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Influence of Mineralogical and Chemical Composition on the geotechnical index properties and compaction characteristics of Borrow Pit Soils and Onitsha River Sand, Anambra State, Nigeria.

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Abstract
The engineering behavior of soils used for construction in Awka Municipal, Anambra State, Nigeria, is strongly influenced by their mineralogical and chemical composition. This study investigates how these factors affect the basic properties of three commonly used soils: Onitsha River sand (ON100) and borrow-pit soils from Amansea (AM100) and Ebenebe (EB100). Laboratory testing included particle size distribution, Atterberg limits, specific gravity, linear shrinkage, natural moisture content, compaction (OMC and MDD), X-ray diffraction (XRD) for mineral identification, and X-ray fluorescence (XRF) for oxide composition. Quartz was the main mineral in all samples (86–96%), with smaller amounts of kaolinite (3–7%), illite/muscovite (<1–4%), and feldspars (3–5%), while the main oxides were SiO_2 (80–84%), Al_2O_3 (5–6.5%), Fe_2O_3 (1.4–6.4%), and TiO_2 (1.1–2.5%). Clear patterns showed that quartz and kaolinite had opposite effects on optimum moisture content, illite improved maximum dry density through better packing, feldspars lowered it by producing extra fines during weathering, SiO_2 strongly increased MDD, TiO_2 sharply reduced OMC, and Al_2O_3 and Fe_2O_3 reduced MDD due to cementing and aggregation. The borrow-pit soil contained moderate silt-rich fines but remained almost non-plastic, while the river sand was nearly pure quartz, uniform, and non-plastic. These results show that mineralogical and chemical composition primarily controls the index properties of soils and can be used to predict their engineering behavior

Keywords: soil composition, mineralogy, chemical oxides, compaction, index properties

1. Introduction

Soils are an important material in civil engineering. They are used as the foundation for buildings, roads, embankments, and dams, and form the base for pavements, earthworks, and plastering (Roy and Kumar Bhalla, 2017). The way soils behave, how they compact, hold water, or support structures affects the safety, stability, and durability of these projects. Inadequate knowledge of soil properties can lead to structural failures, excessive settlement, or poor workability in construction materials such as concrete and plaster (Ogbuagu & Okeke, 2019). Understanding soil properties is therefore important for successful construction (Ogbuchukwu et al., 2019; Roy & Kumar Bhalla, 2017). Index properties, including particle size distribution, Atterberg limits, and specific gravity, provide important information about the physical characteristics and classification of soils. These properties are widely used to predict soil behavior and check the suitability for construction uses. For instance, the plasticity of clay soils influences their shrink-swell potential, while particle size distribution affects compaction and permeability (Seli et al., 2025). Accurate determination of index properties is therefore a prerequisite for engineering design and construction practices (Ogbuagu and Okeke, 2019).

The physical behavior of soils is largely determined by their mineralogical and chemical makeup. Different clay minerals, such as kaolinite, montmorillonite, and illite, show distinct plasticity, swelling, and water retention characteristics. Similarly, the chemical composition of soils, including oxides of silicon, aluminum, iron, calcium, and magnesium, affects soil reactivity, cohesion, and stability (Seli et al., 2025; Sun et al., 2023). By understanding these relationships, engineers can explain and predict variations in index properties and thereby assess the suitability of soils for various construction applications (Amadi et al., 2015). Previous studies have shown the strong link between soil mineralogy/chemistry and index properties. Schmitz et al. (2004) correlated clay mineralogy with Atterberg limits across kaolinite, illite, and smectite/montmorillonite clays; they discovered that liquid limit and plasticity index are mainly controlled by the minerals. Smectite showed high swelling values due to its expandable structure and surface area, while kaolinite exhibits lower plasticity with minimal swelling. Tiwari and Dhungana (2009) used lab mixtures of quartz, smectite, and illite to show smectite dramatically increases liquid limit, swelling, and compressibility, whereas illite and quartz reduce plasticity, confirming dominant clay types drive index properties and volume changes. Many studies on lateritic soils have shown that iron and aluminum oxides, also called sesquioxide, strongly influence engineering properties. They cause fine particles to cement and aggregate, which reduces the clay content, lowers plasticity (low Atterberg limits), changes particle size distribution by forming silt-sized clusters, and affects compaction behavior, often resulting in lower optimum moisture content and variations in maximum dry density, even when the soils contain moderate fines (Kamtchueng et al., 2015; Nwakaire et al., 2024; Seli et al., 2025). Closer to this study, Ogbuagu and Okeke (2019) examined lateritic soils from Nimo and Nteje (Anambra State), reporting plasticity indices of 17-21%, AASHTO A-2-7 classification, and moderate-high plasticity tied to kaolinite and iron/aluminum oxides; the soils needed stabilization for subbase use due to varying plasticity and low CBR.

Despite growing research on lateritic and alluvial soils in southeastern Nigeria (Ogbuagu and Okeke 2019; Nwakaire et al., 2024), a clear gap remains in understanding how quartz, kaolinite, illite, feldspars, and key oxides (particularly SiO_2 and TiO_2) quantitatively control compaction and grading behaviour of this specific non-plastic to low-plasticity materials. Most previous works focused on plastic laterites or general index tests without linking them to detailed mineralogical and chemical data. This study fills that gap by establishing empirical regression relationships and providing a mechanistic explanation of how mineralogical and chemical composition governs the engineering behaviour. This study also provides quantitative regression models linking mineral phases and major oxides to key index and compaction properties of the studied soils. Derived from three representative samples, these correlations offer practical guidance for material selection for road construction, subgrade stabilization, and mortar production within the Awka-Onitsha region.

2.0 Materials and methods

2.1 Geology of the study area

Awka North Local Government Area, which includes the Amansea and Ebenebe borrow pits, is mainly underlain by the Imo Shale Formation (Paleocene–Lower Eocene), made up of clayey shales with occasional sandstone and ironstone layers. The Ebenebe Sandstone occurs locally within this formation and contains sandstone, siltstone, and mudstone (Ogbuchukwu et al., 2019; Onuoha & Ogbo, 2023). The Onitsha area along the Niger River is underlain by the Eocene Ameki Formation and associated river deposits. The Onitsha River sand (ON100) was obtained from dredged riverbed materials and consists of typical fluvial sediments such as sand, silt, and minor clay (Arazu & Ogbeibu, 2017).

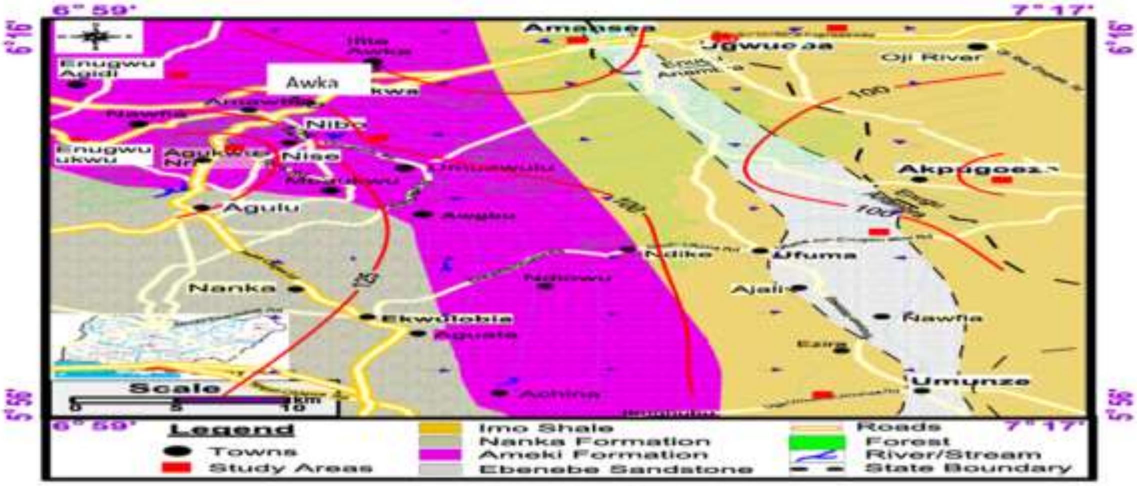

Figure 1: Geological map of Awka North (Ogbuchukwu et al., 2019).

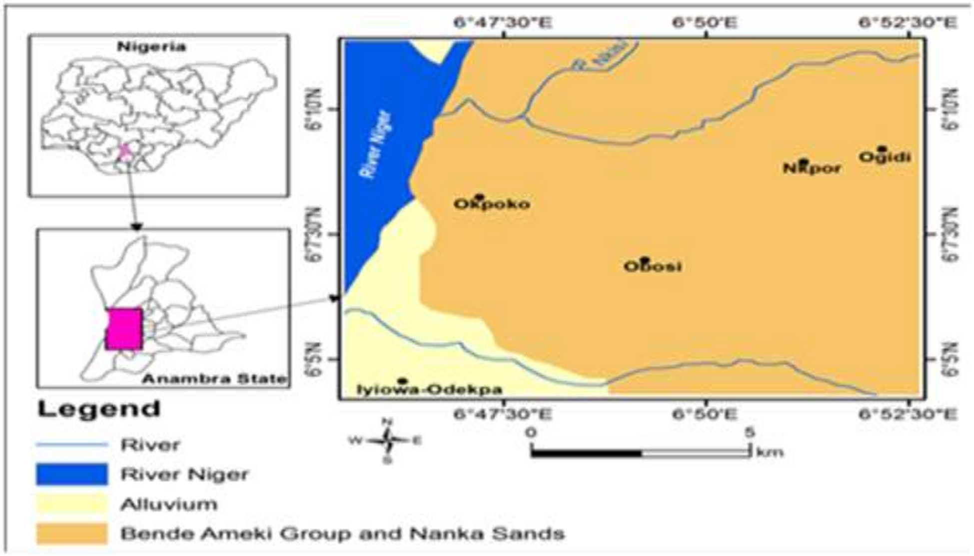

Figure 2: Geological map of Onitsha and River Niger (Asowata & Olatunji, 2019).

2.2 Description of soils

Bulk disturbed soil samples (~50 kg each) were collected from active borrow pits at Ebenebe and Amansea and from dredged River Niger sand stockpiles at Onitsha beach, all of which are commonly used by local contractors for construction purposes. The samples are summarized in Table 1 and Figure 3.

Table 1: Description and source of raw soils

Sample ID	Composition (dry weight)	Source
EB100	100% Ebenebe soil	Ebenebe, Awka North LGA
AM100	100% Amansea soil	Amansea, Awka North LGA
ON100	100% river sand	River Niger, Onitsha South LGA

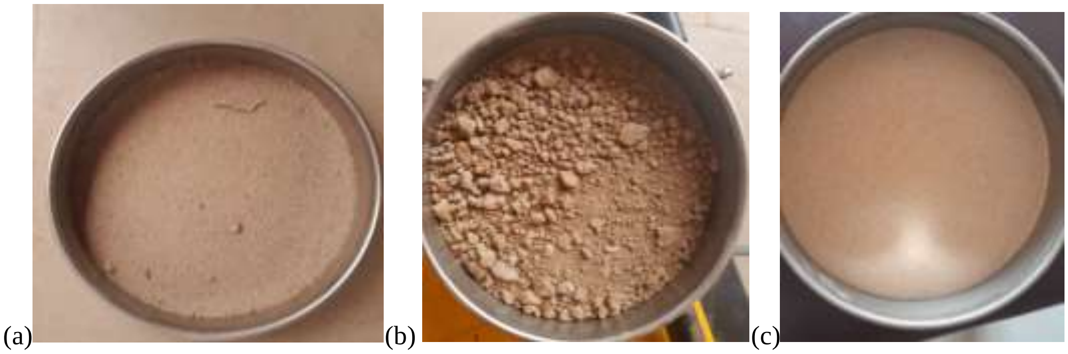

Figure 3: Photographs of the soils studied: (a) Ebenebe borrow pit soil. (b) Amansea borrow pit soil, and (c) Onitsha River sand.

2.3 Methods

All geotechnical tests followed BS 1377- 2,4:1990 (British Standards Institution, 1990 and aligned with BS EN ISO 17892 standards). Natural moisture content was determined by oven-drying ~500 g of soil at 105-110 °C for 24 hours (ASTM International, 2019a). Particle size distribution included dry sieving (0.075–2.00 mm) and hydrometer analysis for fines with sodium hexametaphosphate dispersant (ASTM International, 2019b, 2023). Atterberg limits and linear shrinkage were measured on soil passing the 425 μm sieve (ASTM International, 2017). Specific gravity used the density bottle method on soil passing the 2 mm sieve (ASTM International, 2022). Mineralogical composition was determined by X-ray diffraction (XRD) using a PANalytical Empyrean diffractometer with Cu-Kα radiation (Moore & Reynolds, 1997). Chemical composition (major and minor oxides) was analyzed by X-ray fluorescence (XRF) using a Rigaku ZSX Primus IV spectrometer (Jenkins, 1999). XRD, XRF, and hydrometer tests were conducted at Springboard Research Laboratory, Awka, Nigeria.

2.3 Equipment used

The experimental work utilized standard laboratory equipment, including a drying oven (105–110°C), electronic weighing balance, sieve set (0.075–2.00 mm) with mechanical shaker, hydrometer apparatus, Atterberg limits apparatus (Casagrande device and glass plate), linear shrinkage mould, and density bottle. Compaction tests were conducted using Standard Proctor equipment (mould and rammer). For advanced characterization, an X-ray diffractometer (PANalytical Empyrean) and an X-ray fluorescence spectrometer (Rigaku ZSX Primus IV) were used for mineralogical and chemical analyses, respectively

3.0 Result and Discussion

3.1 Index properties of soil samples

The index geotechnical properties of the three soil materials are summarized in Table 2.

Table 2: Summary of geotechnical index properties of the soil samples

Parameter / Property	ON100 (Onitsha River Sand)	AM100 (Amansea Borrow Pit Soil)	EB100 (Ebenebe Borrow Pit Soil)
Sand (%)	99.1	66.5	73.7
Fines (%) (passing 0.075 mm)	0.9	33.5	26.3
Silt (%) (0.002 – 0.075 mm)	—	23.45	14.58
Clay (%) (< 0.002 mm)	—	10.05	11.92
Coefficient of Uniformity (Cu)	2.36	2.25	7.90
Coefficient of Curvature (Cc)	1.16	1.05	1.14
Fineness Modulus (FM)	2.35	2.31	1.64
Average Specific Gravity (Gs)	2.65	2.59	2.55
Natural Moisture Content (NMC, %)	4.4	10.6	21.4
Optimum Moisture Content (OMC, %)	16.0	9.0	11.0
Maximum Dry Density (MDD, Mg/m³)	1.69	1.62	1.78
Liquid Limit (LL, %)	Non-plastic	Non-plastic	18.9
Plastic Limit (PL, %)	Non-plastic	Non-plastic	Non-plastic
Plasticity Index (PI, %)	Non-plastic	Non-plastic	Non-plastic
Linear Shrinkage (%)	0.00	0.07	0.14
USCS Classification	SP (Poorly graded sand)	SM (Silty sand)	SM (Silty sand)
AASHTO Classification	A-3	A-2-4	A-2-4

ON100 is a clean, poorly graded sand with negligible fines and no plasticity, typical of alluvial river sand (Table 2). The borrow-pit soils (AM100 and EB100) contain moderate fines (26.3-33.5%), predominantly silt-sized with clay fractions of about 10-12% yet remain essentially non-plastic (PI = 0%), with only EB100 showing a minor liquid limit (18.9%) and negligible linear shrinkage (≤0.14%) (Table 2). The river sand has the highest OMC (16.0%) and moderate MDD (1.69 Mg/m³), while the borrow-pit soils exhibit lower OMC (9.0-11.0%) and slightly higher MDD in EB100 (1.78 Mg/m³), suggesting improved packing from fines. Natural moisture content is notably higher in EB100 (21.4%) than in AM100 (10.6%) and ON100 (4.4%), likely due to greater clay retention of field moisture. Specific gravity ranges from 2.55 to 2.65 across all samples.

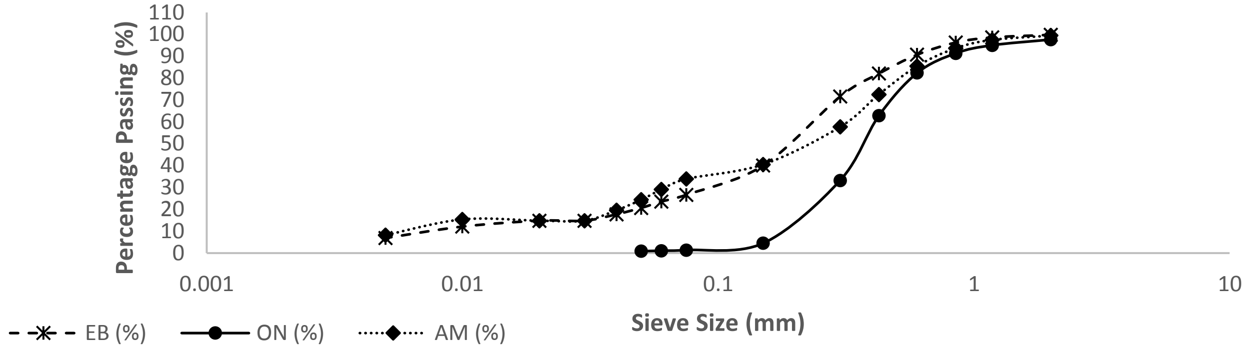

Figure 4. Particle size distribution curve

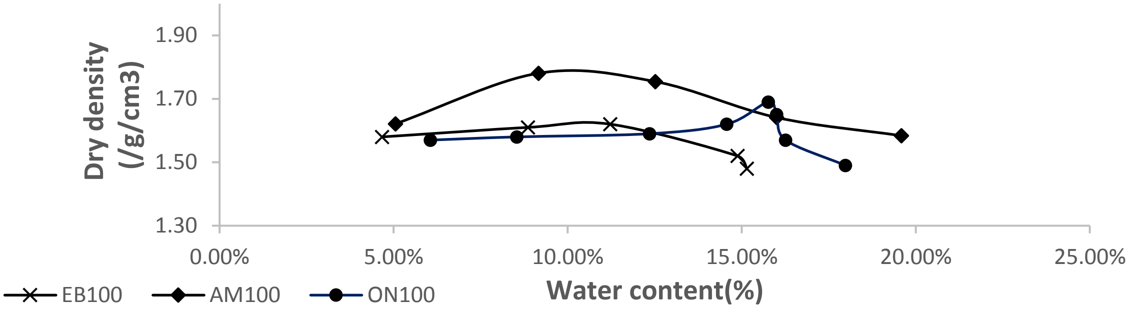

Figure 5. Dry density and water content curve

The graphical representation of these Particle Size Distribution and Compaction test results are shown in Figures 4 and 5. Figure 4 presents the particle size distribution curves, with particle size (log scale) on the horizontal axis and percentage passing on the vertical axis. ON100 shows a steep curve within the sand fraction, indicating a poorly graded uniform sand, while AM100 and EB100 display more gradual curves extending into the fine region, confirming the presence of silt and clay and improved gradation. Figure 5 shows the compaction curves (dry density versus moisture content), exhibiting the typical bell-shaped trend. ON100 has a higher optimum moisture content and moderate maximum dry density, whereas AM100 shows lower OMC and higher MDD due to improved particle packing from fines.

3.2 Mineralogical Composition (XRD Analysis) of soil samples

The mineralogical composition of the three soil samples was determined using X-ray diffraction (XRD) analysis. The mineral percentages derived from peak intensity/area ratios. are presented in Table 3.

Table 3: Mineralogical composition.

Sample ID	Quartz (SiO_2)	Kaolinite	Orthoclase (K-feldspar)	Albite (Na-feldspar)	Muscovite/Illite	Other
EB100	92	3	2	1	4	Tr
AM100	86	7	3	2	2	Tr
ON100	96	<1	2	1	<1	Tr

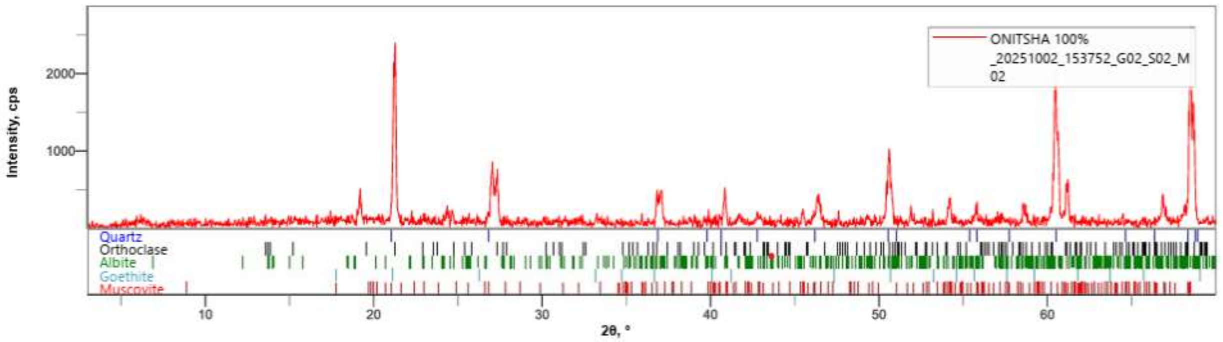

Figure 6. XRD plot for ON100

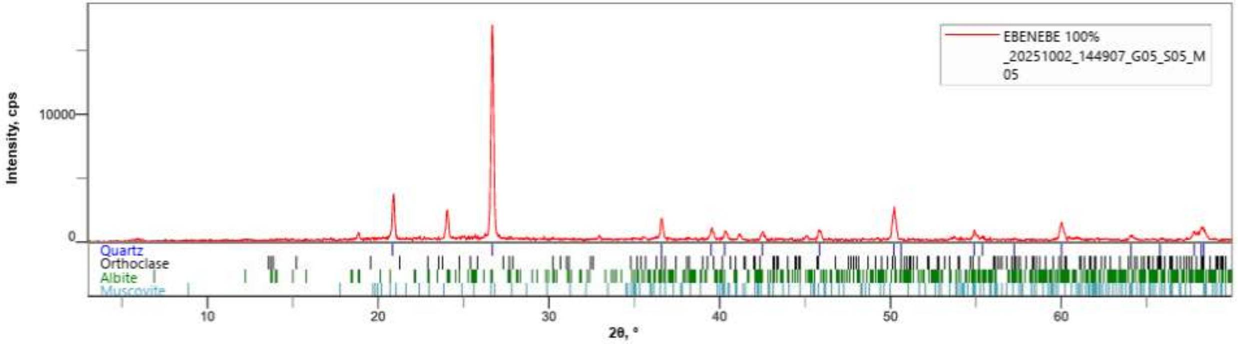

Figure 7. XRD plot for EB100

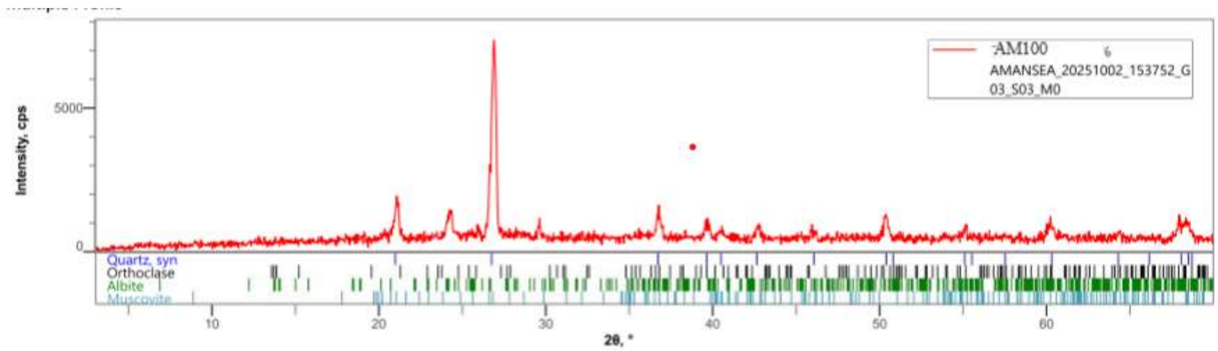

Figure 8. XRD plot for AM100

The X-ray diffraction (XRD) patterns of ON100, EB100, and AM100 is shown in Figures 6–8. The horizontal axis represents the diffraction angle (2θ), while the vertical axis represents peak intensity. Quartz was the dominant mineral in all samples (86–96%), because of the siliceous nature of the parent materials (Imo Shale/Ebenebe Sandstone for the borrow pit soils and alluvial sand for ON100). Minor peaks corresponding to kaolinite, feldspar, and muscovite or illite are also observed in the borrow-pit soils (AM100 and EB100) (Figure 7 and Figure 8), indicating the presence of clay minerals. The higher quartz intensity in ON100 (Figure 6) indicates its nearly pure sandy composition and non-plastic behavior, while the presence of clay mineral peaks in AM100 and EB100 explains their fines content and variation in index properties.

3.3 Chemical Composition of the Soil Samples

The chemical composition of the soils, determined by X-ray fluorescence (XRF), is presented in Table 4. All samples are mostly siliceous, with SiO_2 as the major oxide, indicating quartz-rich parent materials. Al_2O_3 and Fe_2O_3 occur in moderate proportions, with relatively higher iron content observed in AM100. Minor oxides, including TiO_2, CaO, K_2O, MgO, SO_3, and Cl, are present in low amounts across the samples. The total oxide contents are close to 100% for all soils, confirming the reliability and completeness of the chemical analysis.

Table 4. Major Oxide Composition of Soil Samples

Oxide	EB100	AM100	ON100
SiO_2	84.41	80.20	82.29
Al_2O_3	4.98	6.58	5.31
Fe_2O_3	1.38	6.43	2.02
TiO_2	2.17	2.54	1.10
CaO	0.64	0.58	1.89
K_2O	0.15	0.29	4.11
MgO	0.00	0.00	1.66
SO_3	4.69	0.69	0.24
Cl	0.87	1.75	0.77
Others	<1.0	<1.0	<1.0
Total	99.71	99.07	99.39

3.4 Influence of mineralogical composition on fines content and Atterberg limits

The fines content and Atterberg limits are mainly controlled by mineralogy. Borrow-pit soils (AM100 and EB100) have moderate fines (26.3–33.5%), mostly silt (14.58–23.45%) with 10–12% clay, but remain essentially non-plastic (PI = 0%), with only EB100 showing a low liquid limit (18.9%) and negligible linear shrinkage (≤0.14%). This low plasticity arises from low-activity kaolinite (3-7%), which aggregates into silt-sized particles, and minor muscovite/illite (<1-4%), which slightly increases clay content and liquid limit in EB100. Quartz (86–96%) dominates sand and silt fractions without affecting plasticity. Feldspars (3–5%) supply fines through weathering to kaolinite and silt, contributing to higher fines in AM100. Iron oxides (Fe_2O_3) improve aggregation of fines into silt-sized clusters, suppressing plasticity and altering effective PSD. Figure 8 shows a strong positive relationship between total clay minerals (kaolinite + muscovite/illite) and fines content ($R^2 = 0.99$), confirming mineralogy's dominant control over fines development, PSD, and low Atterberg limits. These findings support earlier work by Seli et al., (2025) who reported that soils with high silt content associated with low-activity kaolinite exhibit low plasticity.

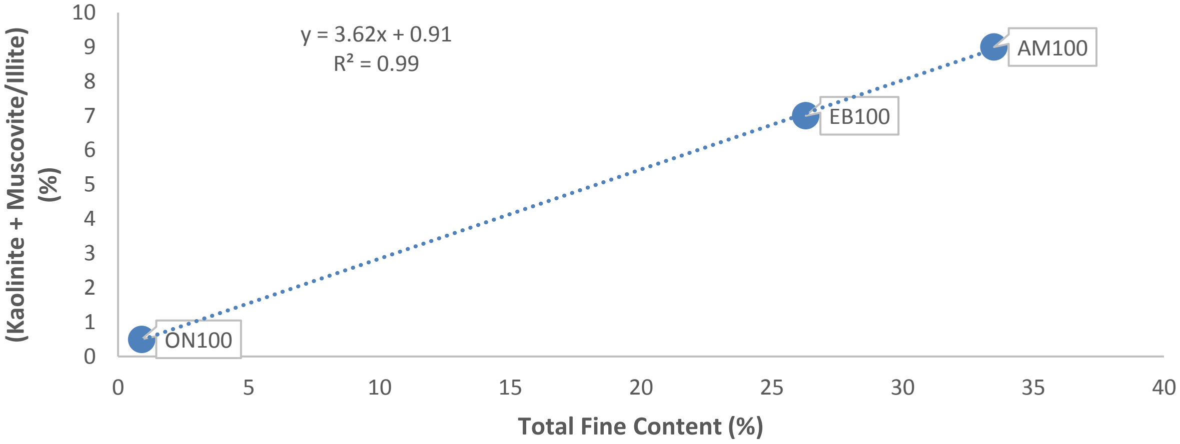

Figure 9. Clay mineral content versus fines content

3.5 Influence of Mineralogical Composition on OMC and MDD

Mineralogical composition strongly influences the compaction properties (OMC and MDD) of the soils, Figure 10 presents linear regression plots with mineral content (%) on the x-axis and compaction properties on the y-axis. The graphs were generated using the least-squares method. Quartz (86–96%) shows a strong positive correlation with optimum moisture content (OMC) ($R^2= 0.878$). The upward trend in the quartz vs OMC graph indicates that higher quartz content requires more moisture for optimum compaction. This is evident in the quartz-rich river sand (ON100), which has the highest OMC (16.0%) due to its low surface area and poor water retention. In contrast, kaolinite (3-7%) exhibits a strong negative correlation with OMC ($R^2 = 0.898$). The downward trend shows that higher kaolinite content leads to lower OMC. This is clearly seen in AM100, which has the highest kaolinite (7%) and the lowest OMC (9.0%), because low-activity kaolinite aggregates into silt-sized particles, reducing the surface area that holds water. Illite/muscovite (<1-4%) displays a moderate positive correlation with maximum dry density (MDD). The upward trend suggests that higher illite content improves particle packing, contributing to the highest MDD recorded in EB100 (1.78 Mg/m³). Feldspars (3-5%) show a negative correlation with MDD ($R^2 = 0.685$). The downward trend indicates that feldspars contribute fines through weathering, which disrupts optimal packing; an effect more pronounced in AM100, resulting in its lowest MDD (1.62 Mg/m³). These relationships (all with $R^2 \geq 0.6$) align with Bhavya and Nagaraj (2025), who noted that low-activity clays typically produce non-plastic behavior with distinct compaction characteristics.

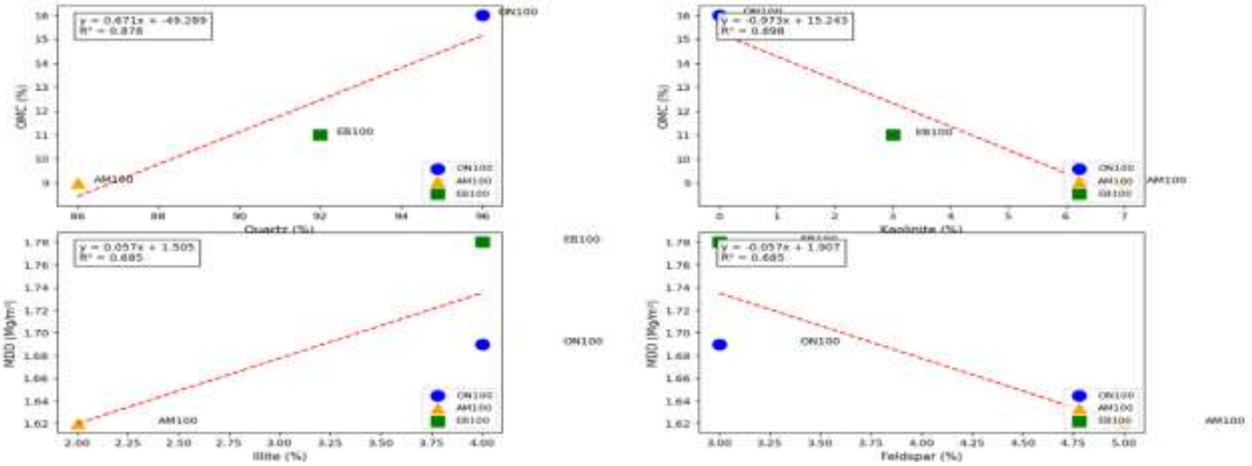

Figure 10. Influence of mineral content on optimum moisture content (OMC) and maximum dry density (MDD) with regression trends.

3.6 Influence of SiO_2 on Soil Properties

Silicon dioxide (SiO_2), the dominant oxide (80.20–84.41%), shows the strongest correlations with the geotechnical properties, mainly due to its close link with quartz (86–96%).Three linear regression graphs with SiO_2 content (%) plotted on the horizontal (x) axis in each case (Figure 11). The graphs were generated using the least-squares method in Microsoft Excel, and the trendlines with their R^2 values were obtained directly from the plotted points. In the first graph, SiO_2 content (x) is plotted against maximum dry density (MDD) on the y-axis. It shows a very strong positive linear relationship ($R^2 = 0.995$). The upward trend indicates that higher silica content improves particle packing and leads to higher achievable dry density. This is clearly seen in EB100, which has the highest SiO_2 content and records the highest MDD (1.78 Mg/m³), compared to AM100 with the lowest values. In the second graph, SiO_2 content (x) is plotted against fineness modulus (FM) on the y-axis. It shows a moderately strong negative relationship ($R^2 = 0.709$). The downward trend means that as SiO_2 content increases, the fineness modulus decreases, suggesting a shift toward a coarser effective particle size distribution. In the third graph, SiO_2 content (x) is plotted against the coefficient of uniformity (Cu) on the y-axis. A moderately strong positive relationship is observed ($R^2 = 0.768$). The upward trend shows that higher SiO_2 content is associated with better gradation and a wider range of particle sizes. This effect is most prominent in EB100, which records the highest Cu value (7.90). These results further align with Gu et al. (2022), who showed that silica improves interparticle bonding and contact, leading to improved soil structure and gradation,

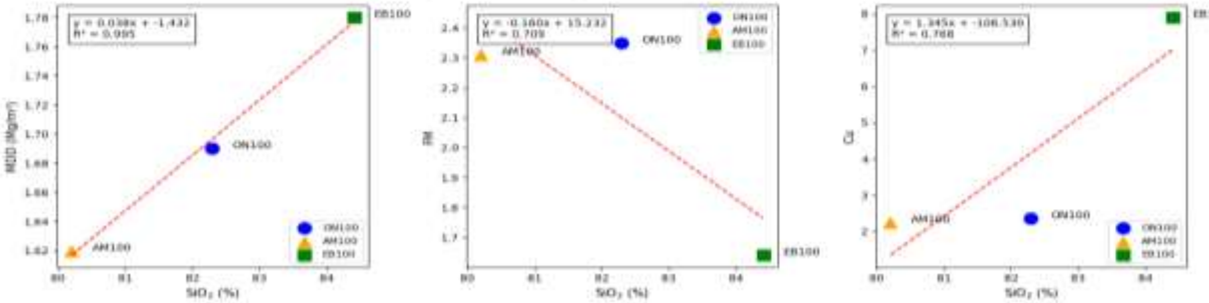

Figure 11. SiO_2 content versus compaction and gradation properties (MDD, Cu, FM) with linear trend lines.

3.7 Influence of TiO_2, Al_2O_3 and Fe_2O_3 on Soil Properties.

Titanium dioxide (TiO_2, 1.10−2.54%) strongly reduces optimum moisture content (OMC), with the highest TiO_2 in AM100 (2.54%) corresponding to the lowest OMC (9.0%) compared to ON100 (1.10%, OMC = 16.0%). TiO_2 also slightly lowers specific gravity (Gs). Sesquioxides (Al_2O_3 + Fe_2O_3) reduce maximum dry density (MDD), with the highest combined content in AM100 (13.01%) yielding the lowest MDD (1.62 Mg/m³), while EB100 (6.36%) achieves the highest MDD (1.78 Mg/m³) due to cementation and aggregation effects that hinder close packing (Table 2 and Table 4). These observations are consistent with the finding of Kamtchueng et al., (2015) and Seli et al., (2025), who reported that the soils that contains sesquuioxides have low MDD as a result of their cemententious nature.

4.0 Conclusion

This study examined the influence of mineralogical and chemical (oxide) composition on the geotechnical index and compaction properties of three locally sourced soils commonly used for construction in Awka Municipal, Anambra State, Nigeria, namely Onitsha River sand (ON100) and borrow pit soils from Amansea (AM100) and Ebenebe (EB100). The research was guided by the objective of establishing how soil mineralogical and chemical composition controls engineering behavior through experimental testing and regression analysis, integrating geotechnical characterization with mineralogical (XRD) and chemical (XRF) evaluations. The findings revealed that all the soils are predominantly composed of quartz (approximately 86–96%), with varying proportions of kaolinite (3–7%), feldspar, and minor clay minerals. The dominance of quartz was observed to influence compaction behavior by increasing the optimum moisture content (OMC), particularly in ON100, due to its relatively low specific surface area and limited water retention capacity. In contrast, the presence of kaolinite contributed to reduced moisture demand and largely non-plastic behavior in the borrow-pit soils, evident by the low activity of the clay minerals present. Minor minerals also played a role in modifying particle arrangement and packing efficiency, where illite/muscovite slightly enhanced maximum dry density (MDD), while feldspars tended to reduce it by introducing fines that disrupt optimal gradation.

Chemical composition further showed strong control over geotechnical properties. Silica (SiO_2), which ranged between 80.20% and 84.41%, exhibited a strong positive relationship with MDD and improved grading parameters such as coefficient of uniformity (Cu) and fineness modulus (FM). Conversely, titanium oxide (TiO_2) showed a near-perfect inverse relationship with OMC, indicating its association with compositional effects that influence compaction water demand. Sesquioxides (Al_2O_3 and Fe_2O_3) were found to reduce MDD, likely due to cementation and aggregation effects that limit particle rearrangement and densification during compaction. These effects were particularly evident in AM100, which exhibited lower dry density compared to EB100 despite having a higher fines content. Regression analysis confirmed statistically significant relationships between oxide composition and key geotechnical parameters, reinforcing the role of mineralogical and chemical controls in governing soil behavior. The study demonstrates that both mineralogical constituents and oxide chemistry are critical determinants of soil performance, influencing particle packing, gradation, moisture interaction, and interparticle bonding. The contribution of this work lies in its integrated approach, combining geotechnical, mineralogical, and chemical analyses to better understand locally sourced construction materials. The findings provide a scientific basis for material selection and optimization in construction applications, particularly for mortar, concrete, and fill use.

5.0 Recommendation

Based on the findings of this study, it is recommended that the mineralogical and chemical composition of soils be considered alongside geotechnical testing in material selection for construction. Soils with high quartz content and favorable oxide composition should be prioritized due to their improved compaction performance and strength characteristics. Borrow pit soils from Amansea and Ebenebe can be effectively utilized; however, their performance requires careful control of moisture content and compaction conditions due to variations in fines and mineral composition. Field compaction practices should account for the influence of oxide constituents, particularly silica and sesquioxide, on optimum moisture content and maximum dry density. Furthermore, routine geotechnical investigations should include mineralogical and chemical analyses to improve the prediction of soil behavior. Future research should explore advanced modeling approaches, including AI-based multivariate analysis, to better understand and predict the combined effects of mineralogical and chemical composition on soil performance.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and Grok to improve grammar, clarity, and language expression. After using these tools, the authors carefully reviewed and edited the content and took full responsibility for the accuracy and integrity of the publication.

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