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Integrated Geotechnical-Mineralogical Characterization of Crystalline Basement Soils: Implications for Pavement Design and Performance in Tropical Terrains

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Abstract
In tropical regions, soils derived from crystalline basement rocks are widely used in road construction; however, their engineering performance is often inadequately characterized due to limited spatial sampling and insufficient integration of geological controls. This study evaluates the geotechnical and mineralogical characteristics of crystalline-derived soils to assess their suitability for pavement applications. Fifty samples collected across multiple lithological units were analyzed for index properties, compaction parameters, California Bearing Ratio (CBR), and mineral composition using X-ray diffraction (XRD). The soils are predominantly fine-grained, with fine content ranged up to 59.6% and generally poor gradation. Atterberg limits indicate low to moderately high plasticity (liquid limit: 14.3–53%; plasticity index: 1.0 - 24.0%), while soil activity ranges from 0.3 to 2.85, schist-derived soils exhibiting the highest variability (mean 1.85) across the lithologies. Compaction results show mean maximum dry density and optimum moisture content of 1.80 Mg/m^3 and 16.9%, respectively. Unsoaked CBR values (40–54%) indicate moderate strength, but a marked reduction under soaked conditions (18–25%) reflects significant moisture susceptibility. XRD analysis reveals that the dominant clay minerals, expressed as mean values are kaolinite (31.5%), pyrophyllite (18.7%), chlorite (18.4%, and illite (15.7%). This finding offers a mechanistic explanation for the observed swelling behavior and the pronounced reduction in strength under saturated conditions which highlights the need for careful material selection and appropriate stabilization measures in pavement design. The study demonstrate that variations in parent lithology and clay mineral assemblages exert a strong control on the engineering performance of the soils, thus emphasizing the importance of integrating mineralogical data with conventional geotechnical testing to improve the reliability of subgrade evaluation in crystalline basement terrains.

Keywords: *X-ray Diffraction, index properties, strength properties, mineralogy, basement complex*

Introduction

All structures and infrastructures are built on or with soil, a geological material whose strength is determined by the structure of grains and arrangement of minerals present in them. The knowledge of these minerals present in a particular soil formation is therefore important to the safety and success of the infrastructure built on/from them. Failure of road pavement is very common in Nigeria and several studies have been conducted to determine the root cause of this menace. Several scholars (Fakeye *et al.*, 2025; Adeyemi *et al.*, 2003; Ogundalu and Oyekan 2014; and Oyediran and Fadamoro, 2015) have identified both geotechnical and mineralogical factors as the key factors inducing road failures in addition to excessive haulage loads, poor construction, poor and inadequate drainage systems. Fakeye *et al.* (2025) reported on the complex mineral assemblage of varying proportions of both clay and non-clay minerals with prevalence in kaolinite and quartz with 10 - 30% of the expansive clay minerals along the same highway section. Adeyemi *et al.* (2003) reported the presence of abundance kaolinitic mineral with quartz, illite, chlorite and vermiculite along Ibadan – Agowoye highway and equally established high correlation between kaolinite and uniaxial compressive strength of the soil. Similarly, Ogundalu and Oyekan (2014) observed the presence of high swelling montmorillonite among other minerals in the black cotton soils along the Maiduguri – Gamboru highway, which negatively influenced the stability of the highway. The aforementioned researchers identified the importance of mineralogy in the mechanism of swelling and shrinkage behaviour of soils and its effect on the soil strength. Roy and Ballah (2017) provided detailed relationships between soils geotechnical properties and performance of civil engineering structures and reported that water content, specific gravity, and gradation have direct effects on the performance of soils as pavement materials. Waziri *et al.* (2013) equally evaluated the geotechnical and mineralogical characteristics of soils derived from Schists along Shango-Chanchaga highway, Minna, Central Nigeria. Their results showed the presence of sands accounting for the high porosity values, while the clay content

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accounted for the cohesiveness and plasticity of the soil. The mineral composition of the rocks was also found to be responsible for the types of soils in the area with variations in geotechnical characteristics such as cohesiveness, porosity and plasticity. They recommended that high moisture soils having low California Bearing Ratio (CBR) values were unsuitable for road construction and should be excavated out and replaced with more suitable soils. This is in addition to providing good drainage systems along the road.

Furthermore, Akande *et al.* (2019) evaluated the geotechnical investigation of soils and underlying basement rocks for the construction of Southern Parkway bridge at Federal Capital Territory (FCT), Abuja, North-central Nigeria. Their results of geotechnical survey indicated that the underlying basement was migmatite-gneiss; capped by silty lateritic regolith. Index properties of the regolith showed its incompetence and unsuitability for the proposed construction. On the other hand, the underlying fresh bedrock had medium to high strength capacity to carry the load of the proposed bridge. The study therefore concluded that the residual top soils in the study area were unsuitable for the proposed construction in contrast with the desired capacity experienced by the basement rock. To ascertain the mineralogical behavior of the soils along Ilorin-Lokoja road, Ige *et al.* (2019) carried out geophysical survey using vertical electrical sounding (VES) on critically failed portions of the road. Their result also showed low resistivity values near the surface, suggesting the presence of clay and elevated moisture resulting in over-saturation of the top soil thus, leading to failure of that portion of the road. This was buttressed by the absence of high level swelling clays, dominance of true laterite with high concentration of iron peroxide (Fe_2O_3) as cementing agent. The samples however, possessed low linear shrinkage, which suggest little potential to shrink or swell when exposed to alternating weather condition. Overall, geotechnical evaluations revealed that the samples could only function effectively as subgrade material in pavement construction. In many cases, subgrade materials used for pavement construction rarely meet the highway specifications. With the overview of several scholars mentioned above and the attendant devastating deterioration of Ilorin – Kabba highway, which spans across two States, occasioned by severe loss of lives from vehicular accident, robbery, undue delays and other economic wastages, it is therefore important to investigate the geotechnical properties and mineralogical composition of subgrade materials derived from basement rocks beneath the highway extensively. This is with a view to determine the subgrade soil quality on the flexible pavement performance.

Location and Geology

The Ilorin – Kabba highway is located in Southwestern Nigeria (Figure 1), between latitudes 6°15'N and 8°30'N and longitudes 4°30'E and 6°50'E. This is one important road that links the mid-west to the capital city, Federal Capital Territory which was constructed several decades ago. Due to poor maintenance culture, a widespread of the highway has failed severely. The topography is made of undulating terrain with a mean elevation of 400m above sea level. Underlying the highway is the Precambrian rocks of the Basement Complex composed of the migmatite – gneiss (PCB), meta-sediments (PCM) and older granite rocks (PCG) (Oyinloye, 2011). Two main widespread types of gneisses common in the area are the fine-grained biotite gneiss with strong foliation and the banded gneiss (Adekeye & Akande, 2006). The older granites that varied extensively in composition occur as large circular masses within the schists and the older migmatite-gneiss complex. The lithologic compositions of the three main rock types are listed in Table 1. These rocks were disintegrated into soils with variable thickness, geochemical, mineralogical and geotechnical characteristics (Buol *et al.*, 2003).

Method of Study

Fifty disturbed soil samples were collected along Ilorin – Kabba highway at the depth of 0.8 - 1.5m (as shown in Fig. 1) at both stable & unstable road portions while taking coordinates and elevation using global positioning system (GPS). Laboratory soil tests were conducted on air-dried (35°C) samples of 0.425mm diameter following the British Standard procedure indicated in 1377 of 1990 for soil testing (BS 1377: 1990) and summarized in Table 2. These tests include index test (particle size distribution and consistency limits), compaction at West African level, soaked and unsoaked California Bearing Ratio. Finer fraction of the same soil samples (10g) were subjected to X-ray diffraction test using Bruker D8 Advance X-ray diffractometer with monochromatic Cu- Kα_1 radiation (λ = 1.54Å) in the range of 10° and 90°, at the Department of Chemical Sciences Laboratory, University of Johannesburg, Doornfontein Campus, South Africa. XRD is a rapid analytical technique used extensively for phase identification of crystalline material based on constructive inference of X-ray and crystalline sample. The diffractograms with the corresponding intensity and 2θ were analyzed in Origin

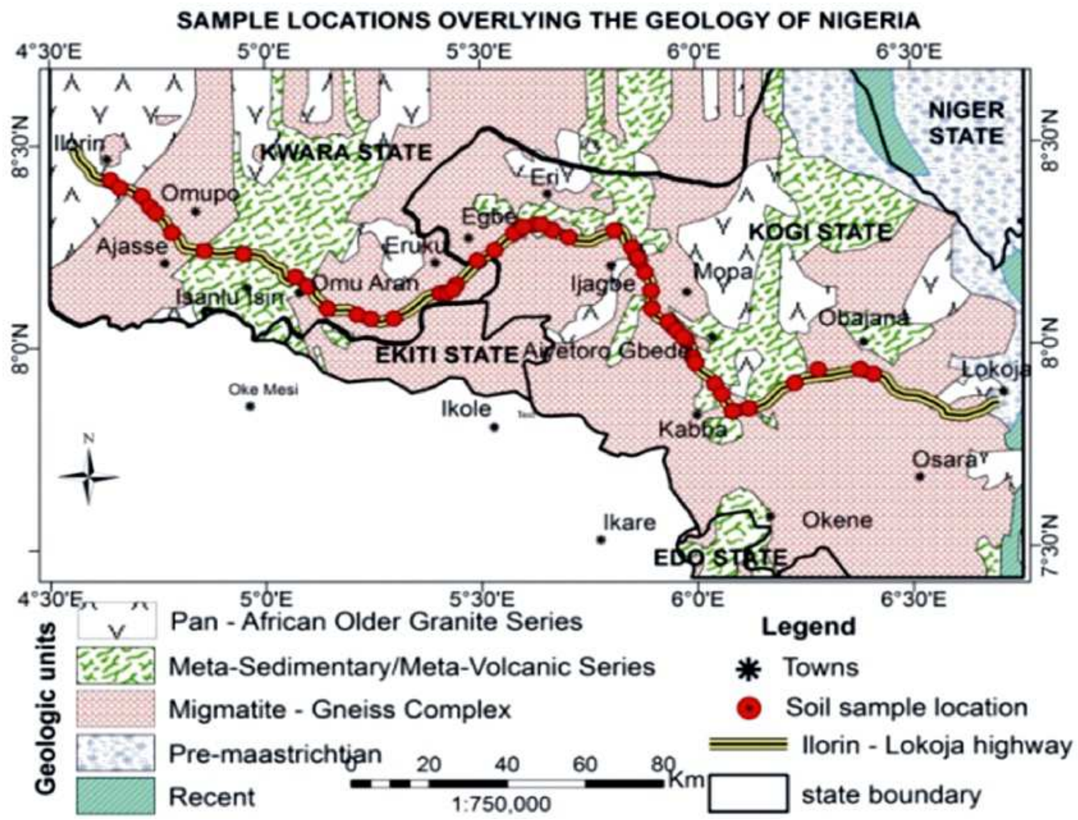

Fig. 1: Geology of Nigeria showing the highway overlain by soil sample locations.

Table 1: Composition of lithologic units found in the Study Area

Geology	Rock Types	Lithology	Codes
Precambrian Crystalline Basement Complex	Migmatite – Gneiss complex (PCB)	Migmatite	MDs
		Banded gneiss / Biotite gneiss	BgDs
	Metasediment / Metavolcanic series (PCM)	Quartzite, quartz schists including flaggy quartzites	QDs
		Undifferentiated Schists, including phyllites, fine grained flaggy quartzites	SDs
	Pan African Older Granite rocks (PCG)	Biotite granite	BDs
		Porphyroblastic granite with gneiss	PgDs

8 & Match 3.1 software packages for pattern fitting and later compared with established Mineral Power Diffraction File Data Book (ICDD-PDF, 2001) to confirm the phase information of different mineral structures. Other information obtained were crystalline size, % crystallinity, phase quantification and lattice parameter determination, which is not included in this paper.

Results and Discussions

Geotechnical Characteristics

Grain Size Distribution

Table 2: Laboratory tests and standards

SN	Test	Method/Standard
1	Particle size analysis	BS 1377: 1990 Part 2 Clause 9.2
2	Liquid limit (LL)	BS 1377: 1990 Part 2 Clause 4.5
3	Plastic limit (PL)	BS 1377: 1990 Part 2 Clause 5.3
4	Plasticity index (PI)	BS 1377: 1990 Part 2 Clause 5.4
5	Natural Moisture Content (NMC)	BS 1377: 1990 Part 2 Clause 3
6	Optimum Moisture Content	BS 1377: 1990 Part 4 Clause 3.3
7	Maximum Dry Density (MDD)	BS 1377: 1990 Part 2 Clause 8
8	California Bearing Ratio (CBR)	BS 1377: 1990 Part 9
9	X-ray Diffraction analysis	Bragg's law
Derived measurements		
10	Activity (Ac)	Skempton 1953

The grain size distribution across the lithologic units shows that the soils are predominantly sandy with appreciable fines (Table 3). Gravel content ranges from 0 - 27.4% in migmatite (MDs) to 22 - 35.0% in porphyritic granite (PgDs), while sand fractions vary between 31.4 - 75.5%. Silt and clay content obtained through hydrometer analysis show wider variability, particularly in quartzite (QDs) (silt: 4.6 - 31.5%, clay: 10.8 - 30.2%) and migmatite (silt: 7.9 - 33.7%, clay: 11.2 - 34.6%). Granite-derived soils (biotite (BDs) and porphyritic (PgDs)) exhibit relatively narrow grading ranges and consistently higher gravel fractions, indicating a well-developed coarse-grained framework. In contrast, quartzite and migmatite show broader fines variability, suggesting heterogeneous weathering and redistribution processes. Recent studies emphasize that grain size variability, rather than mean values, is a critical determinant of soil behaviour, particularly in residual tropical soils where weathering profiles are highly irregular (Akinwumi *et al.*, 2021; Zhang *et al.*, 2022). Similarly, Abija *et al.* (2019) demonstrated that increased silt variability significantly affects permeability and subgrade response, even when clay content remains relatively constant.

Despite lithologic differences, the relatively consistent clay fraction suggests a uniform weathering regime across the study area, likely dominated by kaolinitic clay formation under tropical conditions. However, silt content exhibits significant variability, with quartzite-derived soils recording the highest mean value (20.3%), followed by migmatite (16.4%) and undifferentiated schists (13.5%). This variation reflects the influence of parent rock mineralogy and weathering intensity.

Table 3: Selected properties of the representative soil samples within the three geologic environment - Migmatite-gneiss complex (PCB), Metasediment/volcanic (PCM), and Older granite complex (PCG).

Index Properties	Unit (%)	PCB		PCM		PCG	
		Migmatite (MDs)	*Banded Gneiss (BgDs)*	*Quartzite (QDs)*	*Undiff. Schists (SDs)*	*Biotite (BDs)*	*Porphyritic (PgDs)*
Particle size distribution	Gravel (>4.75mm)	0 – 27.4 (7.07)	0 – 28.2 (10.5)	0 – 29.4 (8.88)	0 – 25.1 (9.3)	20.0 – 37.6 (18.6)	22 – 35.0 (27.3)
	Sand (2mm)	31.4 – 75.5 (57.9)	46.6 – 73.5 (61.4)	41.7 – 64 (52.5)	45.5 – 77.1 (60.2)	33.1 – 58.6 (50.1)	38.9 – 53.2 (44.3)
	Silt (0.002mm)	7.9 – 33.7 (16.4)	4.12 – 25.0 (11.0)	4.6 – 31.5 (20.3)	6.81 – 22.5 (13.5)	4.78 – 14.9 (8.82)	9.22 – 12.8 (10.7)
	Clay (0.001mm)	11.2 – 34.6 (18.6)	9.92 – 28.4 (16.9)	10.8 – 30.2 (18.3)	7.87 – 30.2 (17.4)	8.61 – 13.5 (10.2)	10.1 – 15.6 (12.5)
Atterberg Limits	LL	14.3 – 53 (29.6)	17.5 – 32.5 (25.1)	24.2 – 46.5 (35.4)	19.5 – 44 (33.6)	16.5 – 27.4 (22.7)	18.5 – 32 (23.2)
	PL	8.4 50 (20.3)	12.2 23.2 (18.4)	10.4 25 (20.9)	13.8 31.7 (23.7)	8.6 – 21 (16.7)	13.2 19 (15.5)
	PI	1.9 – 24 (9.29)	1.6 – 14 (6.68)	1.0 – 22.6 (14.5)	2.1 – 21.0 (9.88)	2.6 – 10.0 (6.0)	4.6 – 13.4 (7.77)
	NMC	2.6 – 22.7 (12.0)	3.0 – 14.8 (7.76)	7.3 – 16.2 (11.8)	3.1 – 18.4 (9.75)	3.2 – 10.6 (7.18)	2.4 – 12.2 (7.15)
	Activity	0.1 – 8.5 (1.31)	0.4 – 4.3 (1.44)	0.4 – 1.4 (0.88)	0.2 – 7.8 (1.85)	0.3 – 1.9 (0.77)	0.4 – 1.9 (0.78)
Soil Classifications	USCS	SM	SC, SM	SM	SC, SM	GC-GM, SM	GC-GM, SC-SM
	AASHTO	A-2-4, A-7-6	A-2-4	A-2-6, A-7-6	A-2-4, A-7-6	A-2-4	A-2-4, A-2-6

Migmatite-gneiss and quartzite-derived soils (MDs, BgDs & QDs), despite originating from resistant quartz-rich rocks, show elevated silt content, suggesting mechanical breakdown and possible mixing with finer materials. In contrast, granite-derived soils (BDs & PgDs) retain higher gravel fractions, indicative of incomplete weathering and preservation of coarse mineral grains.

All soils fall within clayey sand (SC), silty sand (SM), silty, clayey sands (SC-SM) mixtures and silty, clayey gravel (GC-GM) groups under Unified Soil Classification System (USCS) (ASTM, 2017), which occur in the migmatite-gneiss rock terrains and their weathering products (Table 3) (Abija *et al.*, 2024) and are classified as A-2-4 to A-7-6 under American Association of State Highway and Transportation Officials (AASHTO) classifications (AASHTO, 2017). The occurrence of A-7-6 classifications in migmatite, quartzite, and schist-derived soils indicates the presence of problematic subgrade materials with high fines influence. However, Adewumi *et al.* (2025) cautions that soil classification systems alone are insufficient to predict engineering performance without considering fines variability and mineralogical factors.

Atterberg limits and other swelling potential characteristics

The Atterberg limits reveal low to moderate plasticity across the lithologies and plotted in Figure 2. Liquid limit (LL) ranges from 14.3 - 53.0%, plastic limit (8.4 - 50%), while plasticity index varies from 1.0 - 24%) (Table 3). Quartzite and migmatite-derived soils exhibit the widest PI range (1.0 - 24%) and relatively high LL values (24.2 - 46.5%; 14.3 - 53%), indicating significant variability in fines interaction. Schist-derived soils also show broad PI variation (2.1 - 21.0%), reflecting mineralogical heterogeneity, particularly the influence of mica. Granite-derived soils display narrower PI ranges (2.6 - 10.0% for biotite; 4.6 - 13.4% for porphyritic granite), suggesting more stable and predictable behaviour. Recent research highlights that Atterberg limits are controlled not only by clay content but also by particle interaction, soil fabric, and fines composition, particularly in mixed sand-silt-clay system (Soltani *et al.*, 2022). In addition, Musbah *et al.* (2024) reported that silt-rich soils can exhibit elevated plasticity due to capillary effects, even when clay mineral activity is low, which is consistent with the behaviour observed in quartzite-derived soils.

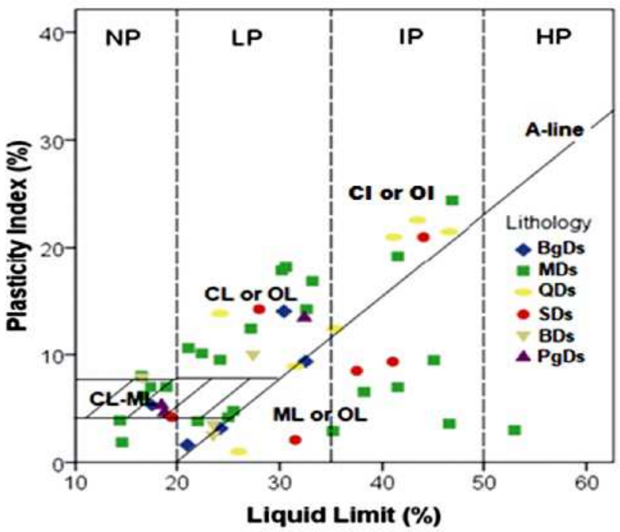

Fig. 2: Plasticity of all the soil samples based on the lithologies (Casagrande, 1948).

Soil activity values range from 0.3 - 2.85, with schist-derived soils exhibiting the highest variability (mean 1.85) across the lithologies. Gneiss and migmatite also show moderate to high activity, while granite-derived soils are predominantly inactive (activity<1). This result indicate Schists contain more active clay minerals, contributing to higher deformation potential, while the lowest value (0.77) occurs in granite-derived soils, showing an indication of stability and presence of non-active clay.Recent studies confirm that soil activity is a key parameter for predicting volume change and long-term deformation, particularly in residual soils influenced by mineralogical composition (Olatunde *et al.*, 2025; Abija *et al.*, 2024). Natural moisture content (NMC) varies from 2.4% - 22.7% with higher higher values observed in migmatite (up to 22.7) and quartzite (7.3 - 16.2%). Granite-derived soils exhibit lower NMC ranges (2.4 - 12.2%). Higher NMC values correlate with increased fines content and reduced permeability, indicating greater moisture retention capacity. This is consistent with findings by Rahman *et al.* (2025), who showed that moisture susceptibility in subgrade soils is strongly influenced by fines distribution and pore structure.

Compaction Characteristics

The optimum moisture content (OMC) and maximum dry density (MDD) vary from 8.12 – 25.0% and 0.89 – 2.6 Mg/m^3 at varying lithologies (Table 4). Migmatite and quartzite exhibit high OMC values (above 20%), reflecting their greater fines content and moisture affinity, while granite-derived soils display relatively lower and narrower OMC ranges, consistent with their coarse-dominated structure and reduced water adsorption capacity. The wide range of MDD values in migmatite reflects its heterogeneous composition, consistent with the particle size distribution.

In contrast, granite-derived soils (BDs and PgDs) exhibit high and more consistent MDD values (1.6 - 1.9 Mg/m^3), indicating improved packing efficiency and particle interlocking due to presence of gravel fractions. Quartzite-derived soils show comparatively lower MDD ranges, which can be attributed to higher fines (particularly silt) interfering with particle packing. This observation aligns with recent findings that coarse-grained soils with lower fines achieve higher dry densities due to improved compaction efficiency (Zhang *et al.*, 2022; Soltani *et al.*, 2022). Abija *et al.* (2024) highlighted that MDD is one of the most influential parameters controlling subgrade strength and CBR performance, as it directly reflects soil densification and load-bearing capacity.

California Bearing Ratio (CBR)

The soaked CBR values show clear lithologic control with lowest CBR occurring in quartzite (11.2 - 13.3%), corresponding to high silt variability, high OMC, moderate to high PI, and influence of illite and smectite

Table 4: Summary of the moisture–density relationship and CBR values

	PCB		PCM		PCG	
	Migmatite (MDs)	*Banded gneiss (BgDs)*	*Quartzite (QDs)*	*Undifferentiated Schist (SDs)*	*Biotite (BDs)*	*Porphyritic (PgDs)*
MDD (Mg/m^3)	0.89 - 2.61 (1.7)	1.5 - 1.94 (1.8)	1.4 - 1.81 (1.6)	1.5 - 1.82 (1.7)	1.58 - 1.86 (1.7)	1.69 - 1.91 (1.8)
OMC (%)	9.9 - 25.0 (14.8)	8.12 - 17.0 (11.7)	10.8 - 21.1 (16.9)	10.1 - 17.5 (14.2)	8.9 - 17.0 (13.6)	11.2 - 15.2 (13.6)
Unsoaked CBR	18.8 - 48.0 (32.0)	29.4 - 42.2 (31.2)	20.2 - 30.2 (20.5)	28.3 - 34.8 (26.6)	30.4 - 58.0 (48.5)	54.2 - 55.8 (54.8)
Soaked CBR	12.4 - 23.4 (15.0)	16.0 - 22.0 (15.1)	11.2 - 13.3 (12.6)	17.8 - 18.2 (12.3)	12.1 - 28.6 (23.2)	20.4 - 27.8 (24.5)

clay minerals, indicating poor load-bearing capacity and high moisture susceptibility. Schist-derived soils exhibit moderate CBR (17.8 - 18.2%), despite its high activity, reflecting relative stability due to moderate compaction response. Migmatite-derived soils show wide CBR range (12.4 - 23.4%), which reflects heterogeneous particle distribution and compaction variability. Granite-derived soils show highest CBR values (up to 28.6%), which may be controlled by high gravel content, high MDD and lower OMC. It is also observed that the soaking of the soils resulted in over 50% CBR reduction, implying that given the geological environment, the strength of the residual soils varies in relation to volume change due to moisture influx which may cause pitting. This result corresponds with the report of Ige *et al.* (2018), Adebisi & Osammor (2017) and Adeyemi *et al.* (2014).

Mineralogical Characteristics

The mineralogical composition is summarized in Table 5 based on the geology of the study area. Five clay minerals and eight non-clay minerals are identified with prevalence of kaolinite and quartz. The migmatite-gneiss-derived soils are dominated by clay minerals, with mean values indicating a polymineralic clay system: kaolinite (22.9), pyrophyllite (18.7%), chlorite (18.4%), and illite (14.3%). This composition suggests an overall moderate to high plasticity soil matrix, as mixed clay assemblages typically increase the plasticity index and compressibility. However, the ranges are extremely wide: kaolinite (0.9 - 67.3%), smectite (0.1 - 23.2%), and quartz (3.4 - 87.3%). These ranges indicate that although kaolinite dominates on average, localized enrichment of smectite (up to 23.2%) becomes the controlling factor for swelling and deformation. Smectite is well known to significantly increase plasticity, swelling potential, and compressibility, even at moderate proportions (Klopp *et al.*, 2020). In contrast, kaolinite contributes to relatively lower swelling but still supports plastic behaviour. The large variation in quartz implies that soil structure alternates between clay-dominated, compressible zones (low quartz) and granular, high-strength zones (high quartz).

The PCM soils are characterized by kaolinite dominance (mean = 31.5%, supported by moderate illite (15.7%) and low chlorite (10.8%). This suggests a generally stable clay system with moderate plasticity, as kaolinite-rich soils typically exhibit lower shrink-swell potential compared to smectite soils. However, the consistent presence of smectite (minimum 4.4%) and its peak at 22.0% indicates that swelling cannot be neglected. Even moderate smectite contents significantly influence plasticity index, swelling pressure, and compressibility, as mineralogical composition strongly governs consistency limits and volume change behaviour. In contrast, quartz and feldspar contribute to mechanical stability and reduced compressibility.

The PCG soils exhibit a framework-dominated mineralogy, with high mean quartz (47.5%) and plagioclase (25.5%), and comparatively lower clay mineral contents (kaolinite: 17.4%, pyrophyllite: 17.2%, chlorite: 17.3%). The ranges are notably narrower compared to PCB with quartz (13.6 - 82.0%), smectite (0.2 - 14.8%), plagioclase (23.7 - 27.2%). The limited smectite content (max 14.8%) suggests reduced swelling potential, while the high quartz fraction ensures low compressibility and high shear strength. Quartz-rich soils exhibit improved load-bearing capacity and reduced plastic deformation due to their granular nature (Karakan & Demir, 2018). Representative X-ray diffraction (XRD) patterns of selected soil samples (Figure3) reveal a variable clay mineral assemblage characterized by varying proportions of illite, pyrophyllite, chlorite, and smectite. These constituents range in concentration from major (>30%) and moderate (10–30%) to minor (2–10%) and trace (<2%) levels. Notably, smectite is present in about 20% of the samples, particularly in the Yagba, Ijagbe, and Mopa areas underlain by metasedimentary rocks (undifferentiated schists and quartzites). The clay index (CI = CM / [Q + F]) ranges from 0.05 to 17.4 (mean = 2.55), with the highest value recorded in the metasedimentary (PCM) unit.

Mineralogical distribution shows strong lithological control: banded gneiss–derived soils are enriched in kaolinite, pyrophyllite, and quartz, while illite is notably absent in porphyritic granite soils, where pyrophyllite, chlorite, and smectite occur only in trace amounts but increase to moderate levels in migmatite–gneiss terrains (Figure 4). Soils containing appreciable smectite (1–25%) and illite (1–40%) exhibit lower strength and higher swelling potential compared to kaolinite-dominated soils with mixed clay assemblages (Kariuki *et al.*, 2004; Yitagesu *et al.*, 2011).

Overall, this mineralogical framework explains the relatively high plasticity and optimum moisture content observed in the metasedimentary soils (Oyediran and Fadamoro, 2015), as well as their increased shrink–swell potential, compressibility, and reduced permeability and shear strength (Abija *et al.*, 2019; 2024). The mineral proportions in the migmatite–gneiss environment are consistent with previous studies (Ige, 2015; Adebisi & Osammor, 2017), although earlier reports did not identify smectite, likely due to limited sampling coverage.

Table 5: Semi-quantitative result of mineral contents (per percent of the crystalline phases)

Geologic environment	Statistical Parameters	CLAY MINERALS (%)					NON-CLAY MINERALS (%)							
		Kaolinite $(Al_2(Si_2O_5)(OH)_4$	**Pyrophyllite** $Al_2Si_4O_{10}(OH)_2$	**Chlorite** $Al_2(Mg,Fe)_5SiO_{11}(OH)_2$	**Illite** $K_{1.5}Al_4(Si_{6.5},Al_{1.5})O_{20}(OH)_4$	**Smectite** $(Na,Ca)([Mg,Fe]Al_3)[Si_8O_{20}](OH)_4$	**Quartz** SiO_2	**Plagioclase** $(Ca,Na)Al_{1.2}Si_{3.2}O_8$	**K-Feldspar** $KAlSi_3O_8$	**Berlinite** $AlPO_4$	**Alunite** $Al_3H_6K_{0.8}Na_{0.5}O_{14}S_2$	**Goethite** $FeOOH$	**Calcite** $CCa_{0.9}Mg_{0.1}O_3$	**Zeolite** $Mg_2Na_7(Si,Al)_{12}O_{48}$
MIGMATITE-GNEISS COMPLEX (PCB) {CI = 2.51}	Min	0.9	0.1	1.0	0.8	0.1	3.4	0.7	0.9	1.5	0.2	3.1	0.8	11.9
	Max	67.3	51.0	55.3	40.3	23.2	87.3	78.7	21.6	59.3	12.3	9.1	17.2	18.9
	Mean	22.9	18.7	18.4	14.3	8.7	28.9	20.9	7.4	21.8	4.7	6.1	9.0	15.4
	SD	14.1	15.4	20.2	12.7	7.8	23.4	20.4	8.4	18.4	5.0	3.0	11.6	4.9
META-SEDIMENT / VOLCANIC (PCM) {CI = 3.48}	Min	4.3	5.7	1.4	2.8	4.4	3.6	2.5	0.8	1.3	4.4	1.3	4.0	6.1
	Max	50.5	17.9	22.1	28.8	22.0	58.3	32.2	63.5	34.6	16.4	10.9	7.9	17.5
	Mean	31.5	11.8	10.8	15.7	9.7	26.2	10.7	20	14.2	9.7	6.7	6.4	11.8
	SD	13.4	8.6	10.5	10.7	7.0	16.8	14.3	25.7	11.1	6.1	4.3	2.1	8.1
OLDER GRANITE (PCG) {CI = 1.0}	Min	5.9	5.4	10.6	0.2	0.2	13.6	23.7	1.9	2.1	13.6	1.1	8.1	-
	Max	29.3	28.9	26.1	17.8	14.8	82	27.2	1.9	13	13.6	18.7	20.7	-
	Mean	17.4	17.2	17.3	9.0	7.2	47.5	25.5	1.9	8.5	13.6	9.9	14.4	-
	SD	10.1	16.6	8.0	12.4	7.9	23.6	2.5	-	4.8	-	12.4	8.9	-

Conclusion

The presence of active clay minerals and weak subgrade soils characterized by high fines are evident along the Ilorin - Kabba highway with inadequate drainage system and poor maintenance.The soils are predominantly inorganic silty to clayey sands of low to moderately high plasticity, and associated swelling potential.The compaction results indicate fair to good suitable construction materials. However, the strength is insufficient for heavy traffic loading under soaked condition, spotlighting a vulnerable state during rainy season.The mineralogical analysis shows a complex mineral assemblage, consisting of kaolinite, quartz,

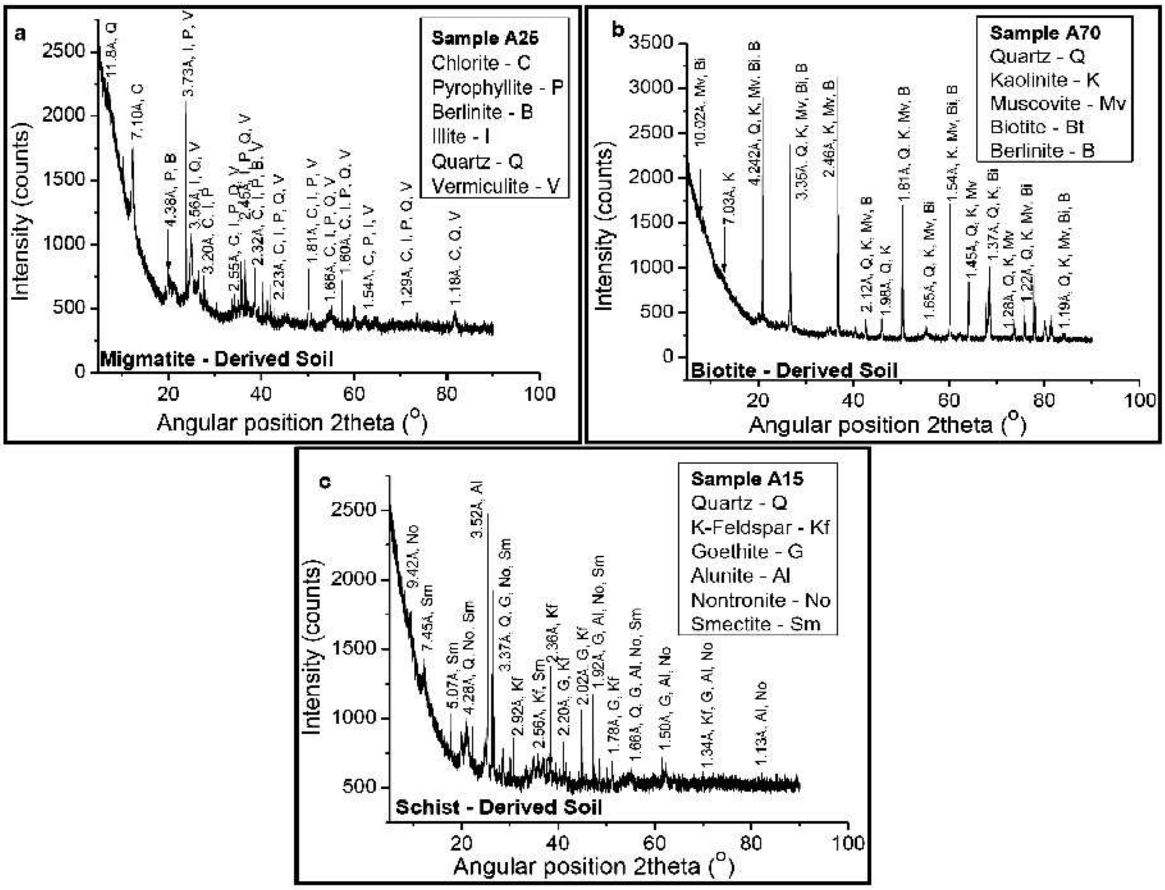

Fig. 3: Representative x-ray diffractograms patterns of three lithology-based soil samples showing abundant mineral compositions.

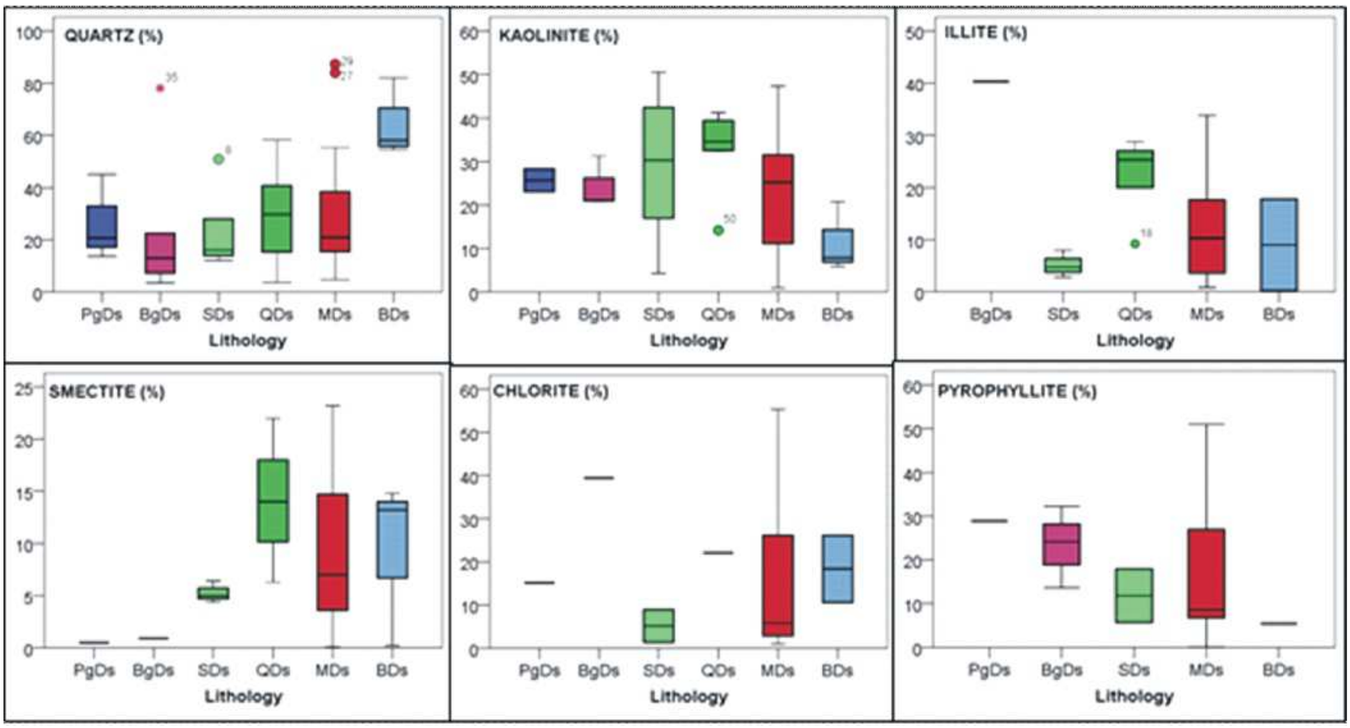

Fig. 4: Boxplots of major minerals showing variation in occurrence based on lithology.Porphyritic (blue), banded gneiss (purple), undifferentiated Schists (light green), quartzite (green), migmatite (red), and biotite (light blue).

chlorite, and preponderance of 2:1 expansive clay (e.g. smectite, nontronites, vermiculites) which impacted on the geotechnical parameters, resulting in subgrade instability and pavement failure.

It is recommended that composite pavement structure be considered as noted by Fakeye *et al.* (2024), with provision of adequate drainage system and stabilization of clayey soils to improve the strength and siffness of the road structure.

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