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

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Abstract

This study characterizes Unbound Granular Material (UGM) used in road construction in Côte d'Ivoire through macroscopic and microscopic petrographic observations of composite samples from fifteen quarries. Results reveal a predominance of granite consistent with the local Birimian bedrock. Based on mineralogical composition and texture, the UGM are classified into four groups: biotite-dominant granites, alkaline granites, a granodioritic facies, and simple granites. The primary mineralogy is dominated by the quartz–feldspar–biotite assemblage, where biotite represents the weakest phase. Observed alteration processes—muscovitization, sericitization, chloritization, and epidotization—affect grain surface properties and increase moisture sensitivity. Biotite-rich granites with extensive muscovitization (>40%) are expected to show reduced bearing capacity and higher abrasion susceptibility. Alkaline granites and granodiorites affected by sericitization are likely to exhibit decreased performance under wet conditions. These findings highlight the decisive role of mineralogical composition and alteration intensity in predicting UGM durability in tropical road construction.

Keywords

Macroscopic and Microscopic Characterizations, Unbound Granular Material (UGM), Côte d'Ivoire, Road Construction

1. Introduction

Transport systems are a fundamental pillar of socio-economic development. They facilitate the movement of goods, provide access to essential services, and promote regional integration. Due to their role in the distribution of agricultural produce and access to markets, road infrastructure influences the competitiveness of economies [1] [2]. In Côte d'Ivoire, roads are a major driver of growth and territorial accessibility, as they account for more than 90% of freight and passenger transport [3].

The strategic importance of roads in socio-economic development is closely linked to their performance. The latter depends on the quality of its various layers. Among these, the base layer plays an essential role, as it must support and redistribute the loads transmitted by traffic to the lower layers. Road geotechnical studies show that the strength and durability of pavements depend heavily on the quality of the materials used in this layer [4] [5]. Among the materials frequently used in base layers, Unbound Granular Material (UGM) occupies a central place due to its local availability and low cost.

However, despite its widespread use and strategic importance, scientific understanding of the behavior of these materials remains incomplete. Indeed, Werkmeister *et al.* [6] studied the permanent deformation of granular materials subjected to repeated loading. Their work showed that resistance to deformation depends on grain size and the mineral nature of the aggregates. However, conducted more than twenty years ago, this work did not incorporate modern analytical tools that allow for a more detailed and reliable characterization of the constituent minerals.

Moreover, Pierre and Légère [7] showed, through laboratory tests on treated granular material and UGM, that mineralogy directly influences the strength and durability of unpaved layers. However, their methodology, focused on controlled laboratory conditions, does not consider the impact of environmental factors such as humidity or variations in actual traffic loads.

Furthermore, Biswal *et al.* [8], working on lateritic soils, showed that their high iron oxide content could improve the cohesion and bearing capacity of these materials. However, the high geological variability of laterites in Africa makes it difficult to generalize their conclusions to other types of untreated gravel used in pavements.

On their side, Varela *et al.* [9] proposed a numerical model of the behaviour of granular materials used in road foundations. Their study led to the development of predictive models linking particle size, compaction, and mechanical properties. However, validation through in situ testing remains limited, and the mineralogical aspect has not been integrated into the approach, reducing the scope of the results for practical use.

Finally, the work of Koné *et al.* [10] in Côte d'Ivoire focused on physical and mechanical properties of UGM and the correlations that exist between these properties. This work, did not address the mineralogical component, which could be essential for understanding the heterogeneity observed between different UGM production sites.

This previous work shows that while mechanical and physical properties have been extensively investigated, the mineralogical dimension remains on the margins of research. It is therefore necessary to fill this gap, particularly for Ivorian roads subject to tropical climatic conditions. It is in this context that this study has set itself the main objective of carrying out a mineralogical characterization of the UGM used as road base layers in Côte d'Ivoire. Specifically, this will involve carrying out:

- macroscopic petrographic analyses with a view to characterizing the type(s) of rock material present in the quarries;
- microscopic petrographic analyses of the aggregates to highlight the mineralogical composition of the rocks, the order of abundance of minerals, and the presence or absence of weathering.

2. Methodology

2.1. Sample Collection

This mineralogical characterization study focused on crushed UGM of type 0/31.5. These UGM were collected from fifteen quarries across Côte d'Ivoire. Sampling and reduction of aggregate samples were performed in accordance with the European standard NF EN 932-1 (1996), which specifies the procedures for sampling, sample reduction, and preparation of aggregates for testing. At each quarry, ten samples weighing 50 kg each were collected at random. The samples were then mixed to obtain three composite samples weighing between 150 kg and 200 kg. Some of these samples were used for macroscopic and microscopic observations of the UGM. This nationwide sampling approach provides a representative overview of the quality of materials available for road construction in Côte d'Ivoire. Figure 1 shows the location of the quarries from which the UGM were taken.

Table 1 below shows the locations of the different quarries.

Table 1. Quarries location.

Quarries codes	Localities	Quarries codes	Localities
BOSO	Bouaké	BOCA	Bouaké
YAMS	Yamoussoukro	ABSI	Abidjan
YAMP	Yamoussoukro	ABIC	Abidjan
KOSB	Korhogo	GASI	Gabiadji
BOTI	Bouaké-Tiébissou	ABOC	Aboisso
SETO	Séguéla-Touba	ATAB	Abidjan
SAPE	San Pedro	ATSO	Abidjan
		ATAM	Abidjan

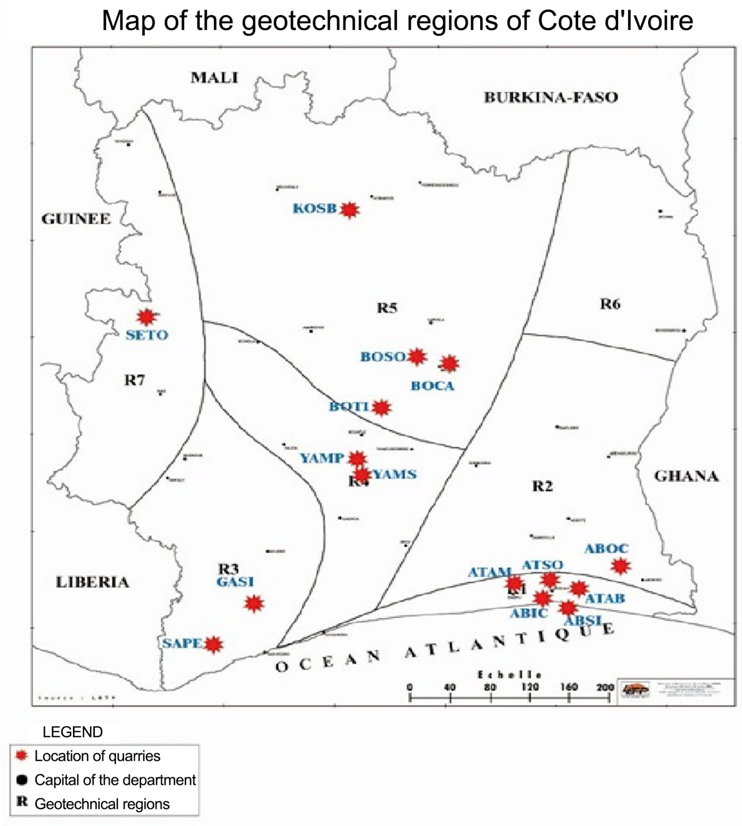

Figure 1. Placement of quarries for the extraction of Unbound Granular Material (UGM).

2.2. Mineralogical Characterization of Unbound Granular Material (UGM)

This characterization was carried out through macroscopic and microscopic observations of the minerals in the UGM of the fifteen quarries studied. These analyses were performed in order to identify the lithological nature of the UGM, to specify their mineralogy and their degree of alteration. After sampling, the samples were sent to the Laboratory of Geology, Mineral and Energy Resources (LGRME) at Félix HOUPHOUËT-BOIGNY University in Abidjan.

The macroscopic petrographic study described the textures, mineralogical composition and alterations. It was carried out after cleaning the samples with water and using a magnifying glass.

The microscopic study of the UGM was carried out on thin sections taken from the UGM. Thin sections are produced according to a rigorous protocol involving several successive steps and the use of highly specialised equipment. The combination of devices, consumables, methods and preparation parameters varies according to the nature of the samples to be processed. The choice of thin sections therefore considered the petrographic diversity observed during the macroscopic phase.

The protocol established for preparing thin sections consists of seven successive stages: sampling from a solid block, cutting the sugar, polishing or lapping the sugar, polishing the glass slide, bonding the sugar to the glass slide, heating and polishing or lapping the thin section.

Using a polarising microscope, the various thin sections were studied in greater detail and then photographed. The main criteria used for microscopic description were rock texture (granular, microgranular, microlithic, etc.), mineralogical composition (quartz, feldspars, microcline, orthoclase plagioclase, etc.) in order of abundance, and the presence of alterations (carbonation, sericitization, chloritization, etc.).

3. Results and Discussion

3.1. Macroscopic Characterization

Various macroscopic observations showed that the aggregates analysed mainly originate from the Ivorian crystalline basement and are all derived from Precambrian plutonic magmatic rocks. The predominance of granites and granodiorites reflects the regional geology of the West African shield.

3.2. Microscopic Characterization

3.2.1. ATSO Quarry

Microscopic study of Unbound Granular Material (UGM) from the ATSO quarry (**Figure 2**) reveals a granite composed mainly of quartz, very abundant, with very low relief, xenomorphic, colourless in natural light and a grey tint of the first order, as well as a characteristic rolling extinction. In addition, large, elongated grains of plagioclase are present, less abundant than quartz, also with low relief and colourless in natural light. The plagioclase is characterized by polysynthetic twinning, which is not very visible.

There is also biotite, which is less abundant than quartz and plagioclase. It is automorphic, brown in natural light and exhibits direct pleochroism, which alters to muscovite.

3.2.2. YAMS Quarry

Microscopic study of the UGM from the YAMS quarry in Yamoussoukro, shown in **Figure 3**, reveals a granite composed of two distinct facies.

The first facies (YAMS1), a biotite granite, has a porphyroid granular texture. It consists mainly of very abundant quartz, colourless in natural light, with very low relief, xenomorphic in shape, with a grey to white first-order hue and characteristic rolling extinction. This quartz often appears in the form of phenocrystals. The facies also contain abundant biotite, subautomorphic to automorphic in shape, brown in colour, showing clear pleochroism and fractures. It locally alters to muscovite and secondary minerals such as epidote. Microcline, colourless and xenomorphic, can be recognised by a barely visible grid-like twinning, often associated with colourless plagioclase with medium relief, which has a well-marked polysynthetic twinning and partial alteration to sericite. Orthoclase, on the other hand, is colourless, xenomorphic and characterised by a simple twin. The high biotite content gives these facies a generally darker colour than that of classic granite.

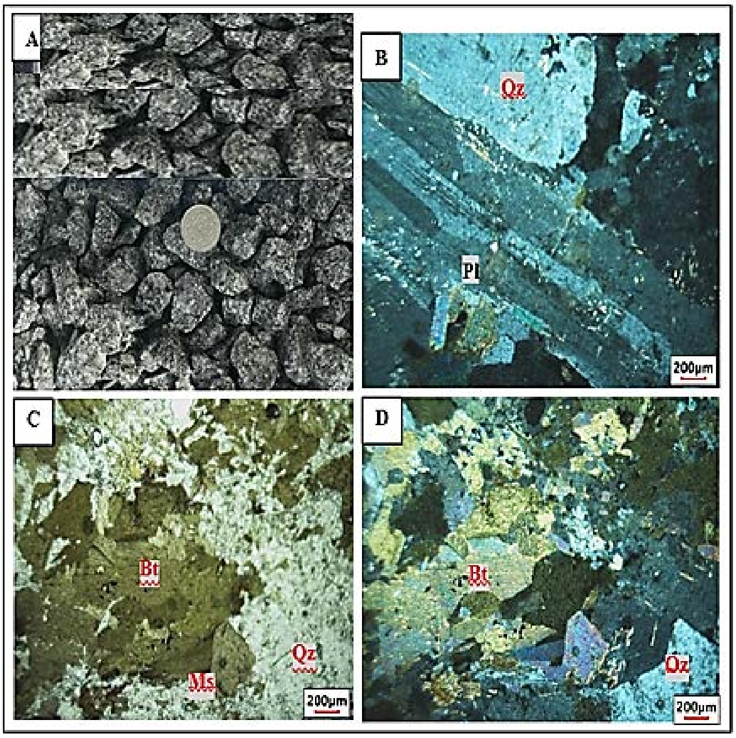

Figure 2. Macroscopic and microscopic photographs of the sample from the ATSO quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

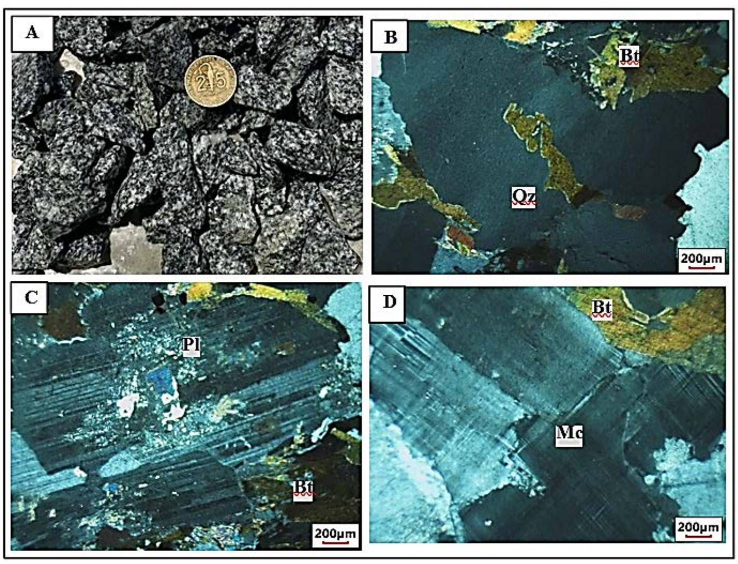

Figure 3. Macroscopic and microscopic photographs of the YAMS facies 1 sample. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light (D): biotite, muscovite, and quartz assemblage in polarized light.

The second facies (YAMS 2) is an alkaline granite (**Figure 4**). This facies has a homogeneous mineral morphology and a granular texture. It is enriched in colourless quartz, with very low relief, xenomorphic in shape, with uniform grains. Microcline is also abundant, colourless, xenomorphic, and recognisable by its clearly visible grid-like twinning. Plagioclase, less abundant, is colourless in natural light, with low relief, and has polysynthetic twinning; it alters in places to sericite. Biotite, automorphic, brown in natural light, shows direct pleochroism and gradually alters to muscovite. This facies is characterised by a regular mineralogical organisation and a more homogeneous composition.

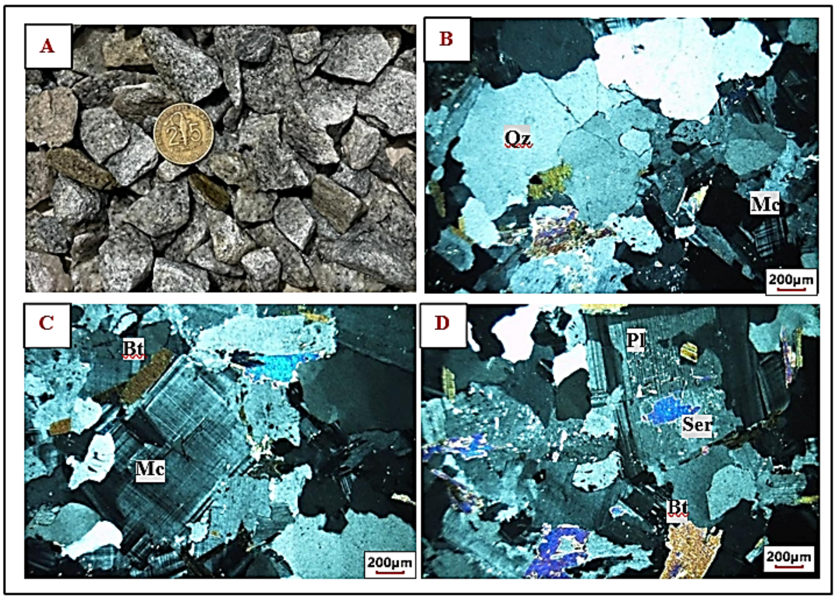

Figure 4. Macroscopic and microscopic photographs of the YAMS facies 2 sample. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.3. BOSO Quarry

Microscopic study of UGM from the BOSO quarry in Bouaké (**Figure 5**) reveals a granular-textured granitic rock composed mainly of quartz, the most abundant mineral. It occurs in xenomorphic form, colourless in natural light, with a grey to light first-order hue. Quartz is followed in abundance by plagioclase, which is subautomorphic to automorphic in form, colourless in natural light, and characterised by a barely visible polysynthetic twinning. Microcline, also present but in smaller quantities, is distinguished by its subautomorphic to automorphic form, its colourless appearance in natural light, and its grid-like twinning. Biotite, significantly less abundant than quartz and plagioclase, is automorphic in shape, brown in natural light, and exhibits marked pleochroism. It has a strong relief and a bright greenish-yellow hue. Through alteration, it partially transforms into muscovite, which is xenomorphic, colourless in natural light, and has a purplish-blue tint in polarised light.

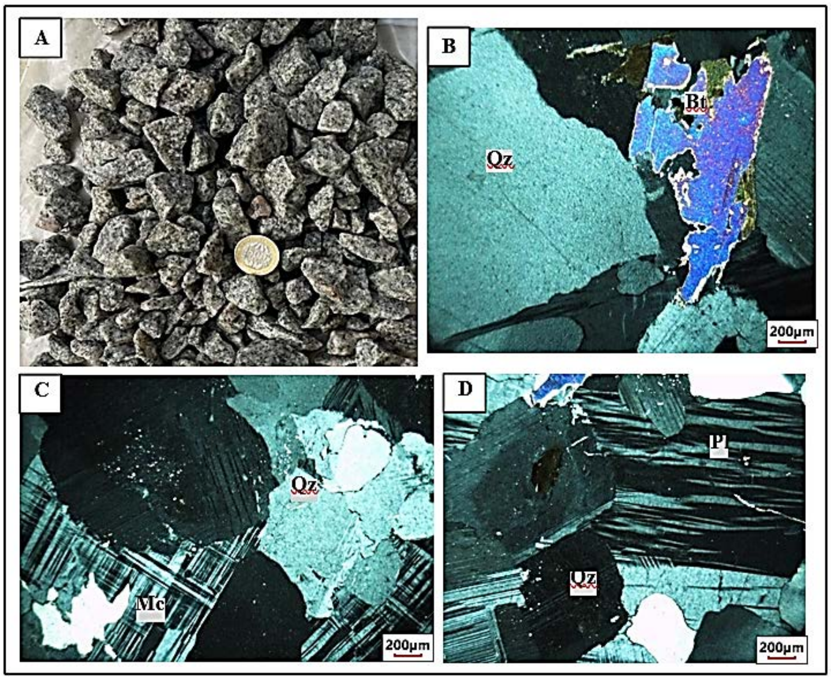

Figure 5. Macroscopic and microscopic photographs of the BOSO sample. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.4. YAMP Quarry

Microscopic study of UGM from the YAMP quarry in Yamoussoukro (**Figure 6** and **Figure 7**) reveals two facies (YAMP1 and YAMP2) that share characteristics typical of granites. In both cases, quartz is present, recognisable by its grey to white colour, its rolling extinction and its low-relief xenomorphic appearance. Feldspars, represented by polysynthetic twinned plagioclases and sericite alterations, as well as grid-twinned microcline, are another common feature. Biotite, present in both facies, systematically exhibits a brown colour, marked pleochroism and partial alteration to muscovite, indicating a common petrogenetic origin.

However, there are notable differences between the two facies. YAMP1 granite is characterised by a porphyroid granular texture with plagioclase phenocrystals and abundant, automorphic biotite showing epidote alteration. In contrast, the alkaline YAMP2 granite has a homogeneous granular texture, enrichment in feldspars (particularly small microcline) and less abundant biotite with extensive chlorite alteration. The presence of orthoclase, although very scarce in YAMP2, is another striking difference compared to YAMP1. These mineralogical and textural distinctions give YAMP2 a more pronounced alkaline character than YAMP1.

3.2.5. ABIC Quarry

Microscopic examination of UGM from the ABIC quarry in Abidjan (**Figure 8**) reveals a porphyroid-textured granite dominated by feldspars. Microcline is very abundant, colourless in natural light, with low relief and small in size. It is distinguished by a clearly visible grid-like twinning and is frequently associated with plagioclases in the rock. Plagioclase, xenomorphic and with low relief, appears in the form of phenocrystals and has a clear polysynthetic twinning. In places, it shows perthite exsolutions. Quartz, which is well represented, occurs in large crystals, with a grey to white colour of the first order and a characteristic rolling extinction. Biotite, which is not very abundant, is automorphic, brown in natural light, with a strong relief and well-marked pleochroism. It is distributed in small crystals scattered throughout the rock. Most of the biotite grains alter to muscovite, a mineral with low relief, appearing as flakes included in the plagioclase and displaying a characteristic purplish-blue colour in polarised light. Chlorite is also observed in the form of flakes, resulting from the alteration of biotite.

3.2.6. ABSI Quarry

Microscopic examination of UGM from this quarry (**Figure 9**) reveals a grainy rock composed mainly of plagioclase. This mineral, which is colourless in natural light, medium-sized and low-relief, has a well-defined polysynthetic twinning. The quartz, which is large and xenomorphic in shape, shows characteristic rolling extinction and a grey to white colour of the first order. Microcline, which is less abundant, sometimes appears as phenocrystals; it is colourless, with low relief, and can be recognised by its barely visible grid twinning. The biotite is pleochroic, changing from yellow to green, and undergoes progressive alteration to muscovite. The latter, which is pale green in colour and has fine cleavage, tends to alter to epidote at the edges of the grains.

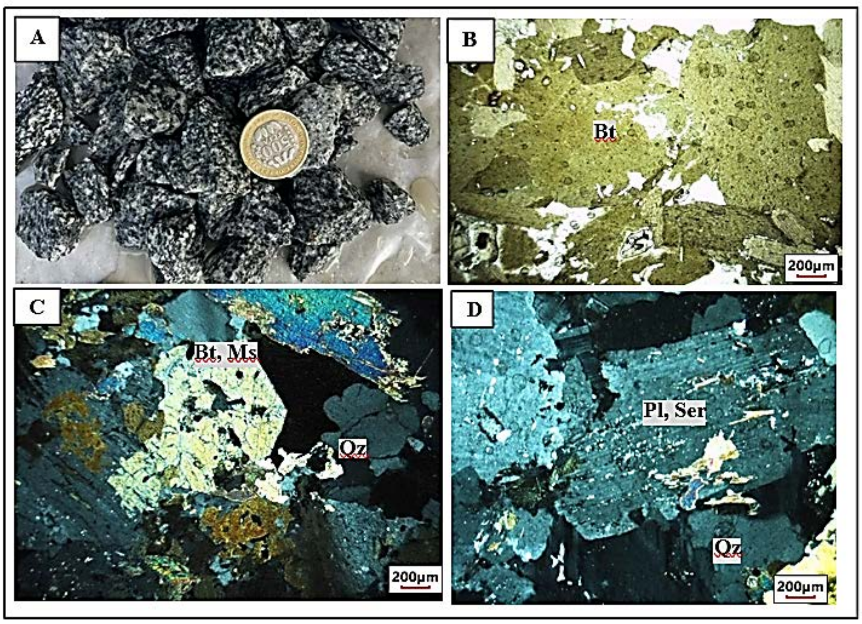

Figure 6. Macroscopic and microscopic photographs of UGM from the YAMP quarry at the YAMP1 facies. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

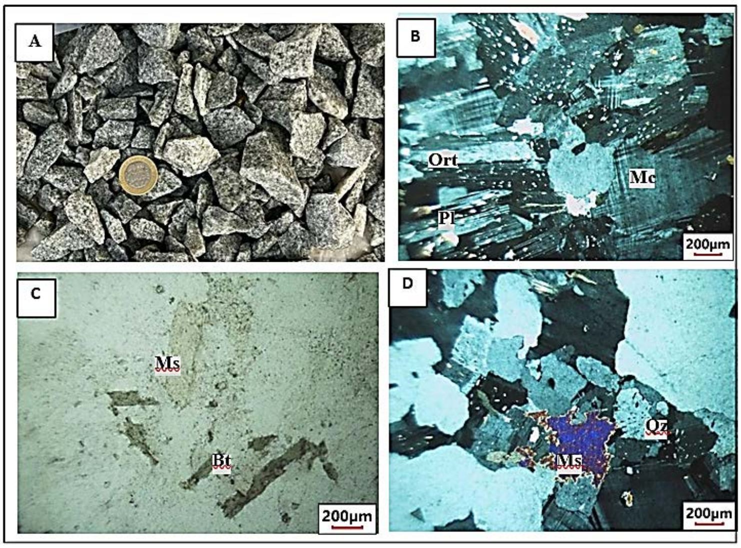

Figure 7. Macroscopic and microscopic photographs of UGM from the YAMP quarry at the YAMP 2 facies. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

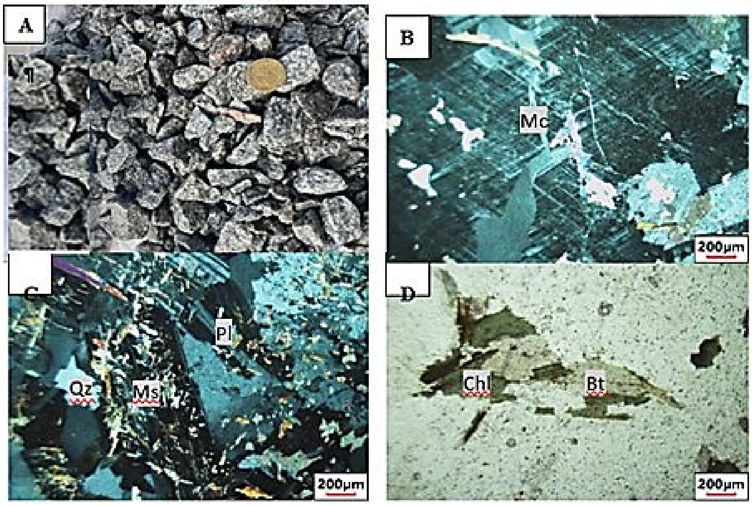

Figure 8. Macroscopic and microscopic photographs of UGM from the ABIC quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.7. BOCA Quarry

Microscopic examination of Unbound Granular Material (UGM) from the BOCA quarry in Bouaké (**Figure 10**) reveals a porphyroid-textured granite dominated by feldspars. Microcline is very abundant, colourless in natural light, xenomorphic in shape, and distinguished by a clearly visible grid-like twinning. It is frequently associated with plagioclases, which are also abundant, colourless, xenomorphic, and exhibit clear polysynthetic twinning and frequent alteration to sericite. Quartz, less abundant, occurs in large crystals with a grey to white colour of the first order and a characteristic rolling extinction. Biotite, greenish brown in colour, occurs as automorphic to subautomorphic crystals with medium to strong relief. It locally alters to muscovite, a rare, colourless mineral with a bluish tint, which appears as small crystals scattered throughout the rock.

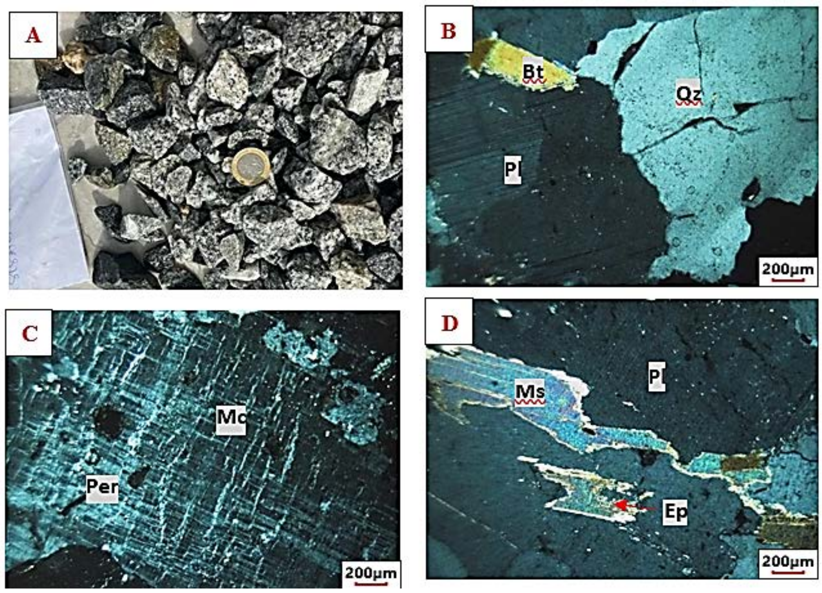

Figure 9. Macroscopic and microscopic photographs of UGM from the ABSI quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

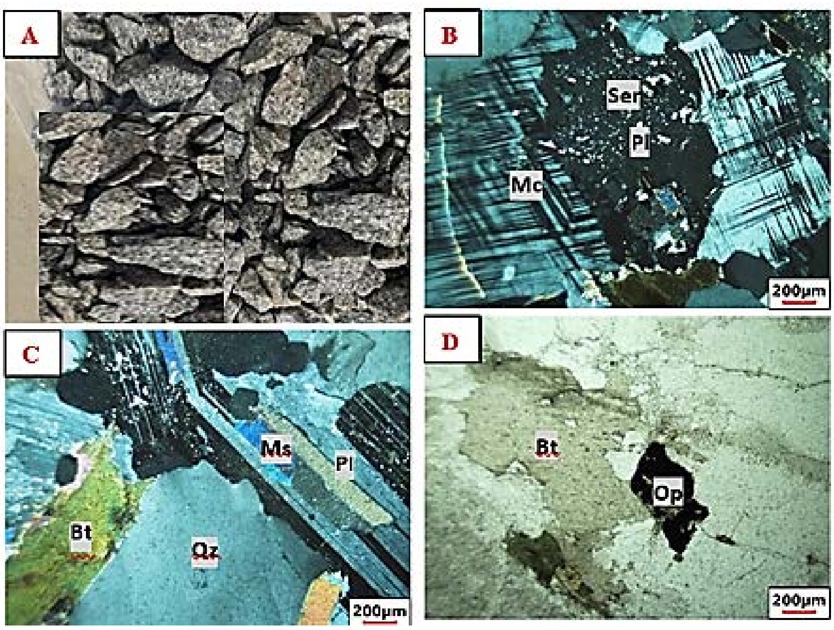

Figure 10. Macroscopic and microscopic photographs of UGM from the BOCA quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light;(D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.8. ATAB Quarry

Microscopic examination of Unbound Granular Material (UGM) from the ATAB quarry in Abidjan (**Figure 11**) reveals granite with a normal granular texture, typical of plutonic rocks. This granite is dominated by feldspars, particularly plagioclase, which is very abundant, colourless in natural light, with low relief, and present in the form of medium-sized crystals. It has a well-marked polysynthetic twinning and shows frequent alterations to sericite. Quartz occurs as xenomorphic, colourless crystals with very low relief, with a grey to white first-order colour and characteristic rolling extinction. Biotite, which is very scarce, occurs as small brown crystals with high relief, exhibiting direct pleochroism. It is mainly altered to chlorite and opaque minerals. Microcline, also very scarce, is colourless, xenomorphic and altered, making it difficult to observe its grid-like twinning.

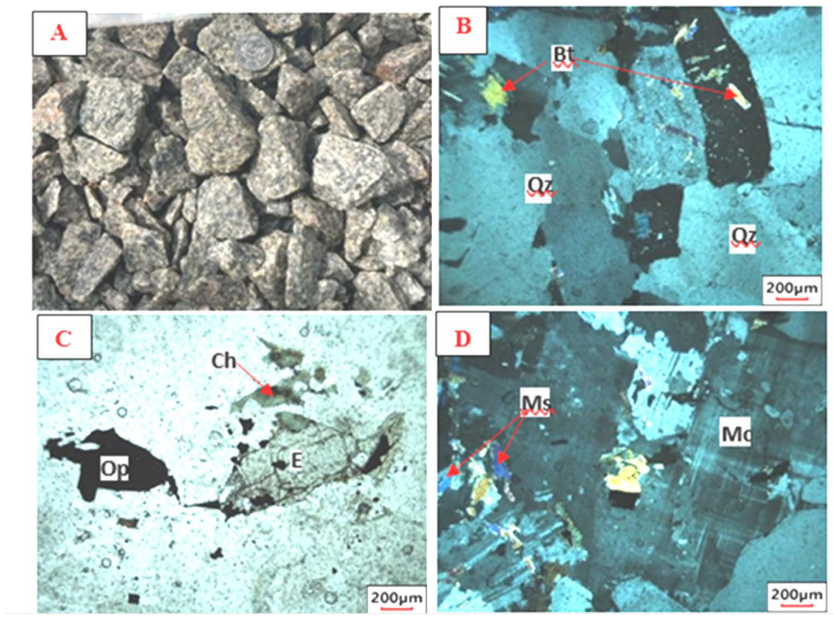

Figure 11. Macroscopic and microscopic photographs of UGM from the ATAB quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.9. BOTI Quarry

Microscopic examination of Unbound Granular Material (UGM) from the BOTI quarry, located on the motorway between Bouaké and Tiébissou (**Figure 12**), reveals a rock with a porphyroid grain texture. This formation is characterised by a composition dominated by quartz, which is very abundant, colourless in natural light, xenomorphic, with very low relief, a grey to white colour of the first order and a characteristic rolling extinction. It occurs in the form of large crystals. Plagioclase, which is less abundant, occurs as large, colourless crystals with medium relief. It has a well-marked polysynthetic twinning and shows sericite alteration in places. Microcline, which is less abundant, colourless and xenomorphic, has a clearly visible grid-like twinning and shows alteration to sericite. Biotite, which is not very abundant, appears altered to muscovite and is often associated with quartz-rich areas. Muscovite, which is very rare, occurs as flakes included in plagioclase and results from the alteration of biotite.

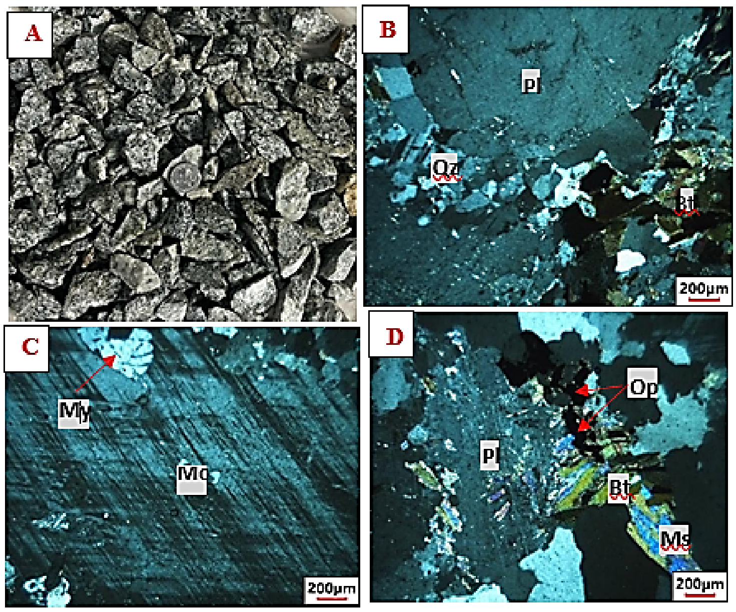

Figure 12. Macroscopic and microscopic photographs of UGM from the BOTI quarry. Pl: plagioclase; Qz: quartz; Bt: biotite; Ms: muscovite; (A): granite aggregate; (B): plagioclase and quartz assemblage; (C): biotite, muscovite, and quartz assemblage in natural light; (D): biotite, muscovite, and quartz assemblage in polarized light.

3.2.10. ABOC Quarry

Microscopic examination Unbound Granular Material (UGM) from the ABOC quarry, located in Aboisso (Figure 13), reveals a grainy rock texture characteristic of granitic facies. This formation is dominated by abundant, large quartz crystals, colourless in natural light, with very low relief and xenomorphic shapes. They are grey to white in colour and exhibit characteristic rolling extinction. Most of the crystals are cracked, indicating possible deformation or post-crystallisation alteration. Plagioclase, which is less abundant, occurs as medium-sized, colourless crystals with low relief. It has a slightly marked polysynthetic twinning and pronounced alteration to sericite. Microcline, also present in medium-sized, colourless crystals with low relief, shows a slightly visible grid twinning. This mineral is altered to sericite and myrmekite, indicating advanced transformation. The brown biotite exhibits marked pleochroism and a subautomorphic to automorphic morphology. It is heavily altered to muscovite, chlorite and epidote, reflecting an advanced process of mineralogical destabilisation.

3.2.11. GASI Quarry

Microscopic examination of Unbound Granular Material (UGM) from the GASI quarry in Gabiadji (Figure 14) reveals a grainy rock texture typical of granitic facies. The mineralogical assemblage is dominated by quartz, varying in size, colourless in natural light, with very low relief and xenomorphic in shape. It has a grey to white colour of the first order and characteristic rolling extinction. Microcline, also xenomorphic, colourless and with low relief, is observed in the form of phenocrystals. It is altered, making it difficult to clearly recognise its grid-like twinning. Plagioclase, less abundant, xenomorphic, colourless and with low relief, shows polysynthetic twinning and signs of alteration into sericite and myrmekite. Biotite, which is scarce, brown, subautomorphic to automorphic in morphology, is largely altered to muscovite. The latter, less abundant than biotite, is colourless, low relief, and distinguished by a purplish-blue hue. It appears in the form of flakes preferentially oriented within the granitic matrix.

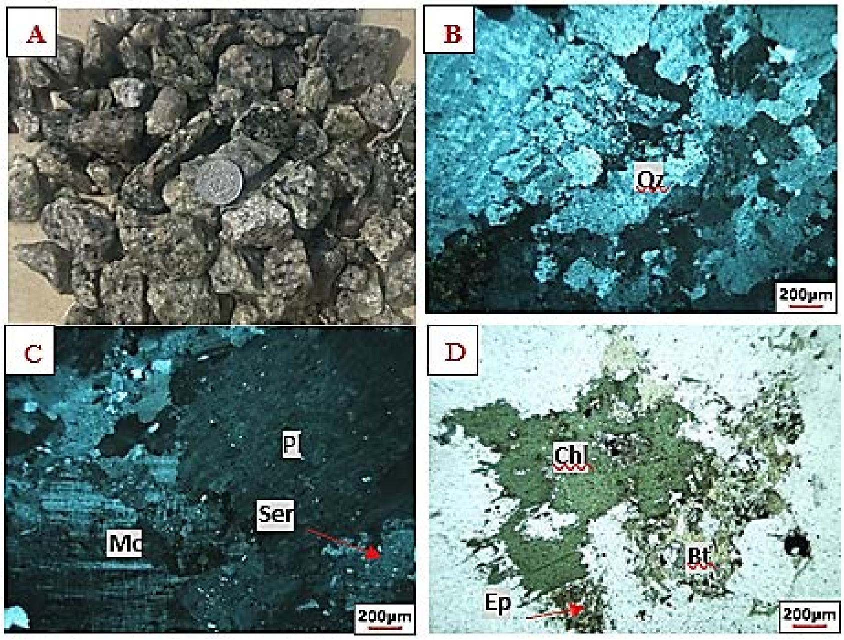

Figure 13. Macroscopic and microscopic photographs of the UGM sample from the ABOC quarry Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Chl: Chlorite; Ser: Sericite (A): Granite granules; (B): Cracked quartz; (C): Assemblage of plagioclase and microcline; (D): Alteration of biotite into chlorite and epidote.

3.2.12. SETO Quarry

Microscopic examination of Unbound Granular Material (UGM) from this quarry (**Figure 15**) reveals a porphyroid-textured rock, typical of slowly cooled granites. The mineralogical assemblage is dominated by plagioclase, which is very abundant, colourless in natural light, xenomorphic in shape, and present in the form of phenocrystals. This mineral shows marked alteration to sericite. Quartz, which is less abundant, occurs as xenomorphic crystals, colourless, with very low relief, with a grey to white first-order colour and characteristic rolling extinction. In places, the quartz crystals are locally cracked. Biotite, which is not very abundant, appears in the form of automorphic crystals, brown in colour, with a strong relief and well-marked pleochroism. It is altered into muscovite, chlorite and opaque minerals. The microcline, which is small, xenomorphic, colourless and with low relief, is altered, making it difficult to clearly observe its grid-like twinning.

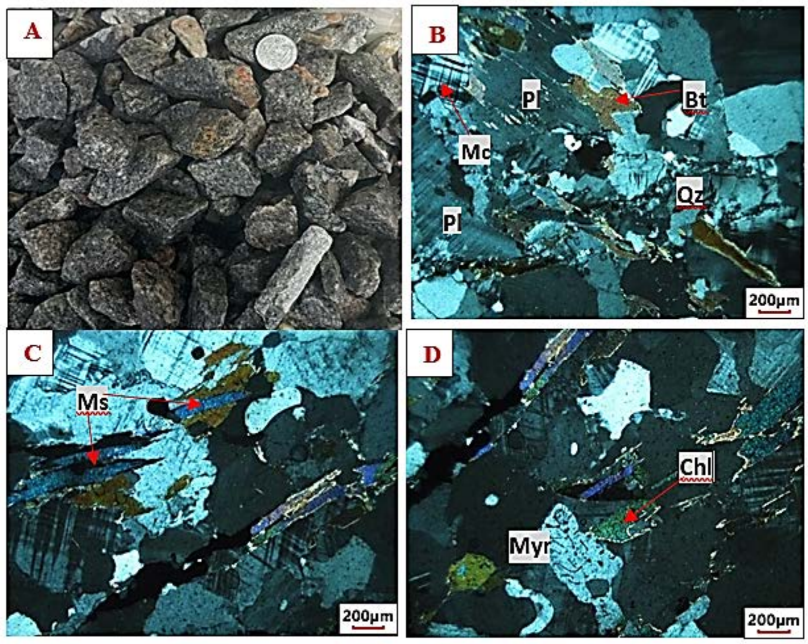

Figure 14. Macroscopic and microscopic photographs of the UGM sample from the GASI quarry. Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Ms: Muscovite; Opq: Opaque; Ser: Sericite (A): Granite grain; (B): Deformed quartz; (C): Muscovitisation; (D): Alteration of biotite to chlorite and exsolution of plagioclase.

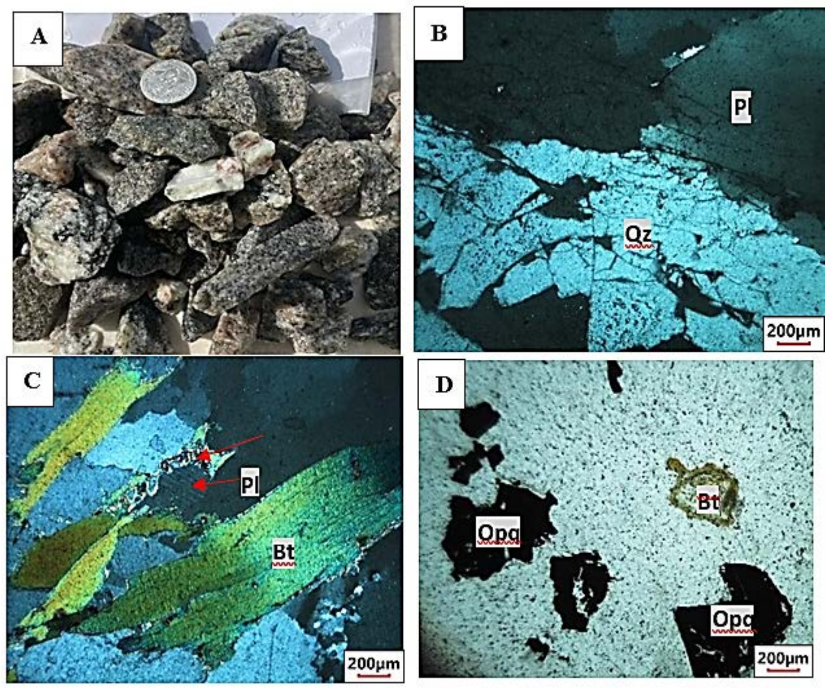

Figure 15. Macroscopic and microscopic photographs of UGM from the SETO quarry. Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Ms: Muscovite; Opq: Opaque; Ser: Sericite; Ep: Epidote (A): Granite granules; (B): Cracked quartz and plagioclase; (C): Biotite and muscovite assemblage; (D): Alteration of biotite into opaque mineral.

3.2.13. ATAM Quarry

Microscopic examination of Unbound Granular Material (UGM) from the ATAM quarry (**Figure 16**) reveals a porphyroid-textured granite. The mineralogical composition is dominated by quartz, which is very abundant, xenomorphic, colourless in natural light, and has very low relief. It has a grey to white colour of the first order and characteristic rolling extinction. The colourless plagioclase, with low relief, occurs in medium-sized crystals, often in the form of phenocrystals. It is characterised by a clearly visible polysynthetic twin and shows perthite alteration. Microcline, xenomorphic, colourless and with low relief, is present in the rock in the form of phenocrystals. It is altered, making it difficult to observe its grid-like twinning. Biotite, which is not very abundant, brown in colour, automorphic, has high relief and well-marked pleochroism. It is altered into muscovite and chlorite. Muscovite, colourless, with low relief, occurs as flakes included in plagioclase, with a characteristic purplish-blue colour. It results from the alteration of biotite.

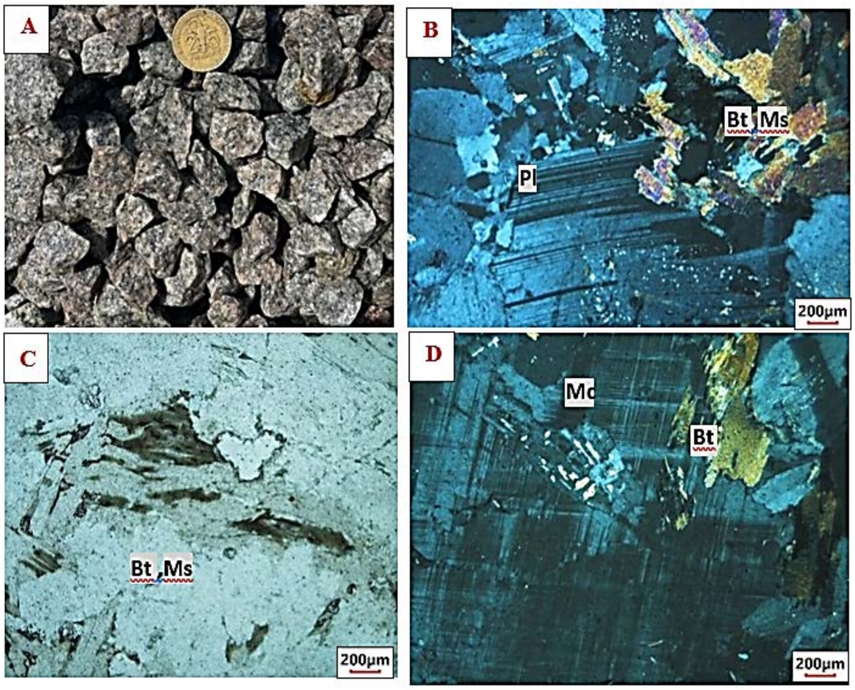

Figure 16. Macroscopic and microscopic photographs of UGM from the ATAM quarry. Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Ms: Muscovite; Per: Perthite (A): Granite aggregate; (B): Combination of plagioclase, biotite and muscovite in; (C): Alteration of biotite to muscovite in natural light; (D): Combination of microcline, biotite and quartz.

3.2.14. KOSB Quarry

Microscopic analysis of the granite identified by macroscopic analysis (**Figure 17**) reveals a porphyroid granular texture, with a mineralogical composition consisting of quartz (50%), which is very abundant in the rock, colourless, with very low relief and xenomorphic in shape. This mineral has a grey to white colour and characteristic rolling extinction. It has grains of varying sizes. Microcline (20%), which is very abundant after quartz, is xenomorphic, colourless and has a low relief. This mineral is found in the rock in the form of phenocrystals. The microcline is altered and gives rise to myrmekite, making it somewhat difficult to observe its grid-like twinning in certain places. It is generally associated with plagioclases (10%), xenomorphic, with low relief and present in the form of phenocrystals in the rock, it has a clear polysynthetic twinning, biotite (20%), not very abundant, brown in colour and automorphic, it has high relief and well-marked pleochroism. It appears in the form of small crystals scattered throughout the rock.

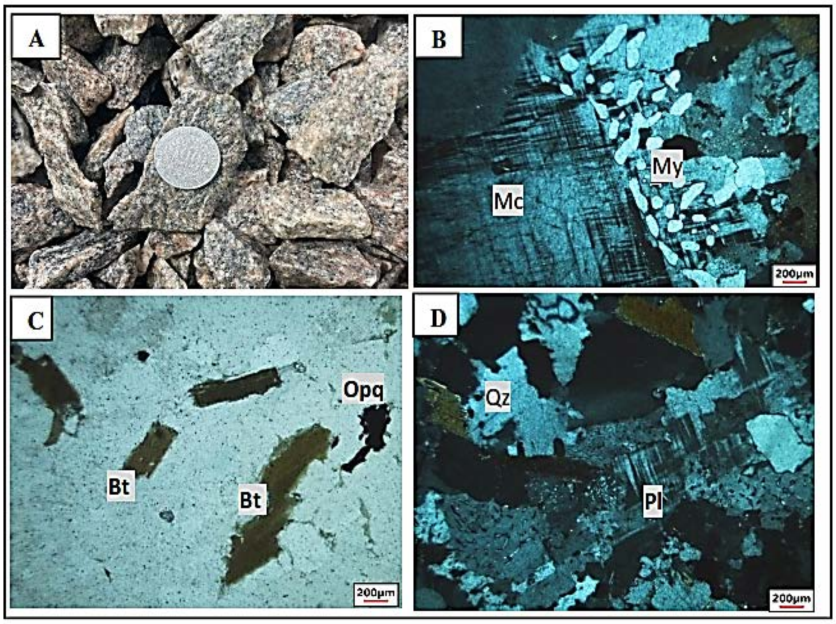

Figure 17. Macroscopic and microscopic photographs of UGM from the KOSB quarry Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Ms; Opq: Opaque; Myr: Myrmekite (A): Granite granules; (B): Microcline altered to myrmekite; (C): Association of biotite and opaque minerals; (D): Plagioclase and quartz assemblage.

3.2.15. SAPE Quarry

Microscopic analysis of sample SAPE 1 (**Figure 18**) confirms our macroscopic observations, revealing a granite with a normal granular texture and a mineralogical composition consisting of quartz, which accounts for 50% of the rock. It is xenomorphic with very low relief, colourless with a grey to white hue and characteristic rolling extinction. The quartz crystals are medium-sized, while biotite, which accounts for about 30% of the rock and is less abundant than quartz, is brown and automorphic, with high relief and marked pleochroism. It appears as small crystals scattered throughout the rock. Plagioclase, which is very scarce in the rock (10%), is colourless with low relief and occurs in medium-sized crystals. It is characterised by a well-marked polysynthetic twinning. Muscovite is present in small quantities in the rock (10%). It is colourless and xenomorphic, with a bluish tint, and occurs in small to medium-sized crystals. It appears to originate from the alteration of biotite.

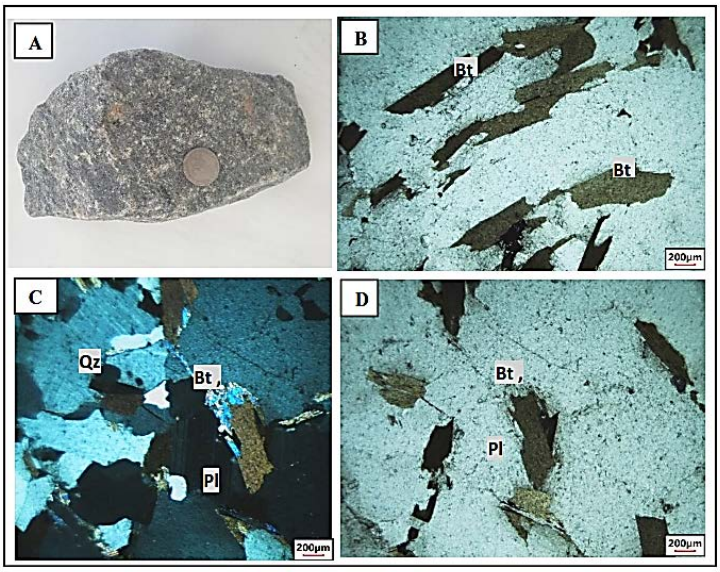

Figure 18. Macroscopic and microscopic photographs of UGM from the SAPE 1 quarry. Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Ms: Muscovite (A): CSP01 sample; (B): Association of biotite and quartz in natural light; (C): Quartz and alteration of biotite to muscovite; (D): Plagioclase, quartz and biotite.

Microscopic observation of sample SAPE 2 (Figure 19) confirms the presence of granodiorite with a normal granular texture. The mineralogical composition shows quartz in the rock. It is abundant with very low relief, colorless and xenomorphic with a gray to white tint of the first order and a characteristic rolling extinction.

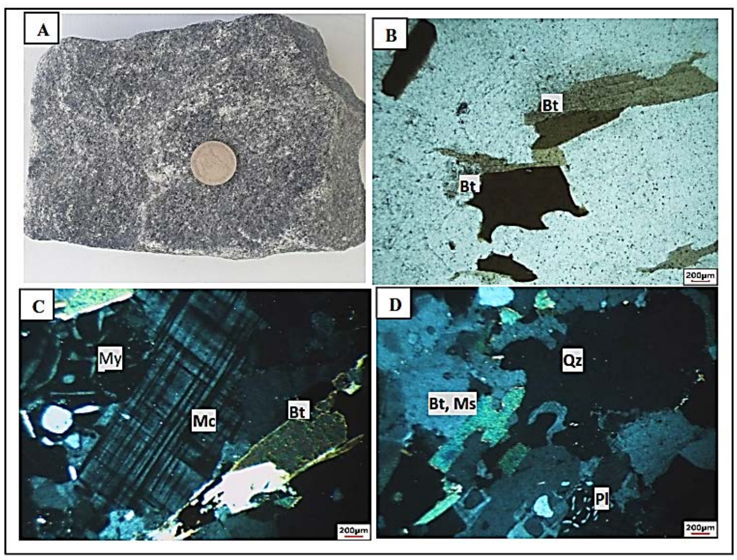

Figure 19. Macroscopic and microscopic photographs of UGM from the SAPE 2 quarry. Mc: Microcline; Pl: Plagioclase; Qz: Quartz; Bt: Biotite; Myr: Myrmekite (A): CSP02 sample; (B): Association of biotite and quartz in natural light; (C): Quartz, biotite and alteration of microcline into myrmekite; (D): combination of plagioclase, quartz and alteration of biotite into muscovite and of plagioclase into myrmekite.

Biotite, which is very abundant after quartz, is automorphic with a brown color and exhibits direct pleochroism, with a strong relief and a bright greenish-yellow hue. It is dispersed throughout the rock.

Plagioclase has a weak relief, is colorless and xenomorphic. It is present in medium-sized crystals and is slightly altered in some places to myrmekite, making it difficult to see its polysynthetic twinning.

Microcline, colorless, with low relief and small in size, is distinguished by clearly visible grid twinning and also shows alteration to myrmekite. It is frequently associated with plagioclases in the rock. Colorless muscovite, with low relief, occurs as flakes included in biotite, with a greenish-blue to purplish tint. It results from the alteration of biotite.

3.3. Summary of the Mineralogical Results of Unbound Granular Material (UGM)

The description of the mineralogy of UGMs enabled us to draw up table II below.

Mineralogical analysis of Unbound Granular Material (UGM) from the 15 quarries studied in Côte d'Ivoire (**Table 2**), representing 15 distinct types of material reveals an exclusive predominance of granitic formations. This observation is consistent with the regional geology of Côte d'Ivoire, dominated by the Birimian basement and associated granitic massifs [11] [12].

Table 2. Summary table of the mineralogy of the Unbound Granular Material (UGM).

Quarry	Rock type	Dominant primary minerals	Main alteration processes	Estimated alteration percentage (%)
ATSO	Granite	Quartz, plagioclase, biotite	Muscovitization (biotite)	10% - 40%
YAMS 1	Biotite-dominant granite	Quartz, biotite, feldspars	Muscovitization, epidotization, sericitization	>40%
YAMS 2	Alkaline granite	Quartz, microcline, plagioclase	Sericitization, muscovitization	10% - 40%
BOSO	Biotite-dominant granite	Quartz, plagioclase, microcline, biotite	Muscovitization, sericitization	10% - 40%
YAMP 1	Biotite-dominant granite	Plagioclase, biotite, quartz	Muscovitization, epidotization	>40%
YAMP 2	Alkaline granite	Microcline, biotite, plagioclase	Muscovitization, chloritization, sericitization	10% - 40%
ABIC	Granite	Quartz, plagioclase, microcline	Muscovitization, chloritization, perthitic exsolution	10% - 40%
ABSI	Granite	Plagioclase, quartz, microcline	Muscovitization, epidotization	10% - 40%
BOCA	Granite	Quartz, plagioclase, microcline	Sericitization, muscovitization, oxidation of biotite	10% - 40%
ATAB	Granite	Plagioclase, quartz, biotite	Sericitization, chloritization	10% - 40%
BOTI	Biotite-dominant granite	Quartz, microcline, biotite	Muscovitization, sericitization, myrmekitization	10% - 40%
ABOC	Granite	Quartz, plagioclase, biotite	Weak sericitization	<10%
GASI	Granite	Quartz, plagioclase, biotite, muscovite	Sericitization, muscovitization, chloritization	>40%
SAPE 1	Biotite-dominant granite	Quartz, biotite, plagioclase	Muscovitization	>40%
SAPE 2	Granodiorite	Quartz, plagioclase, biotite	Muscovitization, sericitization	>40%
KOSB	Alkaline granite	Quartz, microcline, plagioclase	Myrmekitization	<10%

* Rare < 10%; 10% < Present < 40%; Abundant > 40%.

Despite this petrographic homogeneity from a macroscopic point of view, there is a more or less marked diversity in both the primary mineral compositions and the degrees and types of alteration when analysed microscopically. Furthermore, textures vary from simple granular to porphyroid granular, reflecting variable crystallisation conditions [13].

3.4. Classification of Unbound Granular Material (UGM) and Potential Hardness of Minerals

The primary mineralogy of the studied unbound granular materials (UGM) is dominated by the classical quartz-feldspar-biotite assemblage. Quartz, with a Mohs hardness of approximately 7 and concentrations often exceeding 40%, and feldspars (plagioclase, microcline and orthoclase, hardness 6 - 6.5) constitute the mechanically resistant framework of the aggregates. In contrast, biotite (hardness 2.5 - 3) represents the weakest phase. In several samples such as YAMS 1 and YAMP 1, biotite content exceeds 40%, making it the primary site for early weathering, as widely reported in studies dealing with the durability of granitic aggregates and the susceptibility of mafic minerals to weathering [14] [15].

Beyond mineral hardness alone, the nature and abundance of alteration products play a key role in controlling the mechanical behaviour of UGM used in road construction. Based on the main minerals and textures identified, the studied materials can be classified according to their petrographic nature and mineralogical affinity, a classification that is essential for predicting material behaviour in engineering applications [16]. The extent of alteration quantified here as ranging from 10% to over 40% of the mineral surfaces leads to the formation of secondary phases like muscovite, chlorite, and sericite, which modify grain surface properties and increase moisture sensitivity.

The first group, Biotite-dominant granites, identified in the YAMS 1, BOSO, YAMP 1, BOTI, SETO and SAPE 1 quarries, are typical of the West African Shield [17] [18]. They are characterized by significant biotite content (up to >40%) and extensive muscovitization (exceeding 40% in SAPE 1 and YAMS 1). These secondary phyllosilicates are platy minerals with low shear strength that increase plasticity and reduce intergranular friction, leading to reduced California Bearing Ratio (CBR) values and higher Los Angeles abrasion coefficients.

The group of alkaline granites from the YAMP 2, YAMS 2 and KOSB quarries, distinguished by a predominance of microcline (>40%). In YAMP 2, for instance, we observe high levels of muscovitization (>40%) and sericitization (10% - 40%). Although the alkaline framework is intrinsically resistant, sericitization develops along cleavage planes, facilitating water ingress and leading to progressive mechanical weakening. These materials may show a decrease in bearing capacity under wet conditions, despite their favorable primary mineralogy.

The Granodioritic facies represented by the SAPE 2 quarry exhibits a higher proportion of plagioclase relative to microcline, which is the main criterion distinguishing granodiorite from granite [19]. The intense alteration of plagioclase into sericite (10% - 40%) combined with high muscovitization (>40%) increases fines production and reduces grain cohesion, making these UGM particularly sensitive to moisture.

Finally, the Simple granites group includes the ATSO, ABIC, ABSI, BOCA, ATAB, ABOC, GASI and ATAM quarries. While their primary composition is less complex, several show significant secondary phases, notably sericitization and chloritization (ranging from 10% to 40%). In the GASI quarry, for example, both sericitization and muscovitization exceed 40%. The combined presence of sericite and chlorite remains the most critical factor, as these minerals significantly increase plasticity and water sensitivity, compromising the long-term durability of the road base layers.

4. Conclusions

This research on Unbound Granular Material (UGM) of type 0/31.5 used as base layers in roadways in Côte d'Ivoire has highlighted the predominance of granitic formations, which is consistent with the Birimian basement that dominates the country's geology. Macroscopic and microscopic observations of the samples confirmed that the mineralogy of UGM consists mainly of quartz, feldspars and biotite, with the presence of secondary minerals resulting from various weathering processes.

Quartz, due to its high hardness, gives the aggregates good mechanical strength, but the progressive weathering of feldspars and the fragility of biotite – often transformed into muscovite, chlorite or epidote are weaknesses that can reduce the durability of the materials in tropical climatic conditions. These results highlight that mineralogical studies provide essential additional insight to conventional geotechnical tests, enabling the actual behaviour of UGM in road structures to be anticipated.

In this perspective, it seems essential to systematically integrate mineralogical characterisation into quality control protocols for road materials. Such an approach, combining mineralogical and geotechnical methods, would facilitate better selection of quarries based on the expected performance of aggregates and would enhance the durability of infrastructure.

Conflicts of Interest

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

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