Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2005

Microanalysis and physico-mechanical properties of lateritic gravels from southern Benin

Marines Kpatoukpa, Benoit Duchemin, Anne Pantet
University of Le Havre Normandie (ULHN), LOMC, Le Havre, France,marines.kpatoukpa@doct.univ-lehavre.fr

Yvette Tankpinou Kiki
University National of Sciences, Technologies, Ingenierie et Mathematiques (UNSTIM), LaPiT, Lokossa, Benin

ABSTRACT: This study investigates the impact of the microstructure of laterite aggregates on their physico-mechanical properties to optimize their use. Laterites are tropical soils found in several West African countries. The aggregates studied are sourced from two locations in the municipalities of Zogbodomey and Kétou in southern Benin. Physical characterization reveals a balanced grain size distribution with uniformity and curvature coefficients of 2 and 0.78, respectively, for the two extraction sites. The flatness coefficient indicates that aggregates from Zogbodomey are less rounded than those from Kétou. The water absorption coefficients are 6.23% for Zogbodomey aggregates and 6.47% for Kétou aggregates. The apparent and absolute densities are respectively of 1.52 g/cm^3 and 22.64 g/cm^3 for Zogbodomey aggregates, and of 1.45 g/cm^3 and 2.70 g/cm^3 for Kétou aggregates. Mechanical characterization involved determining the aggregates' shock resistance using the Los Angeles coefficient. Kétou aggregates have a slightly higher Los Angeles coefficient than those from Zogbodomey. Electron microscopy analysis of the internal surface of the aggregates reveals a compact texture for Zogbodomey samples and a porous texture for Kétou samples. This microstructure correlates with the physical and mechanical results obtained for each aggregate and partly explains the variation in these properties.

KEYWORDS: Laterites, tropical soils, microstructure.

1 INTRODUCTION

Laterites, prevalent tropical soils in West Africa, are residual soils formed through the physical and chemical weathering of parent rock. These soils can appear in hardened, loose, or gravelly forms and serve as a crucial granular resource for producing compressed earth blocks (CEB) or for earthworks and road embankments. In Senegal, *Fall et al. (2014)* conducted an extensive study on optimizing the treatment of lateritic soils to improve the mechanical performance of unpaved roads. *Millogo et al. (2012)* examined the mechanical performance of compressed earth blocks made from laterite in Burkina Faso.

However, their use is complicated by the high variability of their characteristics, which can differ significantly from one region to another and even from one site to another *(Issiakou 2016)*. This variability, influenced by geological origin and composition, can significantly limit their applications. While the mineralogical composition partly responsible for this variability, the microstructure may also affect their physical and mechanical properties.

In the face of the increasing scarcity of "noble" materials in construction, many studies are exploring the use of these granular soils, either wholly or partially, to replace gravel from massive rock quarries in cementitious materials like concrete and mortar *(Hodé et al. 2018)*. Therefore, a deeper understanding of these soils' properties is essential. Five main granular classes are defined based on grain size: fines, sands, gravel, stone, and coarse aggregates.

This article studies the physico-mechanical and microscopic properties of laterite aggregates, fraction 5/25 mm, corresponding approximately to gravel class, found in two quarries from southern Benin. The objective is to study the potential use of these aggregates in concrete by determining their physical and mechanical properties and examining the links with their internal microstructure. Aggregates have vastly distinctive characteristics depending on their origin. Since these characteristics influence the properties of concrete, it is crucial to understand them thoroughly and ensure compliance with specifications. After presenting the materials and their overall geological context, we will describe the experimental method, followed by an analysis and discussion of the results.

2 MATERIALS AND METHODS

2.1 *Study materials*

The aggregates studied originate from the surface layers of gravelly ferrallitic soils in quarries situated in the municipalities of Zogbodomey and Kétou. These samples were collected from horizons of gravelly ferrallitic soils in these quarries. The geographical locations of the extraction sites, documented using the Global Positioning System (GPS), are shown in Figure 1.

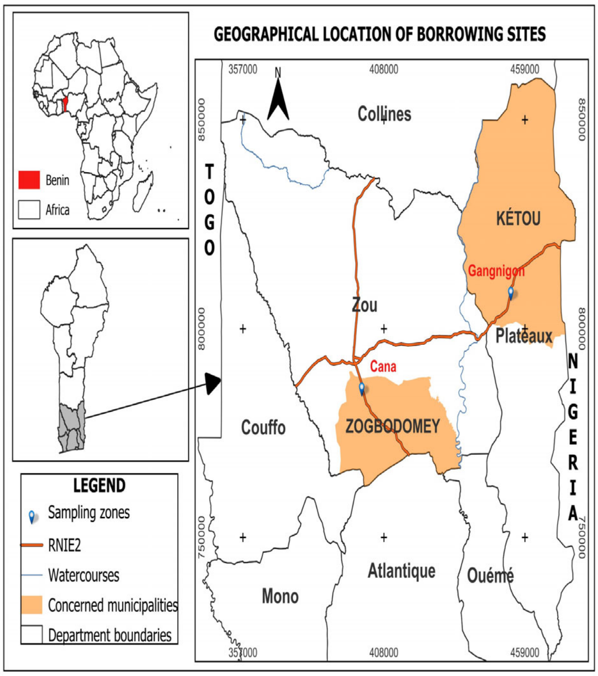


Figure 1. Geographical situation of borrowing sites.

This region is geologically characterized by a coastal sedimentary basin from the Meso-Cenozoic era, comprising a series of seven plateaus formed by sedimentary deposits overlying Precambrian crystalline bedrock *(Attanda et al. 2023)*. Tropical lateritic soils have developed on the surface due to intense weathering processes driven by climatic factors.

2.2 Physico-mechanical characterization of aggregates

Characterization in the laboratory was conducted in accordance the current standards for each test. Each test is performed at least twice to average the trials and ensure the results.

2.2.1 Granulometric analysis by sieving (NF EN 933-1)

A precise understanding of particle size distribution is essential for predicting the optimal concrete mix design. The method used in this study is dry sieving, performed after washing the aggregates. The preliminary washing step helps remove fine particles and impurities that could otherwise affect the test results.

The test consists of separating the material into size fractions using a stack of sieves arranged from largest to smallest aperture. The sieve series used included the following mesh sizes (in mm): 25; 20; 16; 12.5; 10; 8; 6.3; 5; 4; 2.5; 2; 1.25. Determining the granulometric distribution of the aggregates is essential for evaluating their suitability for use in concrete. After completing the test, the particle size distribution curve, as well as the uniformity and curvature coefficients, are calculated.

2.2.2 Flattening coefficient (NF EN 933-3)

Conducted in parallel with the grain size analysis, this test determines the proportion of flat or elongated particles in a gravel sample. A conventional sieving operation is first performed using a stack of square-mesh sieves to separate the aggregates into successive size classes d/D. Each of these size classes is then individually tested using a parallel-slot sieve with a slot width E = d / 1.58 mm.

The flattening coefficient is defined as the ratio of the mass passing through the parallel-slot sieve to the total mass of the corresponding size class. A high flattening coefficient indicates a greater proportion of flat particles, whereas a low coefficient reflects aggregates that are more rounded or equidimensional.

2.2.3 Bulk density (NF EN 1097-3)

This test was used to determine the bulk density of the aggregates, defined as the mass per unit volume, including the voids between particles, and expressed in g/cm³. Standardized concrete molds with known dimensions and mass were used for this measurement.

2.2.4 Absolute density and water absorption: basket method (NF EN 1097-6)

Absolute density is defined as the mass per unit volume of the solid material itself, excluding any voids within or between the particles, and is expressed in g/cm³. The test was performed using the basket method, which is based on Archimedes' principle.

The aggregates were immersed in water for 24 hours, weighed using the hydrostatic method, and then dried. The amount of water absorbed by the aggregates was subsequently calculated from the recorded mass measurements.

2.2.5 Los Angeles (EN 1097-2)

The mechanical characterization of the aggregates involved assessing their resistance to fragmentation using the Los Angeles test. This test evaluates the combined resistance of the material to impact forces and to the progressive degradation caused by mutual abrasion between particles. Its purpose is to quantify the mass of particles retained on the 1.6 mm sieve after fragmentation.

For the test, a mass M of aggregate, sieved to obtain the 10/14 mm size fraction, was mixed with steel balls and subjected to repeated impacts and abrasion within a rotating drum. After 500 revolutions, the material was sieved through the 1.6 mm mesh, and the mass m of the fraction retained on the sieve was measured.

The Los Angeles coefficient (LA) is calculated as the ratio of the mass loss on the 1.6 mm sieve to the initial mass of the sample. The result is rounded to the nearest whole number. A lower LA value indicates greater resistance to wear and fragmentation.

2.3 Scanning Electron Microscope (SEM)

The microstructural observation of the aggregates was performed using scanning electron microscopy (SEM). The SEM technique, based on electron–matter interactions, involves directing a focused electron beam onto the surface of an aggregate sample. Microstructural features were examined and analyzed using a *ZEISS GEMINI–Sigma 360 VP* scanning electron microscope.

High-resolution images at the nanometric scale were obtained, providing detailed visualization of the internal surfaces of the aggregates. These images are generated point by point with nanometer-level resolution. The microscope is operated via a computer equipped with dedicated analysis and data-processing software.

For SEM preparation, the aggregate samples were cut in half and polished to produce a smooth surface, ensuring optimal imaging quality. Multiple sets of micrographs were captured, and the images most representative of each aggregate's overall surface morphology are presented.

3 RESULTS AND DISCUSSION

3.1 Results of physical and mechanical characterization

The results obtained from the various physical and mechanical characterization tests are presented in this section.

3.1.1 Particle size distribution

The particle size distribution of the different aggregate samples is presented in Figure 1. The particle size curves are plotted on a logarithmic scale, along with the lower and upper specification limits that define the acceptable grading range for concrete aggregates. The sieve analysis provides the distribution of particle sizes contained in each sample.

A balanced proportion of the different particle fractions is observed, with the curves showing a complete overlap corresponding to the 1.25 - 25 mm grading envelope. The percentage of material retained on the 25 mm sieve is below 15%, which is attributable to the pre-screening performed on the samples to remove oversized and excessively fine particles.

It's observed that the grading curves of both samples do not fall entirely within the specified limits. The curve for the Zogbodomey sample slightly exceeds the upper limit, while that of the Kétou sample lies directly on the upper limit. Overall, the particle size distribution of the two aggregate samples is homogeneous.

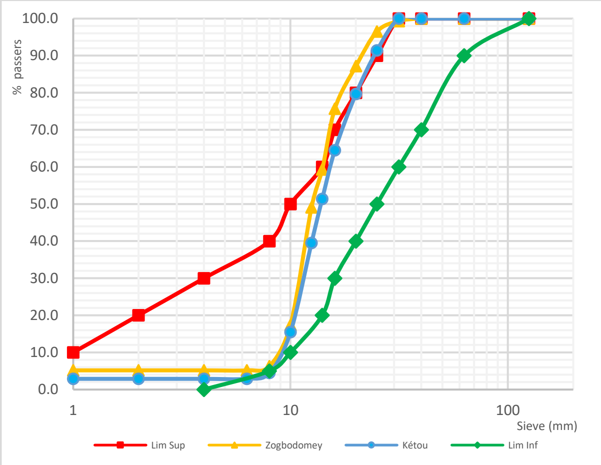


Figure 2. Grain size distribution curves of the studied samples.

The uniformity coefficients (Cu) and curvature coefficients (Cc) were then determined for each sample. The aggregates from both localities (Zogbodomey and Kétou) exhibit a uniformity coefficient of Cu = 2, indicating a relatively narrow and uniform particle size distribution. The curvature coefficient obtained for both samples is Cc = 0.78. Since this value is less than 1, it suggests that the particle size distribution is homogeneous.

The aggregates from Zogbodomey and Kétou therefore display adequate grading and moderate uniformity, which may make them suitable for use in concrete. However, proper mixing during concrete formulation is essential to prevent aggregate segregation. Achieving an optimal concrete mix will require adjusting the overall granulometric distribution by incorporating the other constituents (fine aggregates, coarse aggregates, and cement). Ensuring a well-balanced mixture is crucial for maintaining homogeneity and avoiding segregation.

3.1.2 Flattening coefficient (Fi)

The aggregates collected from Zogbodomey have a flattening coefficient of 4.7, whereas those from Kétou showed a value of 1.6. The high flattening coefficient observed in the Zogbodomey samples reflects a greater proportion of flat particles, while the lower coefficient in the Kétou aggregates indicates a predominance of rounded particles. Rounded aggregates are generally known to improve packing density during concrete production. This test is applicable to particles ranging between 4 and 100 mm in size.

To optimize concrete mix design, the proportion of flat particles within the granular skeleton should be limited. In addition, the presence of angular particles is desirable, as they ensure better adhesion with the cement paste and the mortar matrix. Based on these results, the Kétou aggregates appear to be more suitable for concrete use; however, aggregates from Zogbodomey could also be incorporated if specific optimization strategies are applied to enhance their properties within the concrete mixture.

3.1.3 Apparent and absolute bulk densities (ρ_{app} and ρ_{abs})

The apparent density of aggregates from Zogbodomey is 1.52 g/cm³ and the absolute density is 2.64 g/cm³. Those from Kétou show an apparent density of 1.45 g/cm³ and an absolute density of 2.70 g/cm³.

However, despite their lower apparent density, the aggregates from Kétou have a slightly higher absolute density than those from Zogbodomey. This physical characteristic is particularly important when selecting aggregates for concrete, as it influences mix design, compaction, and overall performance of the material.

3.1.4 Water absorption W% and porosity n

The water absorption of the aggregates was measured during the absolute density test using the basket method.

A preliminary analysis shows that both aggregates exhibit relatively high-water absorption. The aggregates from Kétou have a slightly higher absorption capacity (≈ 6.47%) than those from Zogbodomey (≈ 6.23%). Such high absorption levels are generally associated with a significant amount of internal porosity.

The water absorption test quantifies only the water entering open and accessible pores. Therefore, an estimation of the intragranular porosity can be made by combining the absolute density of the aggregates with their water absorption percentage. Based on this approach, the aggregates from Zogbodomey and Kétou both exhibit an accessible porosity (n) of approximately 2.3%. A high absorption rate typically indicates significant porosity; however, this is valid only if the pores are sufficiently interconnected and open to water penetration.

In most cases, dense aggregates tend to absorb less water, as they are generally less porous and more compact. However, the results indicate that the Kétou aggregates - despite having a slightly higher absolute density - exhibit a higher water absorption capacity. This apparent inconsistency suggests that the Kétou aggregates may contain a larger proportion of open or interconnected pores, which increases water uptake despite their higher solid density.

3.1.5 Coefficient Los Angeles (LA)

The Los Angeles test results indicate fragmentation resistance values of 37 for the aggregates from Zogbodomey and 40 for those from Kétou. The Kétou aggregates therefore show a slightly higher Los Angeles coefficient than the Zogbodomey aggregates.

Since a higher Los Angeles value reflects a lower resistance to fragmentation, the Kétou aggregates are less resistant than those from Zogbodomey. The fragmentation resistance of the Zogbodomey aggregates is closer to that typically observed in conventional aggregates.

Despite the difference in performance between the two sources, both aggregates fall within the acceptable limits for fragmentation resistance required for use in concrete.

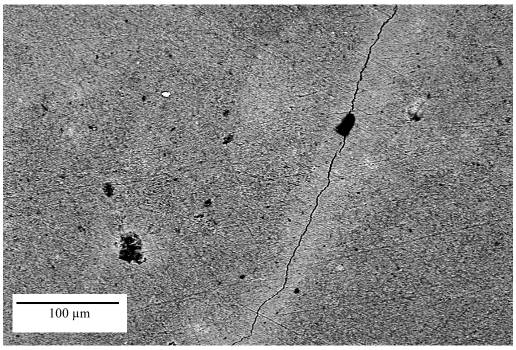
3.2 Microstructure by SEM imaging

The analysis was conducted on the coarse fraction representative of the other aggregates. The images were obtained using backscattered electrons in VPBSD mode (Vacuum Pressure Back Scattered Electron Detector) with a scale of 100 µm.

Figures 3a and 3b show microscopic images of the internal surface of the aggregate samples.

The cross-sections reveal not only the general morphology of the aggregates (whether they appear as massive pieces or not) but also provide indications on their mode of formation (gravel-like, pisolite, or nodular structures).

The dark areas visible in the images correspond to pores, which were likely formed during geological processes such as compaction, cementation, or crystallization. It can be observed that the aggregate sample from Zogbodomey exhibits a denser and less porous internal structure compared to the Kétou sample.

a.


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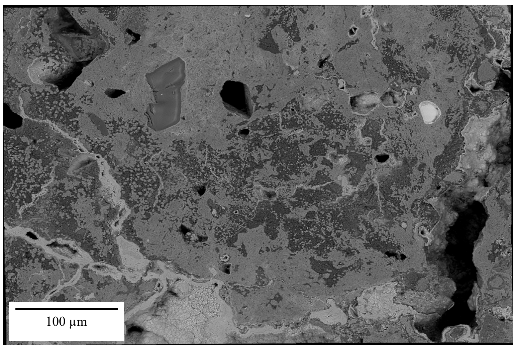

Figure 3. SEM images, a. Sample from Zogbodomey, b. Sample from Kétou (Aggregate of 10 mm).

The aggregate sample from Kétou, by contrast, exhibits a less compact and more irregular texture. The pores, visible as dark areas in the images, are numerous and relatively large for the Kétou samples. They were most likely formed during the geological processes of compaction, cementation, and crystallization. Although many of these pores appear isolated, some are partially connected through micro-cracks. The high-water absorption observed in the Kétou aggregates, as well as their lower resistance to fragmentation, can be associated with this irregular and less compact microstructure characterized by interconnected macro-pores. Such pore connectivity weakens the internal framework of the aggregates, which affects their overall mechanical behavior. The higher absolute density measured for the Kétou samples may be attributed to a greater presence of heavy minerals compared to the Zogbodomey aggregates. Mineralogical analyses will be necessary to confirm this hypothesis.

3.3 *Synthesis of results*

The synthesis of the different results obtained is presented in the table below.

Table 1. Synthesis of the results of physico-mechanical characterization.

Parameter	Symbol	Value		Unit
		Zogbodomey	Kétou	
Uniformity coef.	*Cu*	2	2	-
Curvature coef.	Cc	0.78	0.78	-
Flattening coef.	Fi	4.7	1.6	-
Apparent density	ρ_{app}	1.52	1.45	g/cm³
Absolute density	ρ_{abs}	2.64	2.7	g/cm³
Water absorption	W	6.23	6.47	%
Los-Angeles	LA	37	40	%
Porosity intragranular	n	2.3	2.3	%

4 CONCLUSIONS

The physico-mechanical characterization of the aggregates from Zogbodomey and Kétou provided valuable insight into their suitability as concrete aggregates. Although originating from two extraction sites located within the same general geological context, the aggregates displayed noticeable differences in physical and mechanical properties, particularly in bulk density, water absorption, and fragmentation resistance.

Microstructural imaging revealed structural variations that directly and indirectly influence these properties. These differences may be attributed to factors such as formation processes, the nature of the parent rock, and the specific stratigraphic layer from which each sample was taken. In fact, while the microscopic observations may appear similar at first glance, the underlying microstructural organization differs significantly.

Overall, the results highlight the inherent diversity of lateritic formations, especially about their internal structure, which may range from porous to highly compact. This diversity is closely linked to the influence of multiple pedogenetic and geological factors involved in laterite formation, as well as to the characteristics of the parent rock and the depth of sampling. Generally, the deeper the sampling layer, the less lateritized the material becomes, and the more it resembles the parent rock.

5 ACKNOWLEDGEMENTS

The authors thank the National Research Agency (ANR), the CNRS, as well as all the partners of the PEA-ICAT project for their support. They also express their gratitude to the members of the different laboratory for their assistance during the trials.

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