-H which bind the soil particles together on the one hand, and, on the other hand, by the pozzolanic reactions between the clay minerals and the $Ca(OH)_2$. These properties improve over time, given the consolidation of the C-S-H over time.

5. Conclusion

The geotechnical properties of Bingerville clayey sands in the south of Ivory Coast in their natural state are known, the granulometry test made it possible to know the nature of the soils, to identify them and to know their suitability for lime

and cement mixtures for their treatments.

After the combined lime-cement treatments, the mixtures significantly improve the geotechnical properties of Bingerville clayey sands, in particular the CBR bearing capacity at 95% MOP at 4 days of immersion in water. The integration of the results into the ALIZE-LCPC software will allow the design of reliable and economical structures. This work supports the use of treated local materials for sustainable pavements, especially in areas where access to noble materials is limited.

Abbreviations

CBR	California Bearing Ratio
LBTP	Laboratoire du Bâtiment et des Travaux Publiques (Building and Public Works Laboratory in Cote d'Ivoire)
MOP	Modified Optimum Proctor
C-S-H	Calcium Silicate Hydrate
ALIZE-LCPC	Software for Pavement Structure Design

Author Contributions

Kouassi Kouakou Pierre: Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing

Djomo Agre Seraphin: Formal Analysis, Methodology, Validation, Writing – original draft, Writing – review & editing

Konin Athanas: Conceptualization, Data curation, Methodology, P Resources, Software, Supervision, Writing – original draft

Ouattara Gbele: Data curation, Formal Analysis, Methodology, Software, Validation, Writing – original draft Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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