

To Cite:

Olatunde IC, Adebayo OC, Richard FO. Mineralogical characteristics and engineering properties of genetically different residual soils in the northern part of Ondo State, Southwestern, Nigeria. *Discovery Nature* 2025; 2: e4dn1049
doi: <https://doi.org/10.54905/disssi.v2i3.e4dn1049>

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Peer-Review History

Received: 20 October 2024

Reviewed & Revised: 24/October/2024 to 01/February/2025

Accepted: 05 February 2025

Published: 09 February 2025

Peer-Review Model

External peer-review was done through double-blind method.

Discovery Nature
pISSN 2319-5703; eISSN 2319-5711



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Mineralogical characteristics and engineering properties of genetically different residual soils in the northern part of Ondo State, Southwestern, Nigeria

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ABSTRACT

The influence of mineralogical compositions on geotechnical properties of two genetically different soils around the northern part of Ondo State, Nigeria, was evaluated to better understand the complex engineering performance of clayey soils as derived by the parent rock. The soil samples collected from the region were subjected to XRD analysis, index strength tests, and statistical analysis. Geological mapping revealed Charnockite (Ch) and medium- to coarse-grained granite (OGe) rock types in the area. The OGe-derived soils have a dominance of low-activity clay mineral 1:1. On the other hand, the Ch-derived soils have a dominance of high-activity clay minerals of 2:1. The statistical analysis showed that there is no significant soil variation based on the size of its particle; however, it indicates that there is a significant difference in the coefficient of variations of their respective moisture content. Furthermore, Ch and OGe CBR values indicate a significant difference of 86 coefficients of variation, which account for a 75.61% reduction in the strength values between the two soil types. Ch-derived soil samples plot within the CH region of the plasticity chart, while OGe-derived soil samples plot within the CI region. Ch-derived and OGe-derived soils have optimum moisture content (OMC) mean values that fall above and within FMWH, (1997) recommended specifications, respectively. Ch-derived soils have a lower bearing capacity compared to OGe-derived soils. The OGe-derived soils have different and preferred engineering properties compared to the Ch-derived soils due to mineralogical differences. Hence, mineralogical characteristics of the parent material are responsible for behavioral differences in the engineering properties of soils derived from genetically different parent rock.

Keywords: Clay minerals, Geotechnical properties, Engineering soils, Statistical analysis.

1. INTRODUCTION

The soil formation process begins with the chemical alteration and physical breakdown of the parent rock surfaces, which form the bedrock for the soil. Gerrard, (2000) affirms that bedrock influences soils through the weathering process and afterwards through the weathered material. According to Adeyemi, (1995), the textural and mineralogical characteristics of parent materials could be responsible for behavioral differences in the engineering properties of soils derived from genetically different parent rock materials. Residual soil is characterized by the presence of minerals that have weathered from the parent rock. The consistency, water absorption, and swelling characteristics of clayey soils are usually better understood if the clay mineralogical contents are known (Mesida, 1987).

The most important textural property of fine-grained soils is the mineralogical composition. The type of clay mineral plays a dominant role in controlling the physical and engineering properties of fine-grained soils. In the presence of water, montmorillonite clay minerals can swell to as much as 20 times their own volume (Sridharan and Choudhury, 2002). This high swelling potential of montmorillonite is attributed to the adsorption of hydrated cations and water molecules, resulting in strong repulsive forces and interlayer expansion in the presence of electrolyte solutions (Sridharan and Choudhury, 2002). In addition, double-layer swelling can occur due to the overlapping of the diffuse double layer in between particles and in between the elementary layer (Mitchell, 1993).

Thus, mineralogy can be considered fundamental to the understanding of geotechnical properties. Geotechnical properties have been shown to depend on the texture and mineralogy of soils (Sridharan and Choudhury, 2002; Adeyemi, 2013). The affinity of a soil for water also depends on its predominant clay mineral content. Adeyemi et al., (2012) reported significant influences of mineralogy and texture on some geotechnical properties of six distinct crystalline rocks from parts of southwestern Nigeria. The relatively low amount of quartz and high amount of alkali feldspar could have been responsible for the high-water absorption capacity and low strength of the pegmatite samples.

Adeyemi, (1992) has shown that the degree of stability of the Lagos/Ibadan highway pavement increased with the amount of kaolin, ferric oxide CBR, and UCS of the subgrade (foundation) soils. Clay mineral constituents of earth materials increase the sensitivity of shear resistance to moisture content. The range of moisture content at maximum shearing resistance decreases as the clay minerals become increasingly abundant and as intergranular friction is reduced. The existence of clay minerals and the variability, such as textural characteristics of subgrade materials Ekeocha and Akpokodje, (2012), Adiat et al., (2017), were among the reasons identified by earlier researchers for the frequent road failures. This has generated research interest among many scholars such as Mesida, (1987), Jegede, (2000), Mitchel and Soga, (2005) and Sani et al., (2021) but none of these studies have excluded the effect of textural characteristics. Hence, this study intends to build on this knowledge gap by revealing the due contribution of clay minerals to the geotechnical behavior of engineering soil and for better understanding of the complex engineering performance of clayey soils conditioned fundamentally by the parent rock.

Study Area

The study area covers parts of the F209 road that links Akure with Iju in southwestern Nigeria. It stretches between Latitude 07°16.00'N and 7°28.00'N and Longitude 005°10.00'E and 005°18.00'E. The road has relatively flat to gently rolling slopes around the northern part and undulating topography towards the southwest section with steep slopes (Figure 1).

Geology

The major rock types, which vary in color, structure, mineralogical, and textural composition, make up the geology of the locations the road traverses. These rocks' diverse qualities are mostly a result of the different orogenic and deformational occurrences that have affected them over the course of their evolutionary history (Ajayi, 1987; Ademeso, 2010). The lithologies include medium-to-coarse-grained granite, porphyritic granite, and coarse-grained charnockite; these make up the majority of the rock types that underlie the locations where the route travels.

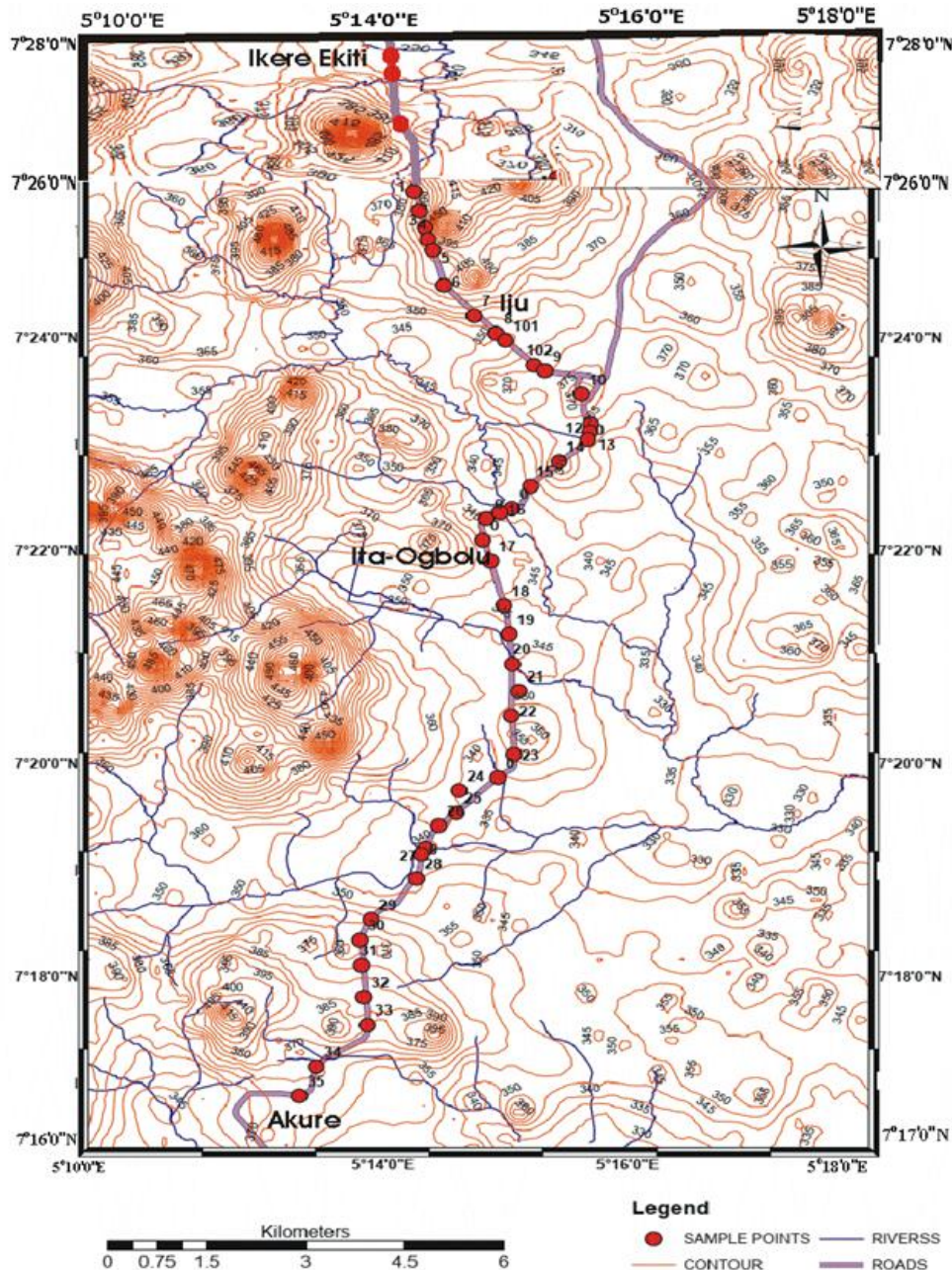


Figure 1 Topographical Map of the Studied Area

2. MATERIALS AND METHODS

Geological Mapping: This includes the identification and description of rock samples and taking coordinates. The soil materials used for this study were granite and charnockite-derived residual soils. Forty samples were collected at an average of 0.8meter interval and properly labelled and transported to Geotechnical Laboratory of Federal Polytechnic Ado-Ekiti for geotechnical analysis while pulverized samples were subjected for X-ray diffraction tests employing a Rigaku D/Max-IIIC model diffractometer, the PW 1800. The index and strength tests were carried out using British Standard procedures. The index analysis carried out were moisture content, grain size analysis, consistency limits, while the strength analysis includes compaction test, uniaxial compressive test, and California Bearing Ratio (CBR).

The sieve analysis was conducted on the clay soil using the wet-sieving method. The liquid limit of the samples was determined using the Casagrande apparatus method, in accordance with. The procedure for the determination of the plastic limits and plasticity indices were derived in accordance with. The compaction characteristics of the samples were determined using the procedures outlined in. However, only ten out of the forty samples' data were considered suitable and selected for this study. Five samples each for both granite medium-coarse grained (OGe) and charnockite (Ch) derived soils.

3. RESULTS AND DISCUSSION

Mineralogical analysis (X-Ray Diffraction Analysis)

Table 1 presents the results of the mineralogical analysis. It was observed that the OGe-derived soils have dominance of low-activity clay mineral 1:1 layer such as kaolinite. On the other hand, the Ch-derived soils have dominance of high-activity clay minerals 2:1 such as illite and vermiculite. This difference in their mineralogical composition can be attributed mainly to their parent rock since the soils are residual. This implies that Ch-derived soils may give rise to soils of higher consistency, water absorption, and swelling and shrinkage tendency in comparison with OGe-derived soil. This agrees with the findings of Bronick and Lal, (2005) reported that high-activity clay minerals are more sensitive to aggregation and dispersivity than low-activity ones.

This agrees with the higher dispersibility of termite mound materials, enriched in mica and expandable clays, as compared to the control soils, dominated by kaolinite. Therefore, Ch-derived soils are expected to have more dispersive and swelling potential in comparison with OGe-derived soils. This implies poorer engineering properties. Mesida, (1987) reported that the dominant kaolinite content has normally imparted limited plasticity to the soil, therefore, it enhanced its engineering properties, while the dominant vermiculite and illite content increase the plasticity to the soil, therefore, reduced its engineering properties. Hence, granite derived soil may possess lower plasticity properties compared with the charnockite derived soil due to this reason.

This suggests that granite-derived soils of the same textural characteristics will have preferred engineering properties compared to charnockite-derived soils. In addition, higher amount of quartz found in the granite-derived soils also has the tendency to further reduce their hydrophilic characteristics. But the lower amount of quartz found in the charnockite-derived soils give more allowance to their hydrophilic characteristics, which will further enhance their water absorption and retention behaviour. Generally, there is a correlation between the clay minerals composition of a soil and its activity.

Table 1 Mineralogical Compositions of the Studied Samples (wt. %)

	Quartz (%)	Kaolinite (%)	Illite (%)	Clinochlore (%)	Vermiculite (%)	Osumilite (%)	Feldspar (%)	Lithology
Range	38 - 55	0 - 27	8 -15	5-7	5 - 18	Nil	7 - 18	Ch
Average	45	6	10	6	12	Nil	13	-
Range	59 - 62	7 - 22	Nil	8 -11	Nil	3 - 4	10 -18	OGe
Average	60	14	Nil	9	Nil	3	13	-
Characteristics	LA	LA	HA	HA	HA	HA	Clay	-

Ch = Coarse-grained charnockite, OGe = Medium- to coarse-grained biotite-hornblende granite.

Characteristics LA = Low-activity, HA = High-active

Particle Size Analysis

Grain size distribution analysis results are presented in (Table 2). It was observed that both OGe- and Ch-derived soils have practically the same textural characteristics. This was attributed to the cautious conservation and consideration taken by selecting ten most suitable samples from the forty samples in course of the study to exclude the effect of textural properties on the experiment. The statistical analysis on coefficient of variations gave values of 2.38 and 1.64 for coarse content (gravel and sand) soil and fine content (clay and silt) of both OGe and Ch-derived soils respectively. This result showed that there is no significant soil variation based on the size of its particle. Hence, the engineering characteristics of soil variation that may result from textual characteristics have been eliminated. Therefore, geotechnical characteristics of the studied soils are controlled mainly by the type of clay minerals constituents.

Table 2 Summary of Grain Size Analysis and Statistical Analysis

Positions						Grain Size Analysis				
SN	MC	Gravel (%)	Sand (%)	Coarse (%)	cv	Silt (%)	Clay (%)	Fines (%)	cv	RT
1	17.56	9.8	31.5	41.3	-	35.1	23.6	58.7	-	Ch
2	18.78	9.1	41.5	50.6	-	26.2	23.2	49.4	-	Ch
3	14.98	3.7	38.4	42.1	2.38	43.3	14.7	58	1.64	Ch
4	25	11.3	28.7	40	-	44	16	60.3	-	Ch
5	18.9	4.1	29	33.1	-	53.3	13	66.3	-	Ch
Mean	19.04	7.6	33.8	41.4	-	40.4	18.1	58.5	-	-
1	16	11	33.8	44.8	-	41.3	14	55.3	-	OGe
2	10.98	2.4	48.2	50.6	-	36.1	13.3	49.4	-	OGe
3	12.7	5.8	26.2	32	2.38	54.2	13.8	68	1.64	OGe
4	16.2	9	38.6	47.6	-	31.7	20.7	52.4	-	OGe
5	14.19	5.5	33.7	39.2	-	46.1	14.8	60.9	-	OGe
Mean	14.04	6.74	36.1	42.8	-	41.9	15.32	57.2	-	-

Ch= Charnockite OGe = granite CV= Coefficient of variations RT= Rock type

Natural moisture content (NMC)

Results of the natural moisture contents of the soil samples are presented in (Table 3). The values of NMC ranged from 14.98% - 25%, with mean value of 19.04 %, for Ch soils and 10.98% – 16.2%, with mean value of 14.04 %, for OGe soil samples. This result indicates distinction in the water absorbing and holding capacity of the two derived soils. This could be attributed to the amount and types of clay minerals which resulted from the difference in their parent rock types, since their textural characteristics are practically the same. It was observed that Ch-derived soils have the higher MC value in comparison with the OGe. As earlier noted in the previous paragraphs relating to clay minerals, the charnockite-derived soil has higher-activity clay minerals, which gives rise to higher moisture contents tendencies.

Whereas, OGe-derived soil has low-activity clay mineral, which gives rise to low moisture contents tendencies. The higher hydrophilic characteristics of the higher-activity clay mineral in the charnockite-derived soils have enabled the soils to have the higher moisture contents. Hydrophilic clay minerals exhibit high water absorption characteristics which automatically increase pore pressure and reduction of the soil shear strength properties and the consequential poor geotechnical performance.

The statistical analysis on NMC coefficient of variations between Ch and OGe soil samples gave values of 20.4. This indicates a significant difference, which accounts for 34.18% increase in moisture content. This implies that for any geotechnical value and performance of OGe soil, 34.18% reduction is expended for Ch soil samples. Reported that the degree of change (reduction) in the strength properties values is directly proportional to the moisture content absorption. Hence, there is distinction in their respective engineering properties and behaviours.

Consistency Limits

The summary of the consistency limits characteristic of the derived soils is presented in (Table 3 and Figure 2). It was observed that each soil type has a distinct field on the Casagrande chart, Ch-derived soil samples plot within the CH soil region while OGe soil plot within the CI region. This is attributed to mineralogical compositions. This may also be attributed to the amount of clay content and type of clay minerals present in the derived soils. This agrees with the trend observed in particle size analysis and natural moisture content results. This implies that each of the two soil types has different engineering properties. The plasticity characteristics of the soils may be interpreted based on their clay size particle content as well as their actual clay mineral content (Mesida, 1987).

As it has been noted earlier, that is; relating to clay mineralogy in the two soils, the charnockite-derived soil has higher activity clay minerals, with higher plasticity tendencies. The dominant kaolinite content of the granite-derived soil has normally imparted limited plasticity to the soil. The higher hydrophilic characteristics of the mixed clay mineral content in the charnockite-derived soil has

enabled the soil to have higher plasticity. This indicates that Ch-derived soils have higher plasticity and compressibility tendencies in comparison with OGe-derived soils. This also agrees with the results obtained from natural moisture content and Casagrande chart. High plasticity and in-situ moisture will take longer periods to dry after the heavy rains associated with the wet season (Jegade, 2000).

Hence, the delay in the periods of dryness especially of the Ch-derived soils may further worsen water logging activity, increase erosion occurrence and consequential poor engineering properties. This may account for the disparities in terms of usefulness in engineering applications as lateritic soils. Furthermore, the statistical analysis between Ch- and OGe-derived soil samples indicates that there is significant difference with 20 coefficient of variations which account for 32.78% difference in their plasticity property. As earlier noted, this percentage difference is good enough to distinguish their respective engineering behaviour.

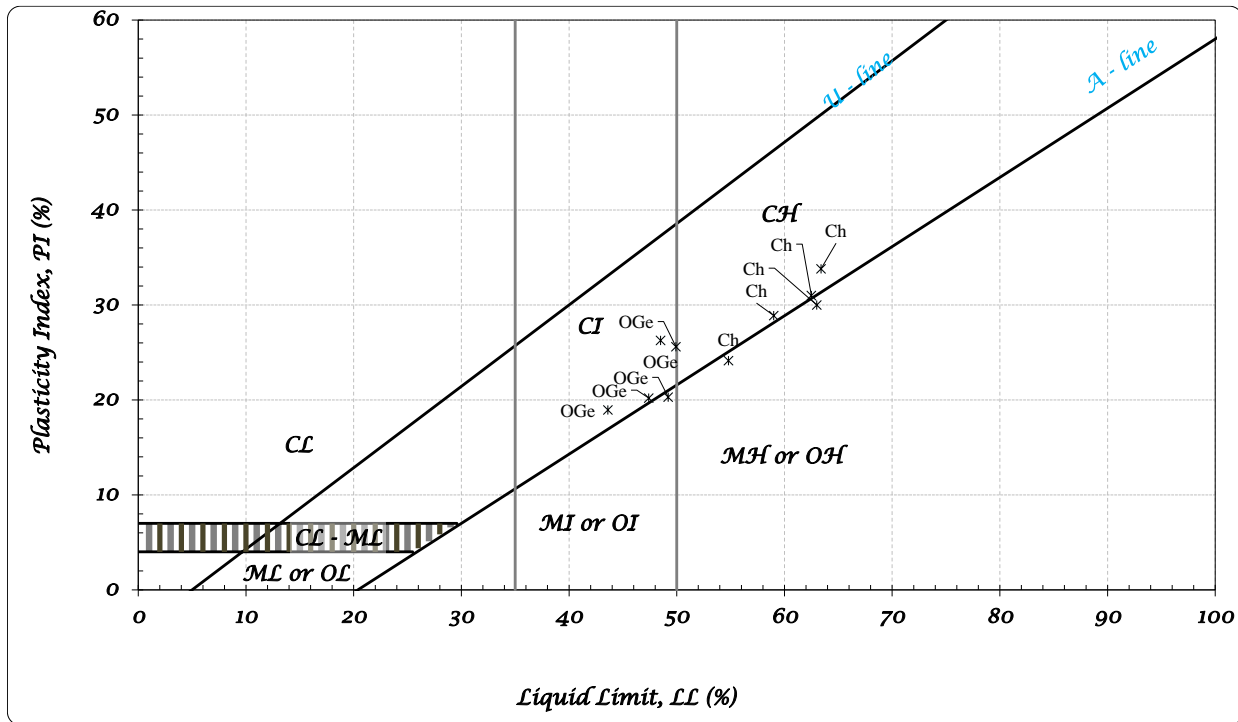


Figure 2 Casagrande chart classification of the Studied Soils

Table 3 Summary of Consistency Limits and Statistical Analysis of the Studied Soils

SN	MC	CV (IMC)	LL (%)	CV (IMC)	PL (%)	CV (IMC)	Plastic Index	CV (IMC)	Group Index	SC	Soil Type
1	17.56	-	63	-	33	-	30	-	14	CH	Ch
2	18.78	-	62.5	-	31.5	-	31	-	10	-	Ch
3	14.98	-	59	-	30.12	-	28.88	-	13	-	Ch
4	25	20.4	63.4	16.75	29.59	13.81	33.81	20	16	-	Ch
5	18.9	(34.18)	54.8	(26.87)	30.65	(21.64)	24.15	(32.78)	14	-	Ch
Mean	19.04	-	60.5	-	30.97	-	29.57	-	13.4	-	-
1	16	-	48.5	-	22.22	-	26.28	-	11	CI	OGe
2	10.98	-	43.6	-	24.65	-	18.95	-	6	-	OGe
3	12.7	-	49.2	-	28.9	-	20.3	-	12	-	OGe
4	16.2	-	49.92	-	24.31	-	25.61	-	9	-	OGe
5	14.19	-	47.4	-	27.21	-	20.19	-	10	-	OGe
Mean	14.04	-	47.7	-	25.46	-	22.27	-	9.6	-	-

SC= Soil classification, % RIS (MC) = % Increase in Moisture Content

Moisture/density relationship

Results of the compaction characteristics of the two soils are presented in (Table 4). Theoretically and practically, the best soils are those that have high maximum dry density values at relatively low optimum moisture content (Jegade, 1998). The charnockite-derived soil has a lower maximum dry density than the granite-derived soil. The average maximum dry density of the coarse granite-derived soil is about 1999 kg/m³, while that of the charnockite-derived soil is about 1815 kg/m³. The optimum moisture content at maximum dry density in the granite-derived soil is about 13.84%, while the charnockite-derived soil has about 18.7%. The actual clay mineral contents in the two soils are the basic reasons for these differences in their moisture/density relation.

This result shows the same trend with the consistency limits and the moisture content results. It was observed that the Ch-derived soil has optimum moisture content at maximum mean value, which lies above FMWH, (1997), the recommended specification of 18% optimum moisture content at maximum for fills and subgrade soil, whereas the OGe-derived soil has a mean value that lies within the recommended specification. This implies that OGe-derived soil has preferred engineering properties to that of Ch-derived soil as subgrade and fills soil. Laboratory California Bearing Ratio Tests Results of laboratory California Bearing Ratio tests are presented in (Table 4). The California Bearing Ratio values of the subgrade soils also differ on account of clay mineralogical characteristics, since textural characteristics are practically the same.

This is because the water-absorbing capacity of the charnockite-derived soil is greater than that of the kaolinite-dominated granite-derived soil. The obtained result indicates that Ch-derived soil has the lower bearing capacity property compared to OGe-derived soils. Furthermore, the statistical analysis between the CBR values of Ch- and OGe-derived soil samples indicates that there is a significant difference with 86 coefficients of variation, which account for a 75.61% reduction in the strength values between the two soil types. Reported that the degree of change (reduction) in the strength properties values is directly proportional to the amount of moisture content absorption.

Hence, the difference in their respective engineering properties and behaviors is primarily due to differences in their mineralogical characteristics, as their texture is practically the same. Uniaxial Compressive Strength Table 4 further reveals the uniaxial compressive strength characteristics of the two soils. The charnockite-derived soil has a lower uniaxial compressive strength than the granite-derived soil. The average uniaxial compressive strength of the coarse granite-derived soil is about 204.46 MPa, while that of the charnockite-derived soil is about 179.62 MPa. The actual clay mineral contents in the two soils may be the basic reasons for these differences.

Table 4 Summary of Strength Properties and Statistical Analysis of the Studied Soils

SN	CBR	CV% (RIS)	OMC	CV%	MDD (kg/m ³)	CV%	UCS	Soil Type
1	4	-	20.80	-	1814	-	215.6	Ch
2	1	-	18.93	-	1835	-	164.2	Ch
3	4	-	17.96	-	1883	-	193.3	Ch
4	2	-	19.71	-	1618	-	169	Ch
5	4	86	16.10	15.05	1924	6.79	156	Ch
Mean	3	(76.61%)	18.7	(27.20%)	1814.8	(9.16%)	179.62	-
1	6	-	16	-	1883	-	192.4	OGe
2	9	-	11.4	-	2056	-	202.3	OGe
3	28	-	16.2	-	1852	-	262.4	OGe
4	6	8	15.4	-	2091	-	174.4	OGe
5	12.5	86	10.2	15.05	2107	6.79	190.8	OGe
Mean	12.3	(76.61%)	13.84	(27.20%)	1999	(9.16%)	204.46	

% RIS (MC) = % Reduction in Strength

One-sample statistics

	N	Mean	Std. Deviation	Std. Error Mean
Ch	6	33.3100	18.13791	7.40477
OGe	6	33.3467	18.82753	7.68631

One-Sample Test

	Test Value = 0					
	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Ch	4.498	5	.006	33.31000	14.2754	52.3446
OGe	4.338	5	.007	33.34667	13.5884	53.1049

4. CONCLUSION

This study carried out on the influence of mineralogical compositions on geotechnical properties of two genetically different soils around the northern part of Ondo State, Nigeria, underlain by charnockites (Ch) and granite (OGe) rock types, revealed the following: OGe- and Ch-derived soils have practically the same textural characteristics. Statistical analysis showed that there is no significant soil variation based on the particle size. Mineralogical analysis shows that OGe-derived soils have a dominance of low-activity clay mineral 1:1, such as kaolinite, while the Ch-derived soils have a dominance of high-activity clay minerals 2:1, such as illite and vermiculite. OGe-derived soils dominant clay minerals impact the limitation on the hydrophilic characteristics of the soil, while Ch-derived soils dominant clay minerals enhance the hydrophilic characteristics.

Ch-derived soil has a higher NMC value in comparison with the OGe. The statistical analysis between Ch- and OGe-derived soil samples indicates that there is a significant difference with a 20.4 coefficient of variations, which accounts for a 34.18% increase in moisture content. Each soil type has a distinct field on the plasticity chart, depicting different engineering characteristics and parameters. Ch-derived soil has higher plasticity and compressibility tendencies in comparison with OGe-derived soils. Furthermore, the statistical analysis between Ch- and OGe-derived soil samples indicates that there is a significant difference with 20 coefficients of variation, which account for a 32.78% difference in their plasticity property.

Ch-derived soil has an OMC mean value of 18.7%, which lies above the recommended specification for fills and subgrade soil, whereas the OGe-derived soil has a mean value that falls within the recommended specification. The statistical analysis between Ch and OGe CBR values indicates a significant difference of 86 coefficients of variation, which accounts for a 75.61% reduction in the strength values between the two soil types. The OGe-derived soil has different and preferred engineering properties to Ch-derived soil due to mineralogical differences. Hence, mineralogical characteristics of parent materials are responsible for behavioral differences in the engineering properties of soils derived from genetically different parent rock materials.

Acknowledgement

We thank masters Kehinde Bosikun, Samuel Ikubuwaje, and Goodness Ikubuwaje, who assisted in the sample collections and laboratory tests. Furthermore, the inestimable supervisory role of Prof. Obasi RA and Dr. Afolagoye LA was highly appreciated.

Author contributions

The work was carried out in collaboration among all the authors. Author 1 designed the study, performed analyses, and wrote the first draft of the manuscript. Author 2 proofread the manuscript and made necessary corrections. Authors 3, peruse the updated manuscript and provide the link of the Discovery Scientific Society.

Informed consent

Not applicable.

Ethical approval

Not applicable.

Conflicts of interests

The authors declare that there are no conflicts of interests.

Funding

The study has not received any external funding.

Data and materials availability

All data associated with this study are present in the paper.

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