American Journal of Civil Engineering and Architecture, 2025, Vol. 13, No. 2, 34-43
Available online at http://pubs.sciepub.com/ajcea/13/2/2
Published by Science and Education Publishing
DOI:10.12691/ajcea-13-2-2

Physical and Mechanical Characterization of Unbound Granular Material (UGM) Used as Road Base Layers in Côte d'Ivoire

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Received April 09, 2025; Revised May 10, 2025; Accepted May 18, 2025

Abstract The aim of this study was to determine the physical and mechanical properties of Unbound Granular Material (UGM) used in road construction in Côte d'Ivoire. From each of the fifteen quarries surveyed, ten samples of gravel were taken and subjected to standardized tests covering cleanliness, bulk density, mechanical strength, grain size and bearing capacity. The results show that the mass of methylene blue (MB) varies from 0.06 to 0.10 g/100g, the apparent density (DA) from 1.44 to 1.77 t/m3, the mechanical strength indices expressed by the tests. Los Angeles and Micro-Deval tests, range from 16% to 34% and from 4.67% to 10.33% respectively. Bearing capacity is also satisfactory, with CBR values ranging from 68% to 87%. Principal component analysis (PCA) was used to distinguish five material classes. Class 1 comprises gravels with high mechanical strength and high dry density. Class 2, represented by samples from the ABSI quarry in Abidjan, has the best bearing capacity, with an average CBR of 87%. Class 3, associated with the GASI quarry in Gabiadji, is characterized by a high fines content, reaching a maximum fines content (AG) of 5.35%, and increased sensitivity to water. Class 4 corresponds to the ATAM quarry in Abidjan, which offers excellent wear resistance, with a minimum Los Angeles index of 16%. Finally, class 5 includes three quarries in Abidjan (ABIC, ATAB, ATSO) and one in Aboisso (ABOC). The gravels from these quarries have high optimum water contents, reaching values of 6.25%, and relatively low dry densities, ranging from 2.30 to 2.36 t/m3.

Keywords: *Unbound Granular Material, physical and mechanical properties, Côte d'Ivoire, road construction*

Cite This Article: Bakary Koné, Athanas Konin, and Augustin Touré, “Physical and Mechanical Characterization of Unbound Granular Material (UGM) Used as Road Base Layers in Côte d'Ivoire.” *American Journal of Civil Engineering and Architecture*, vol. 13, no. 2 (2025): 34-43. doi: 10.12691/ajcea-13-2-2.

1. Introduction

The development of sustainable, resilient infrastructure is essential to support economic growth and improve people's quality of life, particularly in developing countries. This issue is in line with Sustainable Development Goal (SDG) 9, which aims to "build resilient infrastructure, promote inclusive sustainable industrialization and foster innovation" [1]. Around the world, roads are key infrastructure for connecting rural areas to markets and facilitating the mobility of goods and people. Their resistance to climate and different vehicle loads is vital for a long term [2]. Therefore, to ensure their durability, it is crucial to properly select and characterize the materials used in pavement layers, particularly in base courses, such as Unbound Granular Material (UGM) [3].

Indeed, a lack of knowledge of the characteristics of materials used in pavement layers (such as UGM) leads to early deterioration through several key mechanisms. The absence of precise data on the grading, optimum moisture content or erosion sensitivity of materials leads to insufficient compaction. This generates ruts and differential settling under the effect of traffic, especially in wet periods [4,5]. In addition, poorly characterized material permeability causes water to accumulate in the base layers, and accelerates internal erosion of the support soil, promoting the appearance of potholes. More over, a lack of knowledge of the mechanical strength of materials can lead to undersizing of pavements for expected traffic, often resulting in premature deterioration of surface layers [6,7]. Technical failures can lead to higher maintenance costs. Solutions to these problems necessarily involve systematic characterization of materials and adaptation of construction protocols to local conditions. To address this issue, a number of studies have focused on the characterization of UGM. In France, Deodonne [8] in his study of UGM derived from limestone showed a Los Angeles Coefficient (LA) of 15.5% for crushed natural aggregates (GNC) and a micro-Deval (MD) of 21.8%. According to this author, these values are in line with the standards for the characteristics of UGM used in road construction.

Also, in their studies in 2022 Mbengue et al. [9] aimed at stabilizing aggregates derived from lateritic soils in Burkina Faso, obtained in granitic UGM, a fines content (<80 µm) of 15.91%, a Los Angeles index of 25%, and a high specific density of 2.9 t/m³, reflecting high compactness and low porosity.

Other authors [10,11] worked on aggregates in Senegal, these authors whose objective was to characterize local materials (lateritic) for road building, showed that the materials studied have an average percentage of fines (<80 µm) of 16.88%, an average dry density of 2.07 t/m³, an optimum water content (Wopm) of 9.28% and a CBR index with values ranging from 18 to 84%, for an average value of 46%.

However, these results cannot be extended to Côte d'Ivoire given the significant geological and climatic differences. In addition, these studies did not focus solely on Unbound Granular Material (UGM), which has been widely used in Côte d'Ivoire as a base course since the 1970s [7]. Côte d'Ivoire has a paved intercity road network of over 7,500 km, of which more than 40% of the pavement layers are composed of UGM. Numerous worksites are currently underway, and the choice of UGM quality is becoming increasingly important. This increased use of UGM demonstrates importance of a good knowledge of its characteristics to guarantee pavement performance. What's more, the lack of local data in Côte d'Ivoire limits the possibility of establishing specific standards and formulating recommendations adapted to the country's use of Unbound Granular Material of granite origin. In response to this problem, this study will carry out a detailed analysis of the physical and mechanical characteristics of Unbound Granular Material from different regions of Côte d'Ivoire. The results obtained should not only help optimize the use of these materials in pavement base layers, but also contribute to the construction of more sustainable and resilient road infrastructures, in line with the ambitions of SDG 9.

2. Methodology

2.1. Sample Collection

This research focused on the characterization of 0/31.5 crushed Unbound Granular Material (UGM) takenfrom fifteen quarries throughout Côte d'Ivoire. From each quarry, ten samples of 50 kg each were taken at random. The samples were then blended to obtain three composite samples with masses ranging from 150 kg to 200 kg. These samples were used physical and mechanical characterization tests at Laboratory of Building and Public Works (LBTP), Abidjan.

This nationwide sampling approach provides a representative view of the quality of materials available for road construction in Côte d'Ivoire. Figure 1 below shows the location of the quarries from which the UGM was sampled.

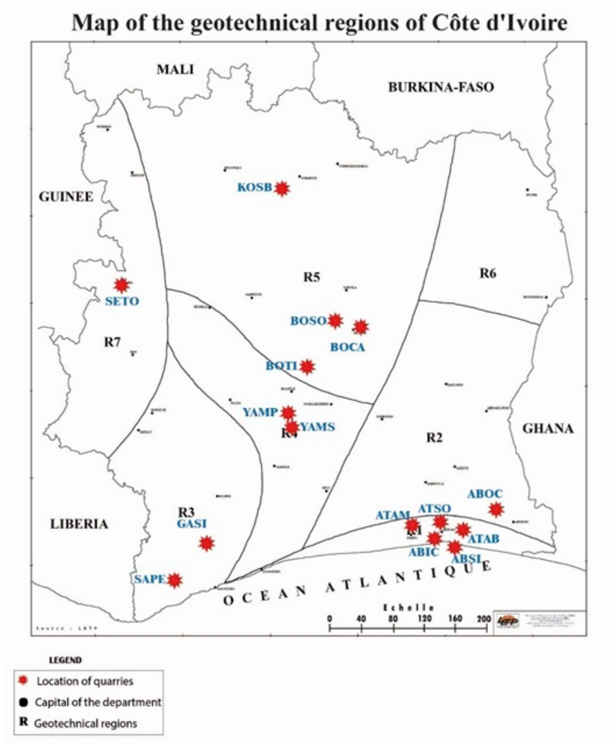

Figure 1. Location of quarries where GNT is extracted

The Table1 below shows the locations of the various quarries.

Table 1. Location of quarries

Career Codes	Locations	Career Codes	Locations
BOSO	Bouaké	BOCA	Bouake
YAMS	Yamoussoukro	ABSI	Abidjan
YAMP	Yamoussoukro	ABIC	Abidjan
KOSB	Korhogo	GASI	Gabiadji
BOTI	Bouake-Tiebissou	ABOC	Aboisso
SETO	Seguela-Touba	ATAB	Abidjan
SAPE	San Pedro	ATSO	Abidjan
		ATAM	Abidjan

The characterization of gravels used in road infrastructures requires a rigorous assessment of their physical and mechanical properties. This study is based on a series of standardized tests guaranteeing the reliability and reproducibility of results.

2.2. Physical Characterization

For the physical characterization of UGM, the following parameters were determined: methylene blue test (MB), flattening coefficient (CA), bulk density (DA), particle size analysis (AG for fines content) and specific gravity (PS).

The methylene blue test carried out in accordance with standard NF EN 933-9+A1 (June 2013) was used to assess the quality of the fines.

Aggregate morphology is assessed by determining the flattening coefficient in accordance with standard NF EN 933-3.

Volumetric properties were determined by measuring bulk density in accordance with NF EN

1097-3 and solid particle density in accordance with ISO 17892-3.

The particle size analysis used to determine fines content was carried out in accordance with standard NF EN 933-1.

2.3. Mechanical Characterization

Compaction characteristics were determined by the modified Proctor test (Wopm and ρdopm) (NF EN 13287-2).

The durability of the gravels was assessed using the wet Micro-Deval test (MDE) and the Los Angeles test (LA) in accordance with standards NF EN 1097-1 and NF EN 1097-2 respectively. The wet Micro-Deval test measures resistance to abrasion in the presence of water, while the Los Angeles test determines resistance to impact and fragmentation, reproducing the mechanical stresses experienced under traffic.

2.4. Characterization using the Statistical Method of Principal Component Analysis (PCA)

The averages of the results obtained after characterization of the UGMs were used to perform principal component analysis (PCA) using R software. The choice of this method is essentially due to the large number of individuals (the different quarries BOSO, YAMS, YAMP, KOSB, BOTI, SETO, SAPE, BOCA, ABSI, ABIC, GASI, ABOC, ATAB, ATSO, ATAM) and the various parameters (variables) involved: MB, DA, LA, MDE, PS, CA, AG, Proctor (Wopm and ρdopm), CBR.

For (N) samples or individuals identified by (p) quantitative variables, PCA reduces the dimension of the initial data by replacing the p initial variables by q appropriate factors (q<p). This multi-dimensional method can be used to summarize information on several variables, highlighting links between variables and forming groups of similar individuals.

3. Results and Discussion

3.1. Physical Characteristics of the UGM Tested

3.1.1. Methylene Blue Test

The mass of methylene blue (MB) is an indicator of aggregate cleanliness. Figure 2 below shows the average methylene blue mass values obtained in Unbound Granular Material from the quarries sampled.

Aggregates from the ABSI, ABIC, ATSO quarries in Abidjan and GASI (Gabiadji) have the highest value at 0.1%. UGM from the BOSO and BOCA quarries in Bouaké show more favorable values at 0.06%, indicating better cleanliness.

According to Liautaud et al. [12], analyses show that aggregates from the quarries studied meet the cleanliness standard (< 2%). These results are consistent with the observations of Rayssac et al. [13] on inert aggregates, highlighting the importance of low porosity to ensure better durability. Furthermore, these observations corroborate those of Guy [14], who identify a strong correlation between a low MB value and increased durability of road materials.

Figure 2. Mass of methylene blue in UGM

3.1.2. Flattening Coefficient

The kurtosis coefficient (CA) measures the shape of aggregates in UGM [15]. Figure 3 shows the average values of the flattening coefficient of UGM from the different quarries studied.

Figure 3. UGM flattening coefficient

Analysis of Figure 3 shows that BOCA gravels have a CA of 13.23%, which is in line with the work of [12]. Based on CA, BOCA UGMs are particularly suitable for sub- bases where good compactness is essential. These gravels can also be used in base courses where good stability is required, or as bitumen gravels where the rounded shape facilitates embedding

Gravels from the ABSI quarry, with a higher CA of 32.37%, have a value that exceeds the thresholds recommended by Liautaud et al. [12]. Therefore, based solely on the flattening coefficient, these gravels could be used with caution in sub-base courses, where form requirements are less stringent, or in engineered embankments, with greater control over placement [16]. Their use is not recommended for wearing courses, where interlocking is crucial. Indeed, gravels with a high CA (>30%) have flattened particles that reduce mechanical interlock between aggregates, increasing the risk of permanent deformation (rutting) and loss of bearing capacity [17,18].

3.1.3. Apparent Density (DA) and Specific Weight (PS)

Bulk density and specific weight are essential parameters for characterizing Unbound Granular Material, as they influence their mechanical behavior and their suitability for compaction [19,20]. Figure 4 below shows average values for bulk density and specific weight of UGM.

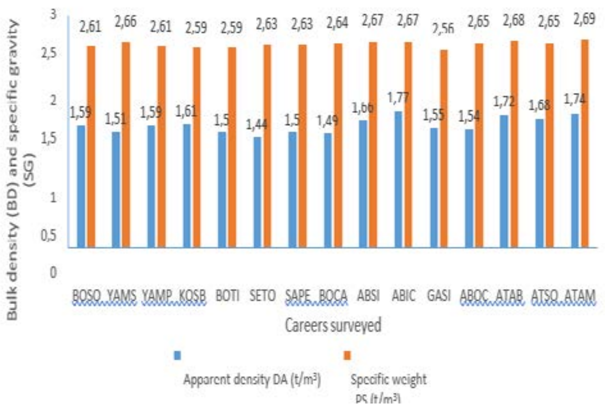

Figure 4. Bulk density and specific weight of GNT

The ABIC quarry shows the highest DA of 1.77 t/m³, confirming the compact quality of these aggregates. In comparison, the SETO quarry on the Seguela-Touba axis shows the lowest value at 1.44 t/m³, which could indicate a reduction in efficiency in applications where high compactness is required.

French road standards for base courses in Unbound Granular Material (UGM) do not explicitly set a universal minimum value for bulk density, but do impose compaction requirements linked to the Optimum Proctor Normal (OPN). However, according to Tahar et al. [21]. aggregates with an DA of less than 1.50 t/m³ tend to offer reduced stability.

Furthermore, the vast majority of quarries are close to the observations of Hyoumbi et al. [22], where basaltic aggregates mixed with lateritic soils achieve an optimum dry density of 1.85 t/m³. In contrast, expanded clay aggregates from Boussafir et al. [23] have a much lower bulk density (0.34 to 0.50 t/m³), limiting their application to infrastructure requiring lightweight materials

The specific weight (PS) oscillates between 2.59 and 2.68 t/m³, typical values for natural aggregates in line with the work of [24,25]. According to these authors, typical values for the specific weight of untreated gravel aggregates are generally between 2 t/m³ and 2.8 t/m³.

3.1.4. Fines Content

The fines content was quantified by particle size analysis (AG) of the UGM. Figure 5 below shows the results obtained.

Analysis of Figure 5 reveals that the GASI quarry at Gabiadji has the highest fines content at 5.35%. The SAPE quarry in San Pedro has the lowest fines content at 1.55%.

However, it is important to note that even the highest values observed remain well within the acceptable limits defined by standard NF EN 13285 [26], which tolerates fines contents of between 7% and 9% depending on the category of UGM.

The low fines content observed in some quarries, notably SAPE, SETO and BOTI, may indicate better resistance to water weathering [13].

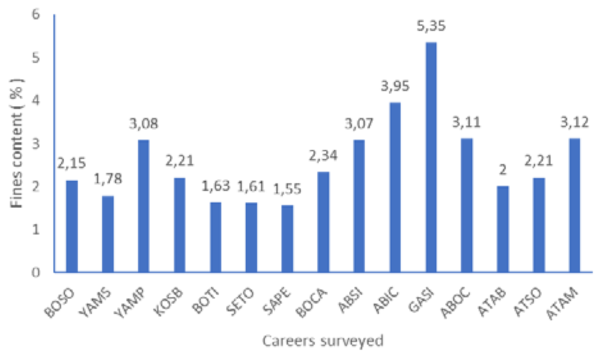

Figure 5. Fines content

3.2. Physical Characteristics of the UGM Tested

3.2.1. Los Angeles (LA)

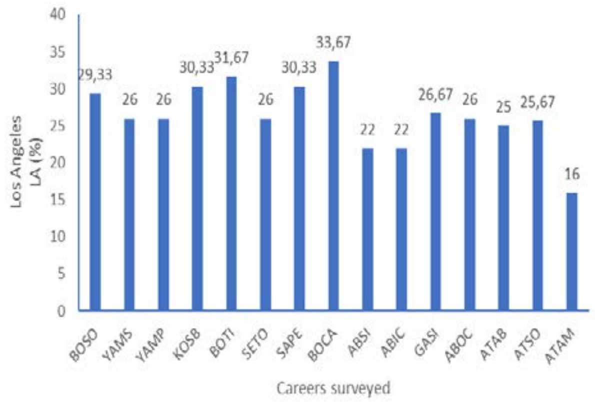

Figure 6. Los Angeles (LA) for UGM

Aggregates from the ABSI and ABIC quarries, both in Abidjan, show a moderate loss of 22%, indicating good strength, while those from the BOCA quarry in Bouaké show a high loss of 33.67%. The high loss of Los Angeles may reflect an increased susceptibility to shattering under heavy loads. However, their low flattening coefficient of 13.23% shows that the gravels from this quarry are rather resistant to wear. This would justify the fact that the Los Angeles of BOCA gravels is less than 35%, which is the maximum limit recommended for base courses in low-traffic areas [12].

Moreover, all quarries comply with this guide value. Our results are better than those obtained in basaltic aggregates reported by Hyoumbi et al. [22] even though a significant improvement in these basaltic UGMs gave results similar to those of the GASI quarry aggregates.

3.2.2. Proctor and CBR

The Proctor (ρdopm) and California Bearing Ratio (CBR) tests assess the optimum compactness and bearing capacity of soils, respectively. Figure 7 and Figure 8 show the values of these tests obtained in the UGMs studied.

Figure 7. Proctor for UGM

Optimum dry densities (ρdopm) range from 2.32 t/m³ for UGM from the ABOC quarry in Aboisso to 3.99 t/m³ for the BOCA quarry in Bouake, revealing significant variability in compaction conditions. These values are highly dependent on the porosity and characteristics of the materials used [27]. These values are higher than those reported in studies on basaltic or expanded clay aggregates [28], reinforcing the quality of the materials analyzed in our study.

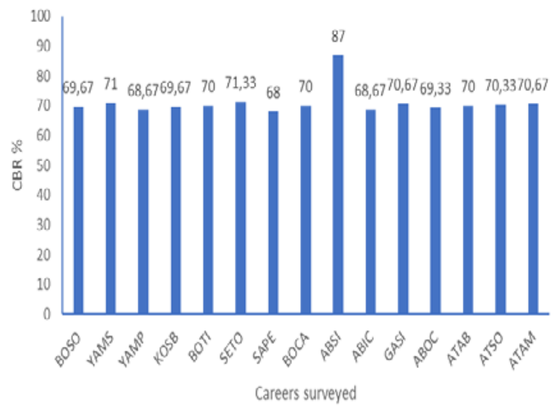

Figure 8. CBR of UGM

In terms of CBR, UGM from the ABSI quarry stands out with a very high CBR of 87%, attesting to its ability to withstand heavy loads. On the other hand, UGMs from the SAPE, YAMP and ABIC quarries have relatively low CBRs, around 68%, indicating a lower strength, which could limit their use to the more highly stressed upper layers.

Road standards require a minimum CBR of 80% for base courses. Consequently, only the ABSI quarry's UGMs meet this condition. These results surpass those reported by Hyoumbi et al. [22], where basaltic aggregates mixed with lateritic soils achieve a maximum CBR of 35% after improvement. This confirms the superiority of GASI aggregates in terms of bearing capacity.

3.2.3. Micro Deval Moist (MDE)

The Micro Deval Moist (MDE) is a test commonly used to assess the abrasive wear resistance of aggregates, particularly in Unbound Granular Material (UGM). This test is particularly important for road materials, as it helps determine their durability in the face of mechanical stresses generated by traffic [29]. Figure 9 presents the average values of Micro Deval Moist (MDE) tests carried out on Unbound Granular Material (UGM) from various quarries in Côte d'Ivoire.

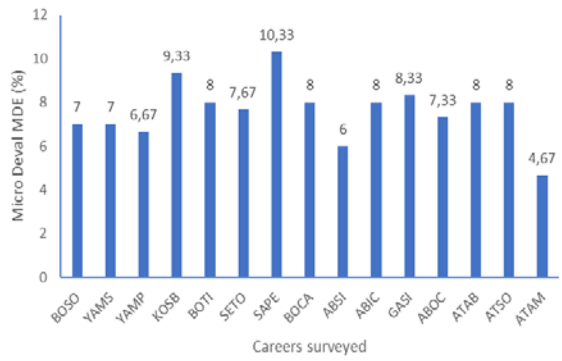

Figure 9. Moist Micro-Deval of UGM

MDE values range from 4.67% to 10.33%, revealing a significant difference in the abrasion and disintegration resistance of the materials. Gravel from the ATAM quarry, with an MDE of 4.67%, shows the best performance, reflecting excellent durability. Conversely, those from the SAPE quarry, with an MDE of 10.33%, show lower resistance, which could limit their use in highly stressed applications.

According to CSA International standard A23.1-00, quoted by Fortin [30] Unbound Granular Material for road base courses must generally have an MDE value of less than 12% to guarantee good durability. In comparison, all the quarries studied meet this requirement. However, particular attention should be paid to materials with values close to the limit, such as those from the SAPE quarry, as a small margin can become problematic under severe conditions of use (prolonged exposure to heavy loads or humid climates).

Gravels with low (<7%) Micro Deval Moist (MDE) values, such as those from the ATAM and ABSI quarries, are particularly suitable for demanding applications such as base courses and wearing courses, where durability is essential. On the other hand, gravels with higher MDE values (>8%), such as those from the SAPE, KOBS Korhogo or GASI quarries, may be limited to sub-base courses or require upgrading, such as mechanical (screening, additional crushing) or chemical (cement or lime stabilization) treatment.

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3.3. Characterization Using the Statistical Method of Principal Component Analysis (PCA)

The characterization of Unbound Granular Material yielded data whose averages for each parameter are shown in Table 2. Descriptive statistics showing an overview of the dispersion of each parameter across all quarries are presented in Table 3.

Table 2. Data table

	PARAMETERS									
Career	MB	DA	MDE	LA	PS	CA	AG	Wopm	ρopm	CBR
BOSO	0,06	1,59	7	29,33	2,61	20,63	2,15	2,49	3,38	69,67
YAMS	0,08	1,51	7	26	2,66	18,67	1,78	2,78	3,05	71
YAMP	0,07	1,59	6,67	26	2,61	26,59	3,08	2,54	3,9	68,67
KOSB	0,07	1,61	9,33	30,33	2,59	17,79	2,21	2,25	3,52	69,67
BOTI	0,08	1,5	8	31,67	2,59	13,9	1,63	2,8	3,17	70
SETO	0,08	1,44	7,67	26	2,63	14,3	1,61	2,56	3,27	71,33
SAPE	0,08	1,5	10,33	30,33	2,63	20,87	1,55	2,27	3,37	68
BOCA	0,06	1,49	8	33,67	2,64	13,23	2,34	2,44	3,99	70
ABSI	0,1	1,66	6	22	2,67	32,37	3,07	2,18	2,69	87
ABIC	0,1	1,77	8	22	2,67	16,95	3,95	3,81	2,35	68,67
GASI	0,1	1,55	8,33	26,67	2,56	20,06	5,35	4,79	2,3	70,67
ABOC	0,09	1,54	7,33	26	2,65	17,91	3,11	5,15	2,32	69,33
ATAB	0,08	1,72	8	25	2,68	23,8	2	4,12	2,36	70
ATSO	0,1	1,68	8	25,67	2,65	11,4	2,21	6,25	2,31	70,33
ATAM	0,075	1,74	4,67	16	2,69	14,4	3,12	5,12	2,36	70,67

Table 3. Descriptive statistics

	MB	DA	MDE	LA	PS	CA	AG	Wopm	ρdopm	CBR
Minimum	0,06	1,44	4,67	16	2,56	11,4	1,55	2,18	2,3	68
Average	0,081	1,592	7,62	26,44	2,64	18,873	2,612	3,439	2,957	71,004
Maximum	0,1	1,77	10,33	33,67	2,69	32,4	5,35	6,25	3,99	87
Standard deviation	0,013	0,1	1,33	4,387	0,04	5,571	1,029	1,33	0,613	4,523

3.3.1. Inertia Distribution

The inertia of the factorial axes indicates, on the one hand, whether the variables are structured and, on the other, suggests the appropriate number of principal components to study. Figure 10 below shows the inertia distribution of the principal component analysis performed.

Analysis of Figure 10 suggests that we limit our interpretation to the first two factorial axes or dimensions. Dimensions 1 and 2 account for 62.60% of total variance. This cumulative inertia rate significantly exceeds the theoretical threshold corresponding to the 0.95 quantile of a random distribution. Thus, only these two axes carry significant structural information in the data, justifying the interpretation of the PCA being restricted to dimensions 1 and 2, which summarize most of the variability of the parameters measured in the Unbound Granular Material samples.

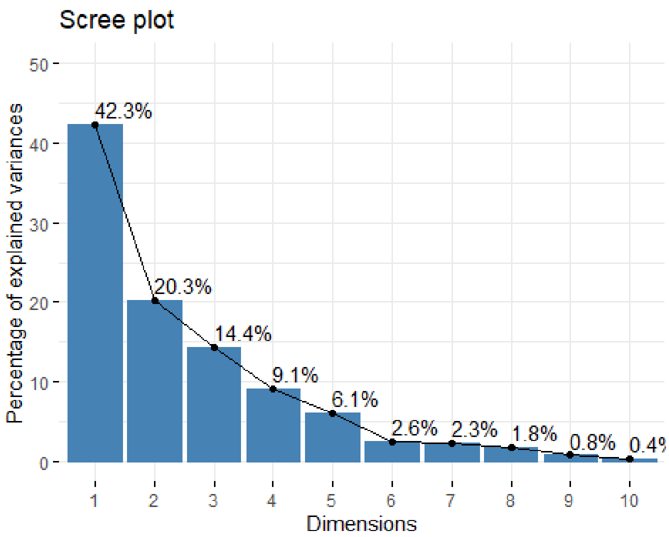

Figure 10. Inertia distribution

3.3.2. Correlation Matrix

Table 4 below shows the correlation matrix produced. This matrix shows the correlations between the parameters studied in Unbound Granular Material.

Table 4 Correlation matrix

Variables	MB (g)	DA (t/m^3)	MDE (%)	LA (%)	PS (t/m^3)	CA (%)	AG (% fines)	Wopm (%)	ρdopm (t/m^3)	CBR
MB (g)	1									
DA (t/m3)	0,395	1								
MDE (%)	0,053	-0,343	1							
LA (%)	-0,456	-0,686	0,694	1						
PS (t/m3)	0,224	0,530	-0,451	-0,613	1					
CA	0,158	0,175	-0,176	-0,189	0,078	1				
AG (% fines)	0,501	0,358	-0,220	-0,407	-0,155	0,199	1			
Wdopm (%)	0,560	0,460	-0,203	-0,473	0,245	-0,382	0,412	1		
ρdopm (t/m3)	-0,824	-0,591	0,256	0,676	-0,420	-0,012	-0,464	-0,765	1	
CBR	0,343	0,136	-0,409	-0,313	0,272	0,589	0,111	-0,209	-0,237	1

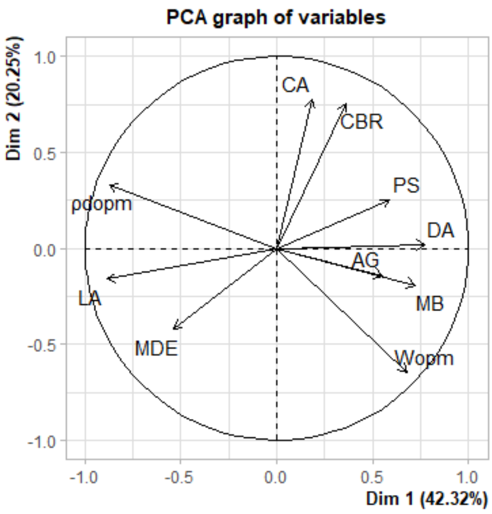

Figure 11. Correlation circle

Analysis of the matrix and correlation circle, shows a strongly negative correlation (-0.824) between maximum dry density (ρdopm) and cleanliness represented by the methylene blue (MB) value. This negative correlation shows that materials containing more fine particles, such as clays, tend to be less dense during compaction due to their ability to absorb more water [31,32]. So more particles gravels contain fine, the more durability and strength of pavements can be reduced.

Furthermore, this analysis also shows a negative correlation of -0.686 between Los Angeles (LA) and bulk density (DA). Similarly, the negative correlation (r = -0.613) between specific gravity (PS) and Los Angeles (LA) coefficient confirms that high-density aggregates have better intrinsic strength, as demonstrated by Fall [28] and Nataadmadja et al. [33].

The analysis also shows a negative correlation of -0.765 between optimum dry density (ρdopm) and optimum water content (Wopm). This strong negative correlation between these two proctor parameters confirms that gravels requiring more water to achieve maximum compactness are generally those with the lowest maximum dry densities. This inverse relationship between these two parameters plays a decisive role in the mechanical behavior of gravels used as pavement sub-base or base courses, directly influencing the load-bearing capacity, resistance to permanent deformation and durability of road structures [34].

The negative correlations between Los Angeles and bulk density on the one hand, and between specific weight and Los Angeles on the other, can also be explained by the mineralogical structure of the rocks. Denser materials are often made up of harder, better-crystallized minerals, conferring greater resistance to mechanical stress [35,36,37]. For road designers, these relationships make it possible to anticipate the mechanical performance of materials based on relatively simple density measurements.

A moderate positive correlation (r = 0.589) also appears between the California Bearing Ratio (CBR) and the flattening coefficient (CA). This result disagrees with previous studies which have shown that a low flattening coefficient would indicate the presence of cubic-shaped aggregates with better bearing capacity [12,38]. However, this correlation between the flattening coefficient and the CBR index would show that even gravels of more elongated shape with a good percentage of fines to fill the voids can have a relatively correct CBR [39]. This correlation could also be explained by the intrinsic hardness of aggregates.

Optimum water content (Wopm) shows a moderate positive correlation (r = 0.560) with the methylene blue (MB) value. This relationship confirms that materials containing more clays require more water to reach their maximum density during compaction. For roadworks, this correlation implies a precise adjustment of the water content when laying gravel containing active fines. Deviations from the optimum, particularly on the dry side, can significantly compromise compaction quality and, consequently, the durability of the structure [40,41].

The positive correlation of 0.694 obtained between the Los Angeles (LA) and Micro Deval Moist (MDE) coefficients underlines the complementary nature of these two mechanical strength tests. UGMs with high impact sensitivity also display low attritional wear resistance in wet conditions [42]. This would thus pose a major problem for pavement layers subject to high mechanical stresses and water infiltration. Hence the selection of materials with low wet Los Angeles and Micro-Deval values is therefore essential to ensure the longevity of road structures under conditions of heavy traffic and exposure to the elements.

The relationship between maximum dry density (ρdopm) and Los Angeles coefficient (LA) shows a positive correlation of 0.676, indicating that materials with better resistance to fragmentation achieve higher compactities. This relationship can be explained by grain

morphology and resistance to rearrangement under compaction [19,27].

3.3.3. Biplot

Figure 12 below shows the biplot representing the careers and parameters studied on dimensions 1 and 2 of the principal component analysis.

The principal component analysis (PCA) represented in this biplot provides a synthetic view of the relationships between the various mechanical and physical properties of Unbound Granular Material and its sources of supply. The first two factorial axes explain 62.60% of the total variance (Dim 1: 42.3% and Dim 2: 20.3%), which is a significant proportion of the information contained in the original data.

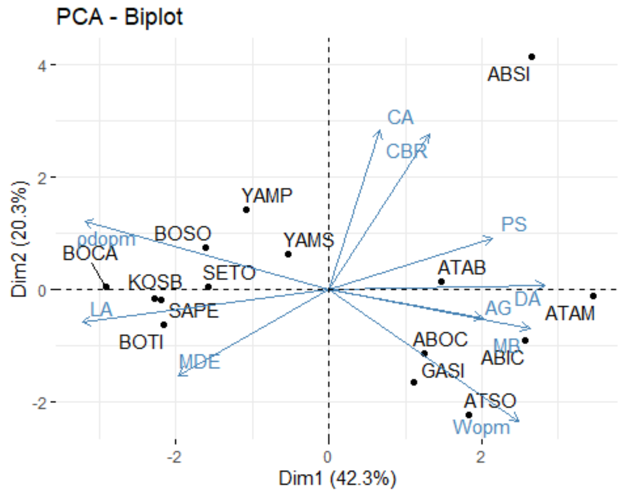

Figure 12. Distribution of quarries and parameters measured in GNT

Dimension 1, which captures most of the variability, clearly contrasts two groups of characteristics. On one side, to the left of the axis, we find the optimum dry density (ρdopm) and the Los Angeles coefficient (LA), indicative of materials with specific mechanical behavior. On the other side, to the right, are the methylene blue value (MB) and the optimum water content (Wopm), indicating materials with a more clayey, water-sensitive character. This structural contrast is fundamental to understanding the dominant properties of Unbound Granular Material. Dimension 2 completes this analysis by distinguishing materials according to their bearing capacity and shape. In the upper part of the graph, the California Bearing Ratio (CBR) and the flattening coefficient (CA) are positively correlated, while a high flattening coefficient suggests flat particles which should be less resistant. This correlation may therefore be due to the origin of the aggregates themselves.

With regard to supply quarries, their distribution on the biplot directly reflects the nature of the materials they produce. The BOSO, BOCA, KOSB, SAPE and BOTI quarries, located on the left-hand side of the graph, supply gravels characterized by good optimum dry density, but with a higher Los Angeles coefficient, suggesting less resistance to fragmentation. These characteristics could indicate material derived from partially altered magmatic rocks. Conversely, the ATAM and ABIC quarries on the right produce materials with a higher clay content, as evidenced by their proximity to the blue mass (MB). These gravels are potentially more sensitive to hydric variations, a critical feature for pavement durability in variable climatic conditions.

The ABSI quarry stands out for its position in the upper part of the graph, indicating the production of gravel with excellent bearing capacity (high CBR) but with a high flattening coefficient, indicating an angular or flat shape of the aggregates. This result, which differs from the usual observations, is due to the fact that this quarry has been in operation for a long time. It is therefore likely that the quarry has reached deeper geological levels, with more homogeneous and healthy rocks that can yield aggregates with very high mechanical strength despite their angular or flat shape. These materials could be particularly well suited to the base and sub-base layers of heavily trafficked roadways, where load-bearing capacity is paramount. In contrast, the ATSO quarry, located in the lower right-hand section, supplies materials with high water content at the proctor optimum and probably rich in flat, elongated particles, less conducive to good mechanical stability.

3.3.4. Hierarchical Classification

Figure 13 below shows the ascending hierarchical classification of careers. This classification shows how careers are grouped according to their similarities on the variables.

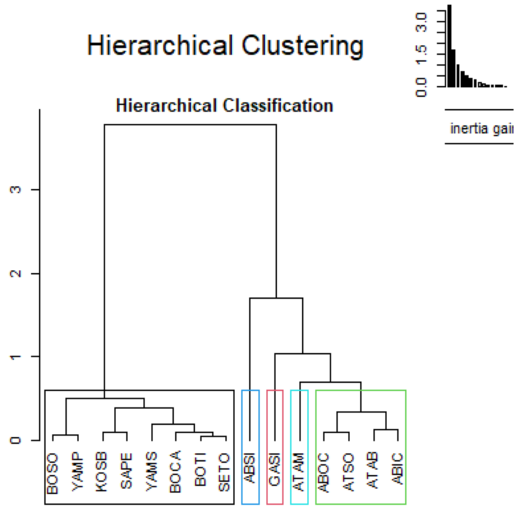

Figure 13. Hierarchical bottom-up classification

Analysis of figure13 shows that the ascending hierarchical classification has grouped individuals into 5 distinct classes according to the variables. Class 1 is made up of the BOSO, YAMP, KOSB, SAPE, YAMS, BOCA, BOTI and SETO quarries. These quarries are located in different geotechnical regions. Gravels from these quarries are characterized by high optimum dry density (ρdopm). On the other hand, their Los Angeles (LA) values are also high. These gravels also have low values for methylene blue mass (MB), optimum water content (Wopm), bulk density (DA) and fines content (AG). This means that they are fairly clean materials, with low clay content and low water sensitivity.

From a geotechnical point of view, these gravels can be used as sub-base or base courses on moderately trafficked roadways. However, their use in base courses is not recommended without improvement, due to their low mechanical strength.

Class 2 consists of the ABSI quarry in Abidjan. This quarry is characterized by high CBR and flattening coefficient (CA) values. This combination of properties gives this material excellent load-bearing capacity, making it an ideal candidate for the base courses of heavily trafficked roadways. However, its high absorption coefficient may call for particular attention to drainage aspects during pavement construction.

Class 3 consists of the Gabiadji quarry (GASI), whose gravels have high values for fine particles and low values for specific weight. These materials are likely to require treatment before use in road structures. They may be suitable for sub-bases, but should be avoided in areas subject to high rainfall or characterized by a high-water table, unless suitably treated.

Class 4 consists of the ATAM quarry located in the Abidjan area, characterized by low values for Los Angeles and Micro Deval Moist. Such durability is particularly advantageous for wearing courses, as the material is likely to retain its mechanical and grading properties under the effect of traffic and rainfall.

Class 5 comprises three quarries in Abidjan (ABIC, ATAB, ATSO) and one in Aboisso (ABOC). These quarries have gravels characterized by high water content at the proctor optimum and the lowest values for optimum dry density.

These properties translate into reduced compactness and increased sensitivity to hydric variations, unfavorable for base and sub-base courses subjected to heavy loads. Low optimum dry density limits load-bearing capacity and increases susceptibility to permanent deformation under repeated traffic. The use of these materials should therefore be combined with improvement techniques, such as stabilization with hydraulic binders, or limited to sub-bases.

4. Conclusion

The aim of this study was to characterize the physical and mechanical properties of Unbound Granular Material (UGM) used in Côte d'Ivoire for the construction of pavement layers. The results of standardized tests and statistical analysis identified several major trends.

From a physical standpoint, most of the UGM analyzed show satisfactory levels of cleanliness (MB), moderate fines content and flattening coefficients compatible with road engineering standards. However, some quarries, notably GASI, show a higher fines content, indicating increased sensitivity to water, which could compromise their in-service stability.

From a mechanical standpoint, the gravels are generally characterized by good resistance to fragmentation and wear, as well as an acceptable bearing capacity for road use. The ABSI quarry stands out in particular for its high CBR, indicating excellent behavior under traffic loads, unlike other materials with lower bearing capacities.

The hierarchical classification enabled us to group the gravel pits into five distinct classes. Class 1 comprises the Bouake, Yamoussoukro, Korhogo, San-Pedro and Seguela-Touba quarries (BOSO, YAMP, KOSB, SAPE, YAMS, BOCA, BOTI and SETO). Class 2 comprises the ABSI quarry in Abidjan. Class 3 comprises the GASI quarry in Gabiadji. Class 4 comprises the ATAM quarry in Abidjan. Finally, class 5 comprises three Abidjan quarries (ABIC, ATAB, ATSO) and the Aboisso quarry (ABOC).

Ultimately, this study provides solid scientific evidence to guide the choice of materials for road projects in Côte d'Ivoire. It thus contributes to the design of resilient road infrastructures, in line with the Sustainable Development Goals (SDG 9) relating to resilient and quality infrastructures.

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