Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 10, October, 2025

Geomechanical Characterization of Lateritic Soil by Combining Crushed Granite and Low Content of Cement

Marie Thérèse Marame Mbengue [1], Jeannot Komi N'tsoukpoe [2], Adamah Messan [1*], Mawuénya Xolali Dany Ayite [2]

[1] *Laboratoire Eco-Matériaux et Habitats Durables (LEMHaD), Institut International d'Ingénierie de l'Eau et de l'Environnement (2iE), Ouagadougou 01 BP 594, Burkina Faso.*

[2] *Department of Civil Engineering, École Polytechnique de Lomé (EPL/UL), University of Lomé, Lomé 01BP1515, Togo.*

Received 24 May 2025; Revised 19 September 2025; Accepted 25 September 2025; Published 01 October 2025

Abstract

Lateritic soils, which are widespread in intertropical regions and traditionally used as pavement sub-base layers in Burkina Faso, often exhibit low geomechanical performance, thereby limiting their long-term durability under increasingly heavy traffic loads. This study investigates a combined stabilization approach consisting of incorporating 20% of 10/20 crushed granite aggregates together with low cement content (0%, 1%, 2%, and 3%). The objective was to improve both the mechanical properties and fracture behavior of these soils, while reducing the environmental footprint associated with cement use. Accordingly, an experimental program was carried out, including geotechnical tests (maximum dry density, optimum moisture content, and CBR at 95% compaction) and mechanical characterizations (unconfined compressive strength, indirect tensile strength, Young's modulus, and full stress–strain behavior under uniaxial compression). The results revealed substantial improvements when 20% aggregates and 3% cement were added to the raw soil: the maximum dry density increased by approximately 5%, the CBR by 2253%, the compressive strength by 134%, the indirect tensile strength by 85%, and the Young's modulus by 195%. Regarding fracture behavior, the same mixture showed an enhanced energy absorption capacity, with increases of approximately 40% for fracture energy, 65% for peak energy, 87% for elastic energy, 18% for plastic energy, and 5% for post-peak energy. These findings confirm that the combination of crushed aggregates and low cement content produces a synergistic effect, yielding a material that is stronger, stiffer, more water resistant, and more ductile. Thus, innovative stabilization approach represents a promising alternative for sustainable road construction.

Keywords: Lateritic Soils; Cement; Crushed Granite Aggregates; Geomechanical Properties; Stabilization; Fracture Energy.

1. Introduction

Lateritic soils cover approximately one-third of the world's continental landmass and are particularly prevalent in tropical and subtropical regions [1]. Crushed aggregates are among the most commonly used materials for road pavement construction in subtropical regions. In Burkina Faso, lateritic soils are readily available and widely used in construction. A significant portion of the sub-base and base layers of roads in the country relies on these materials. However, their systematic use over many years has led to the depletion of high-quality deposits [2]. Additionally, the continuous increase in road traffic, particularly that of heavy vehicles, has restricted the use of untreated lateritic soils on high-traffic roads. These factors highlight the need to enhance the geomechanical properties of lateritic soils to ensure the durability of road infrastructures [3, 4].

* Corresponding author: adamah.messan@2ie-edu.org

http://dx.doi.org/10.28991/CEJ-2025-011-10-020

Over the years, various studies have investigated methods for improving the geomechanical properties of lateritic soils, each with its own advantages and limitations. Among these methods, cement stabilization is widely employed. This involves the addition a predetermined proportion of cement to the soil to improve its mechanical properties. Cement stabilization is particularly advantageous because it significantly enhances the California Bearing Ratio (CBR), strength, durability [5–9], and water resistance of lateritic soils. It generally performs better than other stabilization methods [8].

Wahab et al. [10] studied the strength and durability of a lateritic soil stabilized with cement (0%, 3%, 6%, 9%, and 12% of dry weight). They observed a gradual increase in compressive strength and optimal dry density with cement content, reaching maximum increases of 846.3% and 6.4%, respectively, at 12% cement content. However, they noted a progressive decrease in relative axial strain, with a maximum reduction of 53.88%, also at 12% cement content. These results indicate an increase in the elastic modulus of lateritic soil with increasing cement content. Subsequently, the treated samples were subjected to 15 wetting-drying cycles to assess their durability. They observed an increase in compressive strength with cycles for the samples treated with 9% and 12% cement, whereas a gradual decrease in compressive strength was noted for the samples treated with 6% cement. Conversely, the samples treated with 3% cement collapsed after the first cycle. However, the 6% cement content was retained for stabilization, as it achieved a 7-day compressive strength of 1233.15 kPa after the 15 wetting-drying cycles, far exceeding the 800 kPa threshold required for low-traffic stabilized roads, in accordance with the standards of the Malaysian Public Works Department.

Mengue et al. [11] also studied the effect of cement addition (0%, 3%, 6%, 9% of dry weight) on the geomechanical properties of lateritic soils under different moisture states (-2% of optimum moisture content (OMC), OMC, +2% of OMC). They observed an increase in the CBR index with cement content, rising from approximately 18% in its natural state to a maximum value of 200% with 9% cement. With the addition of 9% of cement, compressive strength, tensile strength, and secant modulus increased by approximately 38%, 51%, and 91%, respectively, compared to the values of raw materials. For example, for a cement content of 9%, when comparing the compressive strength, tensile strength, and secant modulus values of samples molded with Optimum Proctor to samples molded with OPM-2% (dry side) and OPM+2% (wet side) after 7 days of curing, we note that after 7 days of curing of samples treated with 9% cement and molded with Optimum Proctor, the compressive strength decreased by 10.95% on the dry side and 52.07% on the wet side, tensile strength decreased by 36.54% on the dry side and 46.15%, and secant modulus decreased by 10.09% on the dry side and 49.39% on the wet side. The CBR index after 4 days soaked decreased by approximately 22% on the dry side and 36% on the wet side. This result highlights the importance of mixing water content for the success of cement stabilization. In their study, a cement content of 6% met the CEBTP [12] requirements for base layers concerning the various parameters mentioned.

However, a high cement content tends to make the material brittle [6, 10, 11, 13, 14] and increase the vulnerability to cracking [6, 14, 15]. The vulnerability to brittleness and cracking increases with the increasing cement content [6]. Triaxial shear tests carried out by Mengue et al. [11] revealed ductile behavior for untreated lateritic soils and brittle behavior for cement-treated lateritic soils (3%, 6%, 9% dry weight). Similarly, Mbengue et al. [3] observed a tendency for the soil-cement mixture to become more brittle as the cement content increased (1%, 2%, 3% dry weight).

This brittle behavior of cement-treated soil indicates that it loses its ability to deform without breaking under stress as the cement content and curing duration increase. The consequences of such behavior include the following.

- Abrupt failure: Although it can resist a certain degree of deformation, it breaks suddenly under maximum stress, without any noticeable transition phase.
- Vulnerability to dynamic loads due to its low energy absorption capacity before failure;
- Development of microcracks under stress, preventing easy deformation; failure mode that facilitates water infiltration and faster failure.

Therefore, the brittle behavior of treated soil represents a major risk of premature deterioration of roads, particularly when used in base layers. Based on the above, reducing the amount of cement used could favor the ductile and semi-rigid behavior of the improved soil, thereby limiting premature degradation.

Shrinkage is an inherent problem in cement-based materials, potentially leading to harmful cracks that accelerate material degradation [6, 16]. George [17] studied the shrinkage characteristics of 11 cement-treated soils (0%, 3%, 6%, 10%, 15%). The results showed that for nine of the ten analyzed soils, shrinkage decreased between 0% and 3% cement content. Additionally, seven of the 10 soils reached a minimum shrinkage at 3% cement content, after which shrinkage gradually increased, reaching a maximum or stabilizing at 10% cement content. Finally, beyond 10%, shrinkage increased in two out of ten soils, whereas shrinkage in the other eight soils decreased or stabilized. Moreover, for most of the analyzed soils, the cement content that minimized shrinkage was lower than the minimum cement content required for stabilization. Thus, the author suggested optimizing shrinkage by using the lowest cement content to achieve durable stabilization objectives. The interpretation was conducted on ten soils, as the shrinkage in the natural state of one of the studied soils was not presented in the study.

Other authors have also highlighted some limitations of cement stabilization, particularly the difficulty in stabilizing certain types of organic soils as well as soils with a high content of soluble salts such as sulfates, carbonates, and nitrates [18–20]. Finally, direct emissions from the cement industry account for approximately 7–8% of global anthropogenic CO_2 emissions, primarily generated by the calcination of carbonates during the clinker production process [21]. Therefore, reducing cement usage as much as possible would be beneficial not only for the environment, but also for the previously mentioned aspects.

In addition to the method of improving soil by adding cement, there is a much more environmentally friendly alternative: lithostabilization. This technique involves the addition of granular materials to soil to improve its geomechanical properties. Thus, Mbengue et al. [22] worked on improving the geomechanical characteristics of lateritic soils by adding crushed granite aggregates (20%, 25%, 30%, and 35% of the soil's dry mass) of class 0/31.5. With the addition of 20% to 30% crushed aggregates, the CBR index relatively increased by 164% (14% to 37%), the compressive strength by 140% (0.72 MPa to 1.73 MPa), and the elastic modulus by 309% (80 MPa to 327 MPa). Notably, the best improvements were obtained at percentages of 25% and 30% crushed aggregates, allowing their use in subbase layers according to CEBTP [12] criteria.

Issiakou et al. [23] studied the improvement of lateritic soils by adding 10% crushed lateritic nodules of class 0/5. They observed an increase in maximum dry density of 13.9% (18 kN/m³ to 20.5 kN/m³), a 45.5% increase in the CBR index (22% to 32%), a 675% increase in cohesion (4 kPa to 31 kPa), and a 31% decrease in plasticity index (16.21 to 12.30) compared with raw lateritic soil. According to CEBTP [12], in terms of these parameters, the treatment enables the soil to be used as a sub-base layer.

Hyoumbi et al. [24] worked on the improvement of two types of fine lateritic soils by adding basalt crushed aggregates (0%, 20%, 30%, 40%, and 50%). The results showed a progressive increase in the CBR index as a function of the crushed aggregate content for both types of soil, with maximum increases of 104.5% and 136%, respectively. The compressive strength was also evaluated at curing times of 7, 14, and 28 days. After seven days of curing, the treated samples showed higher compressive strength than the untreated samples for both soils. However, at 28 days, the opposite trend was observed: a systematic decrease in compressive strength was observed for almost all treated samples, while the untreated samples continued to strengthen. This drop in performance could be attributed to excessive moisture content loss, leading to a loss of cohesion between the soil and aggregates, and thus a reduction in mechanical strength. This phenomenon could make the method less effective in the long term, particularly in arid regions.

Houanou et al. [25] studied the improvement in the geomechanical characteristics of lateritic gravel from Avlamè through the addition of crushed granite (10%, 15%, 20%, 25%, 30%, and 35%) of 0/31.5 grading. The addition of crushed aggregates led to a reduction in the passing fraction at the 80 μm sieve by 62% (from 27.77% to 10.51%), a decrease in the plasticity index by 36% (from 17.67% to 11.33%), and an increase in the maximum dry density by 3% (from 2.17 t/m³ to 2.23 t/m³). At the same time, the CBR index at 95% OPM increased by 87% (from 58.00% to 108.67%). With the exception of the formulation containing 10% crushed aggregates, all the mixtures met the requirements for use in base course layers, in accordance with CEBTP recommendations [12].

This result raises the question of the durability of materials treated using this improvement method. Additionally, this method only slightly enhances the mechanical properties of materials, as reflected in the very limited increase in CBR index, which at best does not exceed 200% compared with soil, compared with soil-cement mixtures whose CBR values can significantly exceed this threshold [11, 26, 27]. Consequently, the use of lithostabilized soils is generally limited to sub-base layers, and even more so in base courses, especially for high traffic loads, according to CEBTP [12] guidelines [4, 22–24, 28]. Comparative analysis of the immediate CBR index and CBR index after four days of immersion in water also revealed a drastic decrease in the CBR index after four days of immersion in water [4, 22, 24]. Unlike lithostabilized soils, soils treated with cement at a certain rate generally show an increase in the CBR index after 4 days of immersion in water [3, 11, 26].

Given the limitations and inconveniences of these two methods, researchers have explored combined approaches. The aim is to capitalize on the advantages of each technique while minimizing its drawbacks to propose a more efficient and sustainable solution.

Tran et al. [14] conducted an experimental study on the effects of natural rubber latex (NRL) on cement-stabilized lateritic soil (LS) blended with recycled aggregates (SS and RCA). Replacement ratios of 50% and 70% with 5% cement and dry rubber-to-cement (r/c) ratios of 0%, 3%, 5%, and 10% were investigated. The results showed that the NRL influenced compactability, unconfined compressive strength (UCS), and indirect tensile strength (ITS). At an optimal r/c ratio, NRL films coexist with cement hydration products, reducing the porosity and enhancing interparticle bonding. This interaction mitigates the brittle behavior of the stabilized LS, thereby improving ductility and durability. This study demonstrated the potential of NRL and recycled aggregates as sustainable and resilient pavement base layers.

Similarly, Chah et al. [29] studied the incorporation of recycled plastic waste into fine soils that were treated with cement. Four types of plastics (PP, HDPE, PLA, and PET), in the form of flakes or granules, were tested at contents of 2%, 4%, and 6% with 6% cement. However, they observed a progressive decrease in the maximum dry density, compressive strength, tensile strength, and CBR index with increasing plastic content. Sorptivity generally increased, except for PET beyond 4%. Life cycle assessment showed that flakes had a lower environmental impact than granules did. Despite the reduction in strength, mixtures containing up to 6% plastic exhibit acceptable properties with a lower environmental impact. One approach focused more on waste valorization and reduction of environmental impact.

In the same category, Que et al. [30] investigated the use of mining tailings sand (TS) as a partial replacement for sand in cement-stabilized road foundations. Different TS proportions (0%, 10%, 16%, 23%, and 30%) were tested with 5% cement. The maximum dry density increased with the addition of TS before slightly decreasing at higher TS contents, whereas it remained higher than that of the soil without TS. Compressive and flexural strengths decreased with TS but remained > 4 MPa for TS ≤ 16%. Shrinkage and durability under freeze-thaw, wet-dry, and sulfate cycles remained acceptable for TS ≤ 16%. Microstructural analyses showed increased porosity but no significant chemical reactions. The inclusion of TS reduces costs and carbon footprint, thus providing a sustainable solution for valorizing mining residues.

On the other hand, Daheur et al. [31] studied the stabilization of a mixture of tuff and sand (65% tuff + 35% sand) using three types of binders: cement alone (2%, 4%, 6%), lime alone (2%, 4%, 6%), and a lime-cement combination (2%, 4%, 6%). The lime-cement mixture contained two-thirds (2/3) of the lime and one-third (1/3) of the cement in proportion to the dry mass. The proportions of tuff and sand used in their study were the optimal result obtained by mixing these two soils in a previous study [32]. The results showed that all three binders improved the geomechanical properties of the Tuf-Sand mixture to different degrees. Cement alone offers the most notable improvements, followed by the lime-cement mixture and, lime alone. For example, when the binder content increased from 0 to 6%, the compressive strength of the mixture increased by 190% (from 1.71 to 4.98 MPa) with cement, 60% with lime, and 90% with the lime-cement mixture. Under the same conditions, the E50 modulus increased by 230% (from 298 to 987 MPa) with cement, 58% with lime, and 104% with the lime-cement mixture. Similar trends were observed for the CBR index and the resistance to aggressive natural water (water-containing salts). However, the study did not address tensile strength, which is an important parameter for evaluating the performance of soils stabilized with hydraulic binders.

Similarly, Imafidon et al. [33] studied the effect of lithostabilization by adding sand (0%, 10%, 20%, 30%, 40%, 50%), cement stabilization (2%, 4%, 6%, 8%, 10%), and a combination of both methods (mixed) on deltaic lateritic soils in Nigeria. For mixed stabilization, the cement rate was fixed at 2% and 4%, whereas the sand rate varied among the mentioned percentages. Lithostabilization improved the properties of the lateritic soil, making it suitable for use as a sub-base layer. However, the effect was less significant than that of chemical and mixed stabilization. They also showed that the combination of chemical and mechanical stabilization significantly reduced the amount of cement required for soil stabilization, making the method more economical. However, this study was limited to determining the CBR index, which is not the only design parameter. Recent studies have shown that the CBR index, strength, and other essential soil parameters may exhibit divergent trends [22, 34].

Next, Saheli et al. [34] studied the effects of crushed stone residues (0%, 10%, 20%, 30%) and cement (0%, 3%, 5%, 7%) on silty sand. The results showed that crushed stone residues could be combined with cement for stabilization purposes, thereby improving the geomechanical properties of the soil. They noted an increase in maximum dry density and CBR index with crushed stone residues and cement content, with the best values obtained at 30% crushed stone residues, regardless of the cement content. The same trend of increasing compressive strength was observed between 0% and 10% crushed stone residues for all cement contents. However, beyond 10%, compressive strength decreased with the increasing in crushed stone residue content. Nevertheless, the study did not address tensile strength and Young's modulus, which are two important parameters for evaluating cement-stabilized soil.

Savadogo et al. [35] studied the effect of cement addition on two types of lateritic gravel, LG1 and LG2, intended for use in road base layers. Three cement dosages (1%, 1.5%, and 2%) were tested, applied either to the gravel alone or to a 90% gravel–10% crushed aggregate mixture. The results show that cement slightly increases the plasticity index, but mainly improves the bearing capacity. Combined stabilization with crushed aggregates also increased the bearing capacity compared with that of untreated gravel, but less than that of cement alone. To meet the base layer requirements according to CEBTP specifications [12], LG1 requires at least 1.5% cement, and LG2 at least 1%.

Okonkwo et al. [36] also studied three types of stabilization: lateritic soil with different cement contents (3%, 6%, 9%, and 12%), a lateritic soil with different sand percentages (15%, 30%, 45%, and 60%); and finally, a mixture of lateritic soil, cement, and sand at various contents. The CBR index of these mixtures increased as the quantity of cement and sand increased. The soil-cement mixture achieved a CBR of 175% for a cement content of 6%, whereas the soil-sand mixture exhibited a CBR of 86% for a sand percentage of 30%. The soil-cement-sand mixture exhibited a CBR of 112% for, cement percentage of 9% and a sand content of 45%. Similarly, this study was limited to determining the CBR index.

Nevertheless, previous studies combining physical stabilization and cement addition have two major limitations. First, they often overlook essential mechanical parameters such as Young's modulus [37] and tensile strength, which are crucial for reliable pavement design. Second, they rely on relatively high cement content, which increases the brittleness of the resulting composite materials. It should also be noted that some recent studies have attempted to analyze the fracture behavior of cement-stabilized soils. However, these studies have generally limited their assessment to peak-strain comparisons of cement-treated soils [3, 11, 15, 31]. Such an approach is reductive because it does not account for the overall mechanical behavior of the material, particularly the fracture energy, which is a key parameter for pavement durability.

To address these shortcomings, the present study proposes an improvement approach that combines the addition of crushed aggregates with low cement content. By adding crushed granite aggregates, the aim is to reinforce the granular framework of the soil, thereby improving several geomechanical properties. The introduction of cement increases the cohesion and water resistance of the mixture. The combination of both aims to reduce the amount of cement required to achieve the desired performance, thereby limiting both material brittleness and cracking, while reducing its carbon footprint.

The objective was twofold: to significantly improve the geomechanical properties of laterite, while preserving its ductility as much as possible. Therefore, this study goes beyond traditional geotechnical tests (Proctor test, immediate, and soaked CBR index) by integrating the evaluation of the Young's modulus, indirect tensile strength, and a detailed analysis of the compressive behavior of the specimens. On this last point, this paper introduces an analysis of the fracture energy under uniaxial compression, incorporating elastic, plastic, and post-peak contributions.

The paper is structured as follows: Section 2 presents the lateritic soil borrow used as the matrix, other materials employed, and their properties, and describes the methods used for physical, compaction, and mechanical tests. Section 3 is devoted to the presentation, analysis, and discussion of the results, with particular emphasis on the geotechnical and mechanical properties as well as the behavior of the different formulations. Finally, Section 4 provides the conclusion, summarizes the main findings of the study, highlights its limitations, and suggests directions for future research.

2. Materials and Methods

2.1. Materials

The lateritic soil used in this study was collected from the Kamboinsé borrow pit (12° 20′ 00″ N, 1° 30′ 0″W) in Kadiogo province, northwestern Burkina Faso. This borrow pit is well-known and has been used in several road construction projects in the country. A view of the Kamboinsé borrow pit is shown in Figure 1. The soil samples were taken from the B horizon, which is composed of reddish-brown lateritic gravels classified as (10R 4/6) based on the Munsell Soil Color Chart [38]. The grain-size distribution curve of the lateritic soil is shown in Figure 2.

Figure 1. Cross-section of the Kamboinsé borrow pit

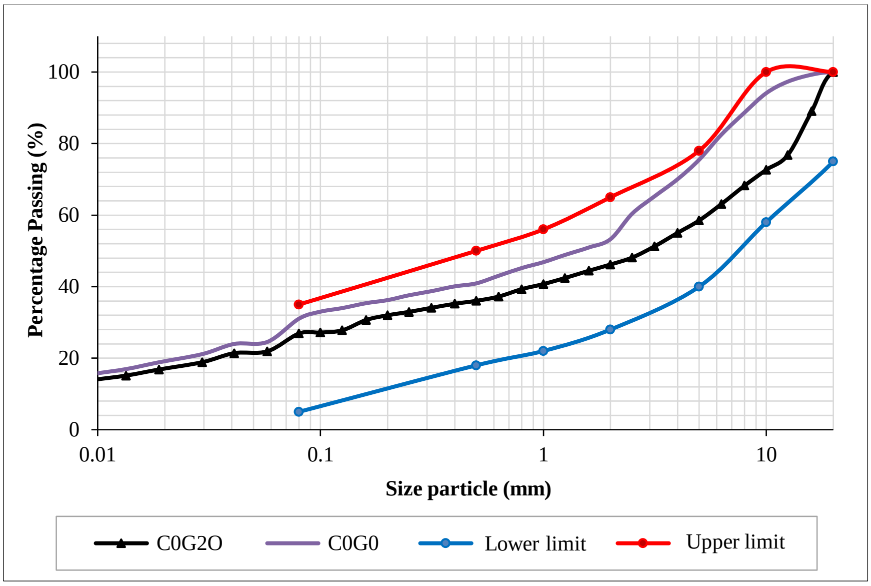

Figure 2. Grain size distribution Lateritic Soil (C0G0) and the Lateritic Soil-with Crushed Aggregate Mixture (C0G20) and comparison with the CEBTP [1] criteria for the application in sub-base layer

Crushed granite aggregates used in this study were supplied by a local company. Aggregates were graded as 10/20. They were characterized by several tests, including particle size analysis, specific gravity, and the Los Angeles abrasion test. The results of these tests are presented in Table 1. The particle size analysis of the crushed granite aggregates is shown in Figure 3. The uniformity coefficient (Cu = 1.21) was less than 4, and the curvature coefficient (Cc = 1.03) was outside the range [1, 3]. These results indicated that the particle size distribution of the crushed aggregates was dense and poorly graded. The Los Angeles abrasion coefficient of 38 (less than 40) is in line with the recommendations of the CEBTP [12] and can be used as a base course.

Table 1. Characteristics of crushed aggregates

Effective particle size (mm)				Curvature Coefficient	Uniformity Coefficient	Coefficient Los Angeles	Specific density (kN/m^3)
	D_{10}	D_{30}	D_{60}				
Crushed aggregates Granite 10/20	11.7	13.1	14.2	1.03	1.21	38	28.3

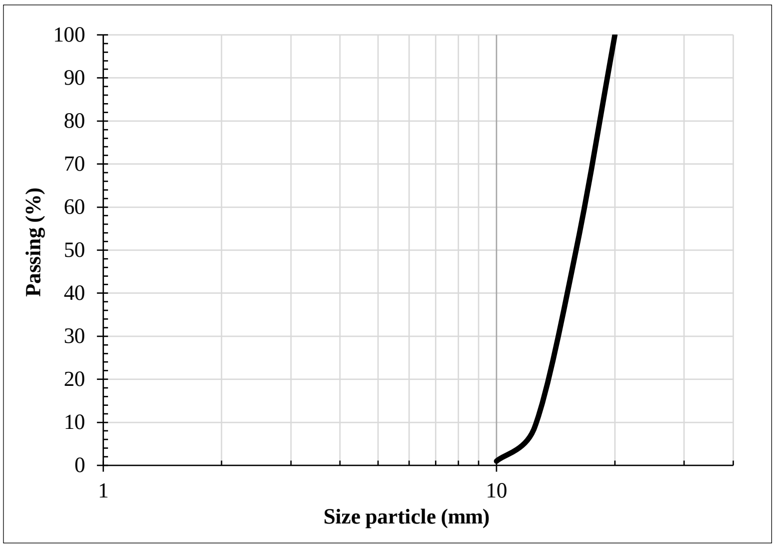

Figure 3. Gradation Curve of Crushed Granite Aggregates

The cement used in this study was CEM II/A-L 42.5 R, which is commercially available in Burkina Faso.

2.2. Methodology

The work methodology is summarized in the flowchart shown in Figure 4. The study began with a field survey to collect the laterite samples. This was followed by geomechanical characterization of laterite soil, crushed aggregates, and various mixes. The quartering method and a sample splitter were used to ensure sample homogeneity.

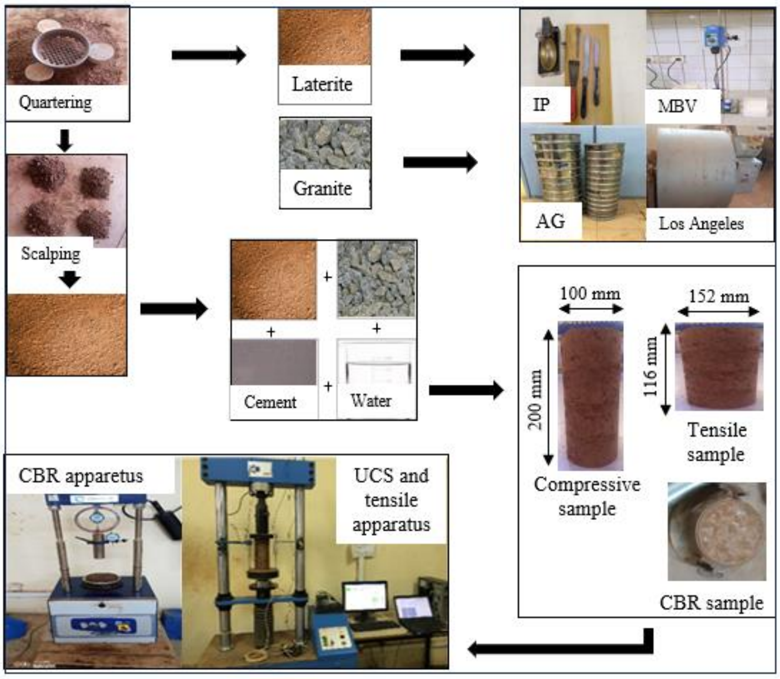

Figure 4. General methodology of the tests

The formulations of the studied mixtures and their nomenclature are presented in Table 2. The proportion of crushed granite aggregates was fixed at 20%, whereas the cement content varied from 0% to 3% in 1% increments. The mix percentages were determined in relation to the dry mass of lateritic soil, which was sieved to remove particles larger than 20 mm.

Table 2. Nomenclature of mixtures

Formula	Lateritic gravel content (%)	Crushed aggregates content (%)	Cement content (%)
C0G0	100	0	0
C0G20	80	20	0
C1G20	79	20	1
C2G20	78	20	2
C3G20	77	20	3

2.2.1. Physical Properties and Compaction Tests

Particle size analysis by soil sieving was carried out in accordance with the standard NF EN ISO 17892 [39] on soil particles retained on the 80 µm sieve, enabling the proportion of materials to be determined according to their diameter. For particles smaller than 80 µm, sedimentation analysis was performed in compliance with the NF EN ISO 17892 standard [39]. The Atterberg limits were determined on 0.4 mm sieve passers according to the standard NF EN ISO 17892-12 [40], whereas methylene blue value tests were performed on 5 mm sieve passers according to the standard NF P 94-068 [41]. Specific gravity of the soil was measured using a water pycnometer. The Modified Proctor test was used to determine the optimum moisture content (OMC) and the maximum dry density (MDD), following the standard NF P 94-093 [42].

2.2.2. Mechanical Properties Tests

The California Bearing Ratio (CBR) index was determined according to the standard NF P 94-078 [43]. The test was conducted on soil particles with diameters less than 20 mm. The immediate CBR index, which indicates the short-term bearing capacity of the soil, was determined for all samples. Then, the CBR index after three days of curing in air and four days of immersion in water was determined for the cement-improved samples. The C0G0 (untreated samples) and C0G20 (samples containing 20% of crushed aggregates) specimens did not undergo a 3-days air cure but were soaked in water directly after production, enabling the measurement of long-term bearing capacity. Air curing involved storing the compacted samples in a conditioned chamber at a temperature of 20°C. The CBR index after immersion provides an assessment of the soil bearing capacity under hydric conditions, reflecting the long-term performance. All CBR indices were determined at 95% of the maximum dry density (MDD).

The unconfined compressive strength (UCS) test was conducted on specimens measuring 10 cm in diameter and 20 cm in height. These samples were prepared via static compaction at the optimum water content and modified Proctor energy. Three specimens for each formulation were prepared and tested. These specimens were then wrapped in plastic bags to prevent water loss and stored for seven days in a room maintained at a temperature of 20°C. The compressive strength was determined according to the standard NF EN 13286-41 [44], whereas the Young's modulus was determined following the standard NF EN 13286-43 [45]. These two parameters, the compressive strength (Rc) and modulus of elasticity (E), were obtained from Equations 1 and 2, respectively

$$R_C = \frac{F}{A_C} \tag{1}$$

where Rc is the compressive strength (MPa), F is the maximum force applied on the specimen (N), and A_C is the cross-sectional area of the specimen (mm²).

Young's modulus was calculated from the ascending slope of the stress–strain curve in Figure 5 [13, 46] according to Equation 2 [45, 46]:

$$E = \frac{\sigma}{\varepsilon} = \frac{1{,}2*F}{\pi D^2 \varepsilon} \tag{2}$$

where, E is the modulus of elasticity (MPa), F is the maximum force applied, D is the specimen diameter (mm), where ε is $\varepsilon_{30} - \varepsilon'$ (Figure 5), ε_{30} (%) is the longitudinal elongation of the specimen when the force is equal to 0,3*F, and ε' (%) is the corrected longitudinal elongation of the specimen when the force is equal to 0.

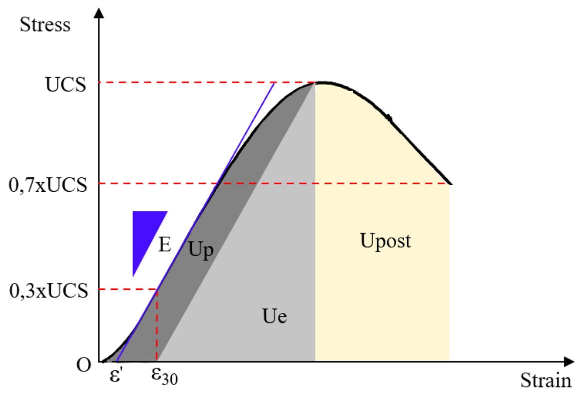

Figure 5. Method for determining Young's modulus and fracture energies (UCS: Unconfined Compression test strength)

The fracture energy (Ur) was determined from Equation 3:

$$Ur = Up + Ue + Upost \tag{3}$$

where Up, Ue, and Upost are the plastic energy, elastic energy, and post-peak energy, respectively, each representing a portion of the area under the stress–strain curve, as shown in Figure 5.

The indirect tensile strength (ITS) tests were conducted in accordance with the standard NF EN 13286-42 [47]. The specimens were molded at the optimum moisture content and compacted manually using Modified Proctor energy. The specimens were 152 mm in diameter and 117 mm in height, with an aspect ratio of 1.3. Samples were stored in plastic bags at a controlled temperature of 20°C. The curing period was seven days, in line with the UCS test.

The indirect tensile strength of the specimen was calculated from the maximum force at failure F, using the relationship shown in Equation 4.

$$R_{it} = \frac{2F}{\pi HD} \tag{4}$$

where; R_{it} is the indirect tensile strength (MPa), F is the maximum force at failure (N), H is the specimen height (mm), and D is the specimen diameter (mm).

3. Materials and Methods

3.1. Geotechnical Properties of C0G0 and C0G20

The results of particle size analysis for C0G0 and C0G20 are presented in Figure 2. Figure 2 shows that the granulometric curves of samples C0G0 and C0G20 fit entirely within the recommended granulometric envelope for sub-base layers, as specified by CEBTP [12]. Both curves exhibit an "S" shape, indicating a well-graded particle size distribution. The curve for C0G20 was below that for C0G0, demonstrating that the addition of 20% crushed aggregates improved the particle skeleton of the raw lateritic soil. The percentage of particles passing through the 80 µm sieve was 30% for C0G0 and 27% for C0G20, indicating a slight reduction in fines due to the addition of crushed aggregates. According to CEBTP [12], these two materials are suitable for use as sub-bases.

The main geotechnical characteristics of C0G0 and C0G20 are summarized in Table 3. The granulometric and plasticity results classified the studied lateritic soil as B6 soil (sandy and gravelly soil with fines) according to the Road Earthworks Guide [48]. According to the HRB [49] classification, the soil belongs to class A-2-6, which corresponds to silty or clayey gravel and sand. Classification using the Casagrande diagram refines the analysis and identifies the fine fraction of this soil, which is highly plastic clay.

Table 3. Geotechnical properties of C0G0 et C0G20

Materials	Passing (%)		PI (%)	MBV	MDD (kN/m^3)	OMC (%)	CBR_Im (%)	CBR (%)	γs (kN/m^3)
	d>80 µm	d>2 mm							
C0G0	30.22	53.27	28	0.91	20.2	12.1	47	17	29.1
C0G20	26.9	46.19	28	0.91	20.9	9.8	102	18	-

d: diameter (mm), PI: Plastic Index, MBV: Methylene Blue Value, OMC: Optimum Moisture content, MDD: Maximum Dry Density, CBR: Californian Bearing ratio after 4 days soaked in water compacted at 95% of the maximum dry density, CBR_Im: Immediate Californian Bearing ratio compacted at 95% of the maximum dry density.

Regarding the plasticity index, this soil cannot be used as a base course according to CEBTP [12] specifications, as its plasticity index is below the required threshold of 15. However, it can be used as a subgrade layer for low-traffic roads where a maximum plasticity index of 30 is allowed. The maximum dry density of the soil was slightly higher than the minimum threshold of 20 kN/m³ 20.2 kN/m³, above the required for use in base layer, and its optimum water content of 12.1% is lower than the maximum limit of 13% recommended by CEBTP [12] for use in base courses. The CBR index after four days of immersion, measured at 95% compaction, was 17%, classifying this soil in category S4 according to CEBTP [12]. Mbengue et al. [3] obtained a CBR index of 49 % for the same lateritic borrow pit in the present study and classified it as category S5. This significant difference in CBR values may have resulted from the samples taken from different layers of the quarry and at different times. This divergence can be explained by the fact that the samples were collected from different quarry layers and during different periods.

3.2. Geomechanical Properties of the Mixtures

3.2.1. Physical Properties of Mixtures

Figure 6 shows the variation in the plasticity index and methylene blue value (VBS) as a function of the cement and crushed aggregate content.

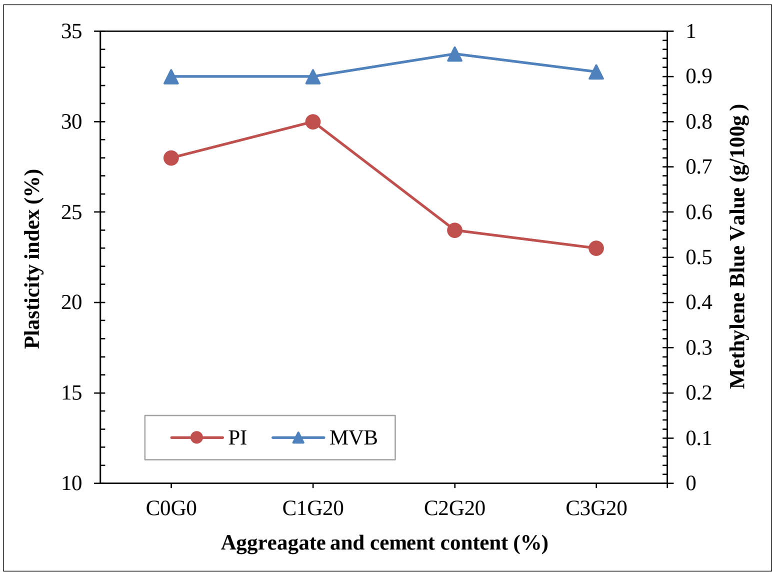

Figure 6. Variation of plasticity index and methylene blue value as a function of cement and crushed aggregate content

Figure 6 shows that the addition of cement influences the plasticity and clay content of lateritic soil, unlike crushed granite aggregates, which do not affect these properties. Indeed, the crushed aggregates (class 10/20) added to the lateritic soil did not contain any 5 mm and 400 µm sieve passings that could influence the methylene blue value and plasticity index. Furthermore, after adding 1% cement and 20% crushed aggregates, the plasticity index slightly increases from 28% to 30%. It decreased to 24% and 23% after the addition of 2% and 3% cement in lateritic soil mixed with 20 % crushed aggregate, respectively. The decrease in PI with the addition of cement was attributed to the cement hydration reactions. These hydration reactions lead to the aggregation and flocculation of fine particles, resulting in the formation of coarser particles, which in turn lead to a decrease in the plasticity index [50–53]. Mbengue et al. [3] also observed a progressive decrease in plasticity with increasing cement content for the Kamboinsé borrow pit in the present study. The plasticity index in their study varied from 19% in the raw material to 12% after the addition of 3% cement.

The MBV is 0.9 for the raw lateritic soil and for the lateritic soil mixed with 20% crushed aggregates and 1% cement. It reaches 0.95 for C2G20 and 0.91 for C3G20. Notably, the addition of cement did not significantly affect the MBV of the material. CEBTP [12] recommends the use of a lateritic soil with a PI less than 15% in the base course and 20% in the sub-base layers, values not achieved by the improved materials. For low-traffic roads, a maximum PI of 30% is accepted for sub-base layers, and a PI below 25% is accepted for base layers. Thus, formulas C2G20 and C3G20 are acceptable according to the criterion related to the PI in the sub-base layer for low-traffic volume pavements.

Figure 7 shows the variation in the maximum dry density and optimum moisture content as a function of the crushed aggregate and cement addition.

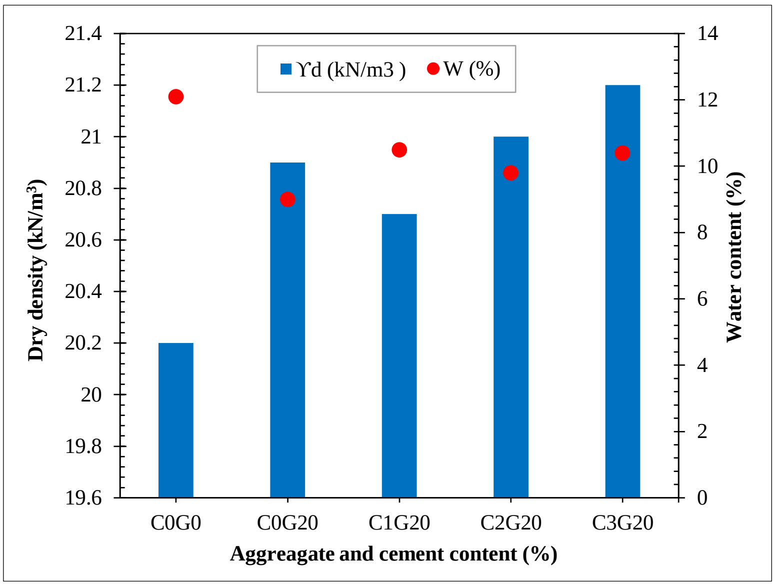

Figure 7. Variation in Maximum Dry Density (MDD) and Optimum Water Content (OMC) as a Function of Crushed Aggregate Addition and Cement Content

The addition of 20% crushed aggregates increased the maximum dry density from 20.2 kN/m³ in its natural state to 20.9 kN/m³. The optimum water content decreases from 12.1% to 9%. This trend can be explained by the reinforcement of the granulometric skeleton of the natural lateritic soil after the addition of 20% crushed aggregates. Consequently, the fines content decreased, reducing the optimum moisture content required for the C0G20 mix.

The addition of cement to C0G20 resulted in a slight increase in dry density and optimum moisture content. Indeed, the maximum dry density increased from 20.9 kN/m³ for C0G20 to 20.7 kN/m³, 21 kN/m³, and 21.2 kN/m³ for C1G20, C2G20, and C3G20, respectively. This trend can be explained by considering cement as a filler that interlocks and fills voids. In addition, cement tends to lubricate soil particles when water is present, resulting in denser compaction. Similar results were reported by Mbengue et al. [3]. Mbengue et al. [3] studied on two lateritic borrow pits, including one in this study. They reported optimal dry densities ranging from 20.3 kN/m³ in its natural state to 20.6 kN/m³ after a 3% cement stabilization for the Saaba borrow pit and from 20.3 kN/m³ to 21 kN/m³ for the Kamboinsé borrow pit.

The optimum water content increased from 9% for C0G20 to 10.5%, 9.8%, and 10.4% for C1G20, C2G20, and C3G20, respectively. This increase can be attributed to the affinity of cement for water. The increase in cement content should be accompanied by an increase in water demand for the dissociation of portlandite [3, 53].

These trends are consistent with the observations of Saheli et al. [34], who showed that the combination of cement and crushed stone waste increases the maximum dry density while reducing the optimum moisture content. Similarly, Imafidon et al. [33] and Okwonko et al. [36] emphasized that the synergistic effect of cement with a granular skeleton (sand) improves the compaction characteristics compared with the use of cement alone. However, Savadogo et al. [35] demonstrated that the effect of the cement–crushed aggregate combination as a stabilizer varies depending on the nature of the laterite considered. Indeed, the joint addition of aggregates and cement led to an increase in the OMC for one soil, whereas a reduction was observed for the other. Regarding the maximum dry density (MDD), cement alone systematically induces an increase, but the introduction of crushed aggregates can generate additional porosity beyond a certain threshold, which limits this gain. These results suggest that the effectiveness of the combination depends closely on the final particle-size distribution of the mixture, which determines its compactness. In their study, the raw soils showed good compliance with the CEBTP granular envelope for the base course material, with one fitting entirely within the range and the other almost entirely.

According to the recommendations of CEBTP [12], all mixtures can be used as base layers because their maximum dry density exceeds 20 kN/m³. Additionally, all recorded optimum water contents were below 13%, the upper limit for base layer applications.

3.2.2. Mechanical Properties of the Mixtures

Figure 8-a illustrates the variation in the Immediate CBR Index (CBR_Im) and the CBR Index after 3 d of air curing followed by 4 d of soaking (CBR_3d_a_+_4d_So) at 95% compaction as a function of different formulations. Figure 8-b presents the swelling of the formulations.

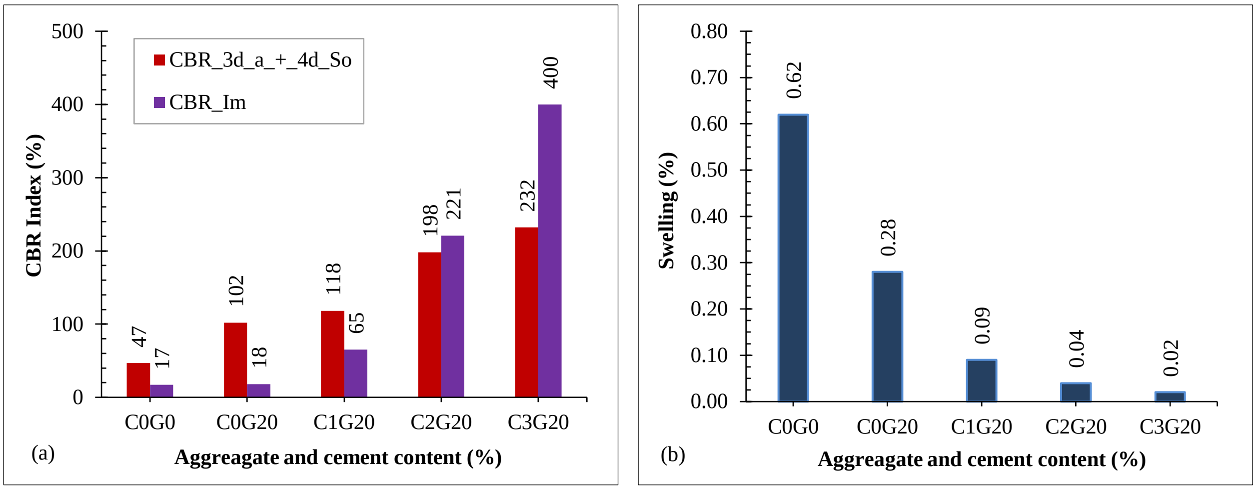

Figure 8. Variation of a) the immediate CBR index and the CBR index after 3 days of air curing followed by 4 days of soaking with respect to cement content and aggregates. b) the swelling with respect to cement content and aggregates

The addition of 20% crushed aggregates to the raw lateritic soil resulted in a significant increase in the immediate CBR index, rising from 47% for the raw soil (C0G0) to 102% for C0G20. This improvement can be explained by better compaction and reinforcement of the granular skeleton due to the addition of the gravel. However, after four days of immersion, the CBR index decreased considerably from 47% to 17% for C0G0 and from 102% to 18% for C0G20. This decrease indicates that raw lateritic soil is highly sensitive to water content variation, and this sensitivity persists even after the addition of 20% crushed aggregates. This could be attributed to the high plasticity indices (28%) of C0G0 and C0G20.

The immediate CBR index and CBR index after three days of air curing followed by four days of water immersion increased with increasing in cement content. The immediate CBR index increases from 102% for C0G20 to 118%, 198%, and 232% for C1G20, C2G20, and C3G20, respectively. Meanwhile, the CBR index after 3 d of air curing and 4 d of water immersion increased from 18% for C0G20 to 65%, 221%, and 400% for C1G20, C2G20, and C3G20, respectively.

The increase in the CBR index with increasing cement content is due to the stiffening of the material resulting from cement hydration and the continuous development of cementitious compounds, such as calcium silicate hydrate (C-S-H). As the lateritic materials studied are water-sensitive, immersion significantly reduced the CBR index compared to the non-immersed sample. At 1% cement content, the immediate CBR index remained higher than the CBR index after immersion due to the high plasticity of the mixture (30%) and the low cement content.

However, after adding 2% and 3% cement, an opposite trend was observed. These higher cement contents allowed for hydration reactions. Cement immersion in water promotes the development of cementitious compounds that are responsible for the rigidity of materials. Similar results have been previously reported [11, 52]. Saheli et al. [34] observed that a progressive increase in the content of crushed aggregate waste and cement led to an improvement in CBR. Imafidon et al. [33] showed that sand–cement association as a stabilizer enables the reduction of the amount of cement required to reach a given CBR value. On the other hand, Savadogo et al. [35] highlighted that although the granite aggregate–cement combination does indeed improve the CBR of laterites, its effect is sometimes less significant than that obtained with cement alone. This result can be explained by the final particle size distribution of the mixture, as mentioned previously, which was used to interpret the Proctor results.

A study by Mbengue et al. [3] conducted on the same lateritic borrow pit reported a CBR index after 3 days of air curing and 4 days of water immersion of 180% compared to 49% for the raw soil, a relative increase of 267.35%. In the present study, the CBR index after 3 days of air curing and 4 days of water immersion for the raw soil was 17%. After adding 3% cement and 20% crushed aggregates, the CBR index increased to 400%, representing a relative increase of 2253%. This demonstrates that combining cement and crushed aggregates significantly increased the CBR index of the soil more than the addition of cement alone in equal proportions. Furthermore, with only 2% cement, the lateritic soil-crushed aggregate mixture already meets the CEBTP [12] criteria for base layer use, with a CBR index after 3 days of air curing and 4 days of water immersion well above the required minimum value of 160%. In a study by Mbengue [3], this threshold was only exceeded after adding 3% cement, demonstrating the positive effect of crushed aggregates.

Figure 8-b shows that the addition of crushed aggregates and cement significantly influenced the linear swelling of the lateritic soil. The addition of crushed aggregates to the lateritic soil reduced the initial linear swelling by more than half, from 0.62% to 0.28%. This reduction can be explained by the decrease in fine content induced by the addition of crushed aggregates, as well as by the physical effect of the aggregates, which partially limits the swelling of the expansive particles. The addition of 1%, 2%, and 3% cement to C0G20 also resulted in a gradual reduction in linear swelling, reaching 0.09%, 0.04%, and 0.02%, respectively. These results can be explained by cement hydration reactions, which limit the activity of expansive fines by creating rigid bonds between particles.

As result, the raw lateritic soil and the studied formulations complied with CEBTP [12] recommendations for use in sub-base and base layers, with linear swelling values below 1%.

Figure 9-a illustrates the compressive behavior of the tested specimens. The curve for a representative sample is shown for each formulation. Figure 9-b presents the fracture energy, Ur, and its different components (Ue, Up, Upost, and Upeak). The combined interpretation of the stress–strain curves and energy parameters allows the evaluation of the consistency between qualitative analysis (curve shape and peak stress strain) and quantitative analysis (fracture energies). The analysis in Figure 9 shows that the combined addition of granite aggregates and cement simultaneously modified the curve shapes and energy distribution. As shown in Figure 9-a, the C0G0, C0G20, and C1G20 specimens exhibited broad curves associated with relatively low compressive strengths. The C2G20 samples exhibited a semi-broad curve with a higher strength, whereas C3G20 exhibited the narrowest curves and maximum strengths. Figure 9a illustrates the corresponding energy variations; a decrease was first observed with the addition of 20% aggregate, followed by 1% cement. This trend is then reversed with 2% cement, where most energies reach their maximum values before slightly decreasing post-peak at 3% cement compared with the levels at 2%. It is also noteworthy that the elastic energy (Ue) constituted the dominant fraction of the peak energy for all formulations, reflecting the overall stiffness of the material, particularly for 2% and 3% cement.

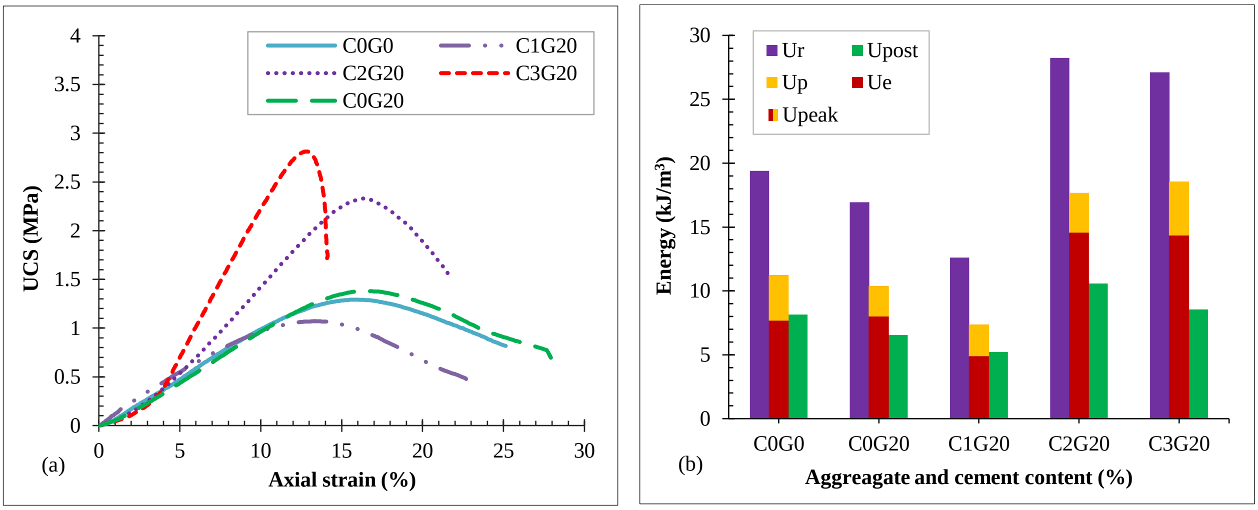

Figure 9. Variation of a) the unconfined uniaxial compressive behavior of lateritic soil at 7 days as a function of crushed aggregate and cement contents. b) fracture energy at 7 days and its components as a function of crushed aggregate and cement contents.

For C0G0, the stress–strain curve exhibited an overall softening behavior. This material is characterized by the highest peak strain (15.9%), indicating a strong deformation capacity. Although its strength remained relatively low compared to that of the improved formulations, it maintained moderate post-peak, plastic, and fractured energy values across all formulations. These characteristics reveal moderate ductility and toughness, which can be attributed to the high plasticity index and plastic modulus of raw laterite reinforced by the natural cohesion provided by the clay fraction.

After adding 20% granite aggregate to C0G0, the stress–strain curve of C0G20 remained relatively broad with a slight decrease in peak strain (15.2%) compared to C0G0 (15.9%). Energy analysis showed a decrease in Ur, Up, and Upost by 12.7%, 33.5%, and 19.7%, respectively, whereas Ue slightly increased by 4.6% compared to C0G0. These results indicated a slight reduction in the overall toughness, plastic deformation capacity before the peak, and ductility. This evolution shows that adding granular material without a binder can reduce toughness and ductility despite a slight improvement in mechanical strength (Figure 9-a and Figure 10), as well as in CBR (Figure 8-a). This result can be explained by the decrease in the plastic modulus and possibly the reduced cohesion in the C0G20 material. However, because the compressive strength of C0G20 remained higher than that of C0G0, the increase in Ue reflected a higher modulus (Figure 11).

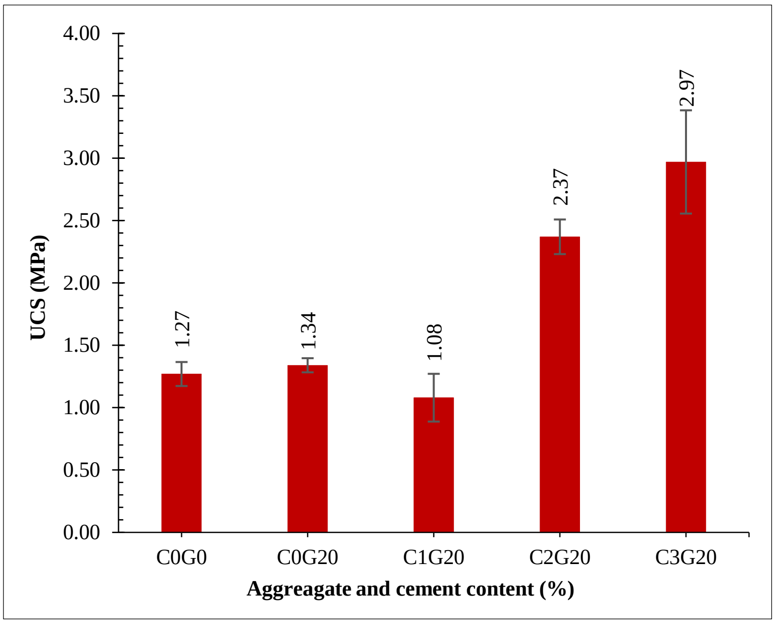

Figure 10. Variation of Compressive Strength at 7 Days as a Function of Crushed Aggregate addition and Cement Content

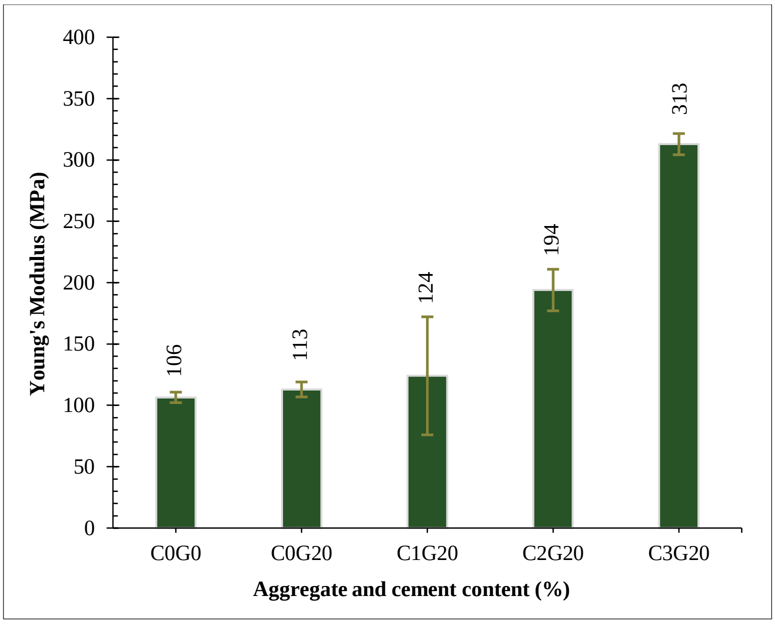

Figure 11. Variation of Young's Modulus (E) at 7 days as a function of aggregates and cement content (%)

With 1% cement added to the C0G20 mix, the stress–strain curve of C1G20 remained relatively broad, but the peak strain significantly decreased to 11.8%. Energy analyses confirmed a loss of ductility: Ur decreased by 25.6%, Ue by 39.1%, Upost by 20.2%, and Up slightly increased by 5% compared with C0G20. These variations indicate a reduction in overall toughness, elastic deformation capacity, and material ductility. A slight increase in the elastic modulus (Figure 11) was observed, reflecting the initial stiffening effect of the cement. Overall, a 1% cement content remained insufficient at 7 d to ensure an effective bond between the matrix and aggregates, explaining the observed decreases. However, more favorable improvements could be expected at 28 days as the cement hydration progressed.

Increasing cement to 2% in the C0G20 mix led to a peak strain of 15.5% for C2G20, very close to that of C0G0. Compared to C0G20, all energy components show a marked increase: total energy Ur increases by 66.7%, elastic energy Ue by 81.9%, plastic energy Up by 29.9%, and post-peak energy Upost by 61.6%. This evolution reflects a significant improvement in toughness, stiffness (Figure 11), and ductility. The fracture energy reaches its maximum value, giving C2G20 the best balance between strength and ductility among all formulations. This behavior results from an optimal synergy between the aggregate addition and cement content, which improves particle bonding and enhances overall soil cohesion [18].

With 3% cement, the stress–strain curve of C3G20 became sharper. The peak strain decreases from 15.2% for C0G20 to 13.8%. Compared to C0G20, notable increases in energy were observed: fracture energy Ur increased by 60.1%, elastic energy Ue by 79%, plastic energy Up by 76.9%, and post-peak energy Upost by 30.7%. This evolution highlights simultaneous improvements in toughness (Ur), stiffness (Ue), and ductility (Up, Upost). These results indicate that beyond achieving the highest strength and Young’s modulus, the material retained good ductility. The increased cement content strengthened the laterite–aggregate bond, as evidenced by the C2G20 formulation.

The results of Daheur et al. [31] indicated that with the addition of cement to the tuff–sand mixture, the post-peak slope becomes steeper, and the peak strain decreases linearly. This evolution reflects a gain in material stiffness attributable to the hydration reactions of the cement. Similarly, Mbengue et al. [3] observed a reduction in the peak strain and hardening of the post-peak behavior with increasing cement content.

Figure 10 illustrates the variation in compressive strength after 7 days of air curing for the different formulations used. Figure 10 shows that adding crushed aggregates and cement improved the compressive strength of lateritic soil. Indeed, adding 20% crushed aggregates to the raw lateritic soil slightly increased its compressive strength from 1.27 MPa to 1.34 MPa. This result can be attributed to the reinforcement of the granular skeleton of the raw lateritic soil by the crushed granite aggregates.

After adding 1% C0G20 cement to C0G20, the strength decreases from 1.34 MPa to 1.08 MPa. This could be attributed to the relatively high optimum water content of the sample (Figure 7). For the cement-containing formulations, C1G20 had the highest optimum water content with the smallest cement content.

The successive addition of 2% and 3% cement to the C0G20 resulted in a progressive increase in compressive strength, reaching 2.37 MPa, and 2.97 MPa, respectively. This increase was due to cement-induced hydration reactions, which became more pronounced as the cement content increased. These results were consistent with those reported by other authors [3, 11, 15]. The results of Saheli et al. [34] confirmed that the combination of crushed aggregate waste with cement improves compressive strength more than cement alone, provided that the aggregate content does not exceed 10%. The beneficial effect was particularly pronounced at curing ages of 28 and 60 days. The authors attributed this improvement to the progressive strengthening of the cementation bonds between particles, as well as to better cohesion of the material over time and with increasing cement content. Daheur et al. [31] showed that for a tuff–sand mixture, the improvement in strength was most significant with cement, followed by the lime–cement mixture, and then lime. Mbengue et al. [3] reported a compressive strength of 0.32 MPa in the raw state for a lateritic soil from Kamboinsé and a strength of 1.42 after the addition of 3% cement, representing a relative increase of 343%. In the present study, the relative increase in compressive strength from C0G0 to C3G20 was 133%, a lower value than that reported by Mbengue et al. [3]. This discrepancy may be due to the differences in the granulometry of the lateritic soil in the two studies.

According to the CEBTP [12] criteria, formulations C0G0, C0G20, and C1G20 are suitable for use as sub-base layers, offering compressive strengths exceeding 1 MPa. Formulations C2G20 and C3G20 achieved values between 1.8 MPa and 3 MPa, making them suitable for base layer applications.

Figure 12 presents the variation in indirect tensile strength (splitting tensile strength) at 7 days for raw lateritic soil and soil improved with 20% crushed aggregates and varying cement contents.

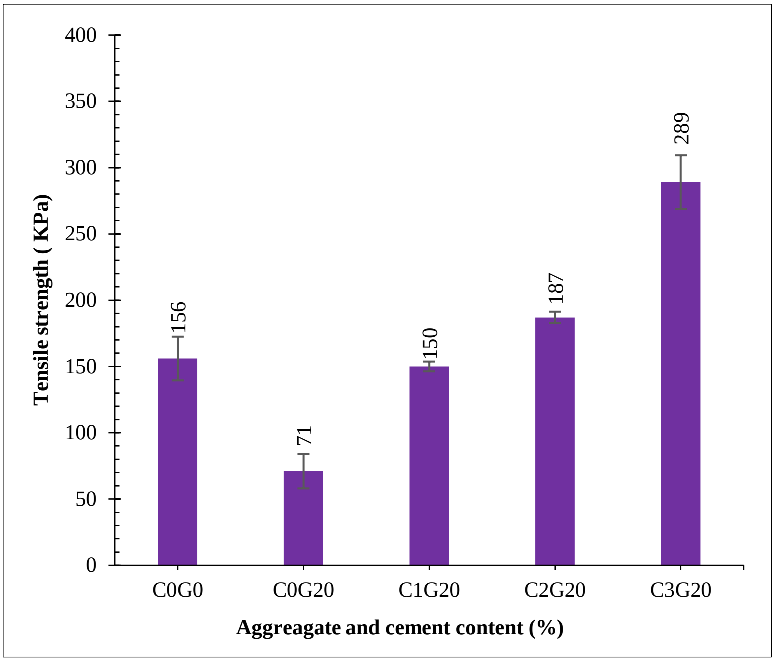

Figure 12. Variation of the indirect tensile strength of lateritic soil improved by the addition of 20% aggregates and varying cement contents

The addition of 20% crushed aggregates decreased the tensile strength from 0.156 MPa for the raw lateritic soil to 0.071 MPa. This decrease can be explained by the effect of crushed aggregates, which makes the soil more pulverulent and thus reduces its cohesion. In fact, the addition of crushed granite reduced the fines content and the optimum water content, whereas soil cohesion tends to increase with higher fines and water content. However, after the addition of 1%, 2%, and 3% cement C0G20, there was a gradual increase in indirect tensile strength from 0.071 MPa to 0.150 MPa, 0.187, and 0.289 MPa, respectively. This result was due to the hydration reactions of the cement, which improved the cohesion of the mix, leading to an increase in the indirect tensile strength. These results agree with those of Mbengue et al. [3] and Mengue et al. [11], who attributed this trend to the formation of hydrated calcium silicate (C-S-H). Mbengue et al. [3] reported a tensile strength of 0.048 MPa for a raw lateritic soil of Kamboinsé and 0.216 MPa after adding 3% cement to the soil.

According to the recommendations of CEBTP [12] concerning the tensile strength of cement-improved soils, none of the formulations are suitable for use as a base course because of their indirect tensile strength below 0.3 MPa.

Figure 11 shows the variation in Young's modulus as a function of the formulations. Figure 11 shows the effect of adding crushed granite aggregates and cement on the Young's modulus of the lateritic soil. The addition of crushed aggregates to C0G0 resulted in a slight increase in the Young's modulus (106 MPa to 113 MPa). The addition of 1%, 2%, and 3% cement to C0G20 increased the modulus, to 124, 194, and 313 MPa, respectively. The results of Daheur et al. [31] confirmed a linear increase in Young's modulus with the addition of cement to the tuff–sand mixture. This result can be attributed to cement hydration, which improves the cohesion and makes the mixture more rigid. Mbengue et al. [3] attributed this increase to C-S-H formation. They obtained Young's moduli of 48 MPa for untreated lateritic soil from Kamboinsé, compared to 103 MPa, 123 MPa, and 216 MPa after adding 1%, 2%, and 3% cement to the soil, respectively. This represents a relative increase of 350% in the modulus of the soil improved by adding 3% cement, compared with the untreated soil. In the present study, the modulus increased by 195% after adding 20% crushed aggregates and 3% cement. The combined effect of cement and crushed stone proved to be more effective in improving Young's modulus than cement stabilization alone [3], without altering the ductility of the material (in the case of C2G20 and C3G20). This result confirms the relevance of the adopted formulations, which aimed to enhance the mechanical properties while preserving the ductility of the mixture.

The highest Young's modulus obtained in this study was 313 MPa after 7 days of curing, which is higher than the minimum threshold recommended by Bagarre [54] and reported by Mbengue et al. [3], namely 300 MPa for use as a base course. Thus, the C3G20 mixture satisfied this requirement and could be considered suitable for use as a base course.

4. Conclusions

This study evaluated the effects of the combined addition of crushed granite aggregates and cement on the geomechanical properties of lateritic soils. The results of this study are as follows:

- The addition of 20% crushed granite aggregates reinforced the granular framework, increased the maximum dry density, and reduced the optimum moisture content of the lateritic soil. The immediate CBR index and the compressive strength increased significantly. The CBR index after four days of immersion was nearly identical to that of untreated lateritic soil. A decrease in tensile strength was also observed. Despite these variations, the addition of aggregates did not alter the ductility of the raw materials.
- The addition of cement (1%, 2%, 3%) to soil mixed with 20% crushed granite aggregates significantly improved its mechanical properties and water resistance, except for the 1% dosage, whose effect remained limited at an early age. The CBR index after four days of immersion at 95% compaction increased from 18 (20% G alone) to 65, 221, and 400 for cement additions of 1%, 2%, and 3%, respectively. Compressive strength increased from 1.34 MPa (20% G) to 1.08 MPa, 2.37 MPa, and 2.97 MPa for the same dosages. The modulus of elasticity increased from 113 MPa (20% G) to 124 MPa, 194 MPa, and 313 MPa. The combination of 20% crushed aggregates and 2% cement achieved CBR and compressive strength values compatible with use in base layers, although tensile strength and the modulus of elasticity remained below the required thresholds.
- The addition of 1% cement to a lateritic soil containing 20% crushed granite aggregates had no significant effect on the early-age mechanical behavior. The combination of 20% crushed granite with 2% and 3% cement significantly improved the ductile behavior and toughness of the material.

Ultimately, the combination of crushed aggregates and low cement content appears to be a promising way to enhance the mechanical performance of laterite while maintaining its ductility. However, this study was preliminary. Further investigations are necessary, in particular, by varying the proportions and particle size distribution of the aggregates, as well as by comparing the performance of stabilization with cement alone and the cement–aggregate combination. In addition, durability tests and the evaluation of resilient moduli would contribute to a better characterization of the behavior of the mixtures under environmental and cyclic loadings. Finally, integrating economic analyses with a life-cycle assessment would provide a more comprehensive view of the technical and practical relevance of this approach.

5. Declarations

5.1. Author Contributions

Conceptualization: A.M., M.T.M.M., and. D.A.; methodology, A.M., M.T.M.M., K.J.N., and D.A.; validation, K.J.N., M.T.M.M., A.M., and D.A.; formal analysis, M.T.M.M. and K.J.N.; investigation, K.J.N., M.T.M.M., A.M., and D.A.; resources, A.M. and D.A.; data curation, M.T.M.M. and K.J.N.; writing—original draft preparation, M.T.M.M. and K.J.N.; writing—review and editing, M.T.M.M., A.M., and D.A.; visualization, A.M. and D.A.; supervision, A.M. and D.A.; project administration, A.M. and D.A.; funding acquisition, A.M. and D.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Colin, F., Beauvais, A., Ambrosi, J. P., & Nahon, D. (2004). Laterites in tropical environments, a source of metals of economic interest. Assises de la Recherche Française dans le Pacifique, 23-27 August, 2004, Nouméa, New Caledonia. (In French).

[2] Kouassi, K. P., Atto Yapi, D. S. R., Konin, A., & Grehoa, A. M. (2023). Chemical and Mineralogical Characterisation of Clayey Sands from the Ivorian Serimentaru Basin in Road Construction. European Scientific Journal, ESJ, 19(30), 94. doi:10.19044/esj.2023.v19n30p94.

[3] Mbengue, M. T. M., Lawane Gana, A., Messan, A., Mone, O., & Pantet, A. (2023). Effect of the Type of Lateritic Soil on the Effectiveness of Geomechanical Improvement Using a Low Quantity of Cement for Sustainable Road Construction. Materials, 16(21), 6891. doi:10.3390/ma16216891.

[4] Legma, A. A. (2023). Improvement of Lateritic Gravelly Soil Using Cement and Litho-Stabilization and Its Application Case of Main Road Artery on the City Side of the New Ouagadougou-Donsin airport. Academic Journal of Architecture and Geotechnical Engineering, 5(6), 51-60. doi:10.25236/ajage.2023.050610.

[5] Okeke, Z. U., Onunkwo, O. C., Agidi, A. A., Amadi, B. M., & Onwuchekwa, C. C. (2024). Engineering Behaviour of Cement-Stabilized Lateritic Soils Derived from Various Geologic Formations in Awka Area. Southeastern Nigeria. Engineering Research Journal, 4(4), 32–53.

[6] Solihu, H. (2020). Cement Soil Stabilization as an Improvement Technique for Rail Track Subgrade, and Highway Subbase and Base Courses: A Review. Journal of Civil and Environmental Engineering, 10(3), 1-6. doi:10.37421/jcde.2020.10.344.

[7] Afrin, H. (2017). A Review on Different Types Soil Stabilization Techniques. International Journal of Transportation Engineering and Technology, 3(2), 19. doi:10.11648/j.ijtet.20170302.12.

[8] Roshan, M. J., & Rashid, A. S. B. A. (2024). Geotechnical characteristics of cement stabilized soils from various aspects: A comprehensive review. Arabian Journal of Geosciences, 17(1), 1. doi:10.1007/s12517-023-11796-1.

[9] Roshan, M. J., A Rashid, A. S., Jusoh, S. N., Horpibulsuk, S., Razali, R., Tamassoki, S., Malistani, N., & Ismail, A. (2024). Behaviour of Cement-Stabilised Lateritic Soil: An Experimental Study. Indian Geotechnical Journal, 55(5), 3176–3192. doi:10.1007/s40098-024-01115-0.

[10] Wahab, N. A., Roshan, M. J., Rashid, A. S. A., Hezmi, M. A., Jusoh, S. N., Norsyahariati, N. D. N., & Tamassoki, S. (2021). Strength and durability of cement-treated lateritic soil. Sustainability (Switzerland), 13(11), 6430. doi:10.3390/su13116430.

[11] Mengue, E., Mroueh, H., Lancelot, L., & Eko, R. M. (2017). Mechanical Improvement of a Fine-Grained Lateritic Soil Treated with Cement for Use in Road Construction. Journal of Materials in Civil Engineering, 29(11), 4017206. doi:10.1061/(asce)mt.1943-5533.0002059.

[12] CEBTP. (1984). Practical guide to pavement design for tropical countries. Centre Expérimental de Recherches et d'Études du Bâtiment et des Travaux Publics (CEBTP), Paris, France. (In French).

[13] Liu, B., Zhu, L., Liu, X., Liu, Q., Fan, Y., Yao, W., & Deng, W. (2024). Energy evolution and damage deformation behavior of cemented broken coal specimen under triaxial compression condition. Energy, 310, 133203. doi:10.1016/j.energy.2024.133203.

[14] Tran, N. Q., Hoy, M., Suddeepong, A., Horpibulsuk, S., Kantathum, K., & Arulrajah, A. (2022). Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. Construction and Building Materials, 347, 128547. doi:10.1016/j.conbuildmat.2022.128547.

[15] Sariosseiri, F., & Muhunthan, B. (2009). Effect of cement treatment on geotechnical properties of some Washington State soils. Engineering Geology, 104(1–2), 119–125. doi:10.1016/j.enggeo.2008.09.003.

[16] Tran, N. P., Gunasekara, C., Law, D. W., Houshyar, S., Setunge, S., & Cwirzen, A. (2021). A critical review on drying shrinkage mitigation strategies in cement-based materials. Journal of Building Engineering, 38, 102210. doi:10.1016/j.jobe.2021.102210.

[17] George, K. P. (1968). Shrinkage characteristics of soil-cement mixtures. Highway Research Record, 255, 42-58.

[18] LCPC-SETRA. (2000). Soil treatment with lime and/or hydraulic binders: Application to the construction of embankments and subgrade layers. (In French).

[19] Sabahy, A., EL-Sheshny, A.-R. A., Elsamra, E. A., Eid, M. M. M., & Essam, M. (2024). Effects of Varied Soil Leveling Methods on Physical Properties: A Comparative Analysis. Civil Engineering Journal, 10(11), 3672-3682. doi:10.28991/CEJ-2024-010-11-014.

[20] Verástegui-Flores, R. D., & Di Emidio, G. (2014). Impact of sulfate attack on mechanical properties and hydraulic conductivity of a cement-admixed clay. Applied Clay Science, 101, 490–496. doi:10.1016/j.clay.2014.09.012.

[21] Massoumi Nejad, B., Enferadi, S., & Andrew, R. (2025). A comprehensive analysis of process-related CO2 emissions from Iran's cement industry. Cleaner Environmental Systems, 16, 100251. doi:10.1016/j.cesys.2024.100251.

[22] Mbengue, M. T. M., Gana, A. L., Messan, A., & Pantet, A. (2022). Geotechnical and Mechanical Characterization of Lateritic Soil Improved with Crushed Granite. Civil Engineering Journal (Iran), 8(5), 843–862. doi:10.28991/CEJ-2022-08-05-01.

[23] Issiakou, M. S., Saiyouri, N., Anguy, Y., Gaborieau, C., & Fabre, R. (2015). Study of Lateritic Materials Used in Road Construction in Niger: Improvement Method. Rencontres Universitaires de Génie Civil, 27-29 May, 2015, Anglet, France. (In French).

[24] Hyoumbi, W. T., Pizette, P., Wouatong, A. S. L., Abriak, N. E., Borrel, L. R., Razafimahatratra, F. N., & Guiouillier, T. (2019). Investigations of the Crushed Basanite Aggregates Effects on Lateritic Fine Soils of Bafang Area (West-Cameroon). Geotechnical and Geological Engineering, 37(3), 2147–2164. doi:10.1007/s10706-018-0751-0.

[25] Houanou, K. A., Dossou, K. S., Prodjinonto, V., Ahouétohou, P., & Olodo, E. (2022). Mechanical characteristics of Avlamè lateritic gravel improved with granite crushed for its use in road construction in Benin. World Journal of Advanced Research and Reviews, 15(2), 279–292. doi:10.30574/wjarr.2022.15.2.0820.

[26] Daheur, E. G., Goual, I., & Taibi, S. (2015). Effect of Immersion on the Mechanical Behavior of a Gypsomalicary Tuf Treated with Organic or Hydraulic Binders. 3ème colloque international sur les sols non saturés, 16-17 November, 2015, Batna, Algeria. (In French).

[27] Melbouci, B. (2017). Comparative Study of the Treatment of Marl Soil with Lime and Cement in Road Sub-Layers. Communication Science & technology, 18. (In French).

[28] Ndiaye, M., Magnan, J. P., Cisse, I. K., & Cisse, L. (2013). Study of the improvement of laterites in Senegal by the addition of sand. Bulletin des laboratoires des ponts et chaussées. (In French).

[29] Chah, C. N., Sekharan, S., & Katiyar, V. (2025). Geotechnical characterisation and sustainability assessment of plastic waste inclusions on a cement-treated fine-grained soil for pavement applications. Transportation Geotechnics, 51, 101515. doi:10.1016/j.trgeo.2025.101515.

[30] Que, Y., Jia, S., Wang, L., Fang, L., & Mu, H. (2025). Substitution of Tailings Sand in Cement-Stabilized Gravel Base Material for Road Construction: Mechanical Properties, Durability, and Microstructure. Journal of Materials in Civil Engineering, 37(4), 4025045. doi:10.1061/jmcee7.mteng-18380.

[31] Daheur, E. G., Li, Z. Sen, Demdoum, A., Taibi, S., & Goual, I. (2023). Valorisation of dune sand-tuff for Saharan pavement design. Construction and Building Materials, 366, 130239. doi:10.1016/j.conbuildmat.2022.130239.

[32] Daheur, E. G., Goual, I., Taibi, S., & Mitiche-Kettab, R. (2019). Effect of Dune Sand Incorporation on the Physical and Mechanical Behaviour of Tuff: (Experimental Investigation). Geotechnical and Geological Engineering, 37(3), 1687–1701. doi:10.1007/s10706-018-0715-4.

[33] Imafidon, D., Ogirigbo, O. R., & Ehiorobo, J. O. (2021). Improvement of deltaic lateritic soil using river sand and cement for use as pavement construction material. Nigerian Journal of Technology, 40(2), 168–176. doi:10.4314/njt.v40i2.1.

[34] Salehi, M., Bayat, M., Saadat, M., & Nasri, M. (2021). Experimental Study on Mechanical Properties of Cement-Stabilized Soil Blended with Crushed Stone Waste. KSCE Journal of Civil Engineering, 25(6), 1974–1984. doi:10.1007/s12205-021-0953-5.

[35] Savadogo, N., Traore, Y, B,. Kocty, R & Mone, O. (2024). Stabilization of lateritic soil with Portland cement and crushed granite for pavement base courses. World Journal of Advanced Research and Reviews, 23(3), 3090–3099. doi:10.30574/wjarr.2024.23.3.2914.

[36] Okonkwo, V. O., Omaliko, I. K., & Ezema, N. M. (2022). Stabilization of Lateritic Soil with Portland Cement and Sand for Road Pavement. OALib, 09(06), 1–15. doi:10.4236/oalib.1108560.

[37] Hoy, M., Tran, N. Q., Suddeepong, A., Horpibulsuk, S., Mobkrathok, M., Chinkulkijniwat, A., & Arulrajah, A. (2023). Improved fatigue properties of cement-stabilized recycled materials – Lateritic soil using natural rubber latex for sustainable pavement applications. Transportation Geotechnics, 40, 100959. doi:10.1016/j.trgeo.2023.100959.

[38] Pegalajar, M. C., Ruiz, L. G. B., Sánchez-Marañón, M., & Mansilla, L. (2020). A Munsell colour-based approach for soil classification using Fuzzy Logic and Artificial Neural Networks. Fuzzy Sets and Systems, 401, 38–54. doi:10.1016/j.fss.2019.11.002.

[39] NF EN ISO 17892-4. (2018). Geotechnical investigation and testing - Laboratory tests on soils - Part 4: Determination of particle size distribution. Association Française de Normalisation, Paris, France. (In French).

[40] NF EN ISO 17892-12. (2018). Geotechnical investigations and testing - Laboratory tests on soils - Part 12: Determination of liquid and plastic limits. Association Française de Normalisation, Paris, France. (In French).

[41] NF EN 933-9. (2022). Tests for geometrical properties of aggregates - Part 9: assessment of fines - Methylene blue test.Association Française de Normalisation, Paris, France. (In French).

[42] NF P 94-093. (2014). Soils: investigation and testing - Determination of the compaction reference values of a soil type - Standard proctor test - Modified proctor test. Association Française de Normalisation, Paris, France. (In French).

[43] NF P 94-078. (1997). Soils: investigation and tests. CBR after immersion. Immediate CBR. Immediate bearing ratio. Measurement on sample compacted in CBR mould. Association Française de Normalisation, Paris, France. (In French).

[44] NF EN 13286-41. (2003). Unbound and hydraulically bound mixtures - Part 41: test method for the determination of the compressive strength of hydraulically bound mixtures. Association Française de Normalisation, Paris, France. (In French).

[45] NF EN 13286-43. (2003). Unbound and hydraulically bound mixtures - Part 43: test method for the determination of the modulus of elasticity of hydraulically bound mixtures. Association Française de Normalisation, Paris, France. (In French).

[46] Mengue, E. (2015). Evaluation of the mechanical behavior of a cement-treated lateritic soil for road applications. PhD Thesis, University of Lille, Lille, France. (In French).

[47] NF EN 13286-42. (2003). Unbound and hydraulically bound mixtures - Part 42: test method for the determination of the indirect tensile strength of hydraulically bound mixtures. PhD Thesis, University of Lille, Lille, France. (In French).

[48] GTR. (2000). Construction of Embankments and Subgrade Layers, Booklets I and II (2nd ed.). GTR SETRA-LCPC, IDRRIM: Paris France. (In French).

[49] HRB (1958). Proceedings of the annual Meeting-Highway Research Board. Highway Research Board, Washington, D.C., United States.

[50] Bakaiyang, L., Madjadoumbaye, J., Boussafir, Y., Szymkiewicz, F., & Duc, M. (2021). Re-use in road construction of a Karal-type clay-rich soil from North Cameroon after a lime/cement mixed treatment using two different limes. Case Studies in Construction Materials, 15, 626. doi:10.1016/j.cscm.2021.e00626.

[51] Bekki, H., Djilaili, Z., Tlidji, Y., & Daouadji, T. H. (2015). Durability of treated silty soil using lime and cement in road construction – a comparative study. The Online Journal of Science and Technology (TOJSAT), 5, 23–31, 5(2), 23–31.

[52] Millogo, Y., Hajjaji, M., Ouedraogo, R., & Gomina, M. (2008). Cement-lateritic gravels mixtures: Microstructure and strength characteristics. Construction and Building Materials, 22(10), 2078–2086. doi:10.1016/j.conbuildmat.2007.07.019.

[53] Portelinha, F. H. M., Lima, D. C., Fontes, M. P. F., & Carvalho, C. A. B. (2012). Modification of a lateritic soil with lime and cement: An economical alternative for flexible pavement layers. Soils and Rocks, 35(1), 51–63. doi:10.28927/sr.351051.

[54] Bagarre, E. (1990). Use of lateritic gravels in road construction. Institut des Sciences et des Techniques de L'équipement et de L'environnement pour le Développement (ISTED). (In French).