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Characterisation of soils derived from different parent rocks from north central Nigeria

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Mineralogy and geotechnical properties of residual lateritic soils derived from sandstone and migmatite–gneiss (MG) were compared. The aim was to determine the influence of the parent rock geology of sandstone and MG on their engineering properties. This was done using the statistical method of Student's *t*-test. Thin sections show that the MG samples are rich in feldspars and micas with up to 45 and 23% modal estimates, respectively. The dominant clay mineral in the two soils was kaolinite, while the dominant oxides were silicon dioxide, aluminium oxide and ferric oxide. The silica/sesquioxide ratio of the MG-derived soils (MGS) ranged from 1·7 to 3·2 while those of sandstone-derived soils (SS) were 2·9–6·6. SS samples which contained essentially quartz grains exhibited better compaction characteristics, higher California bearing ratio and lower plasticity than MGS. Better engineering properties exhibited by SS can be attributed to the high quartz content present in the parent rock. Feldspars and micas present in MG are weathered into plastic and hydrophilic clay minerals. These are likely to have a negative impact on the engineering properties of the derived soils. Statistical treatment of all determined engineering parameters showed significant differences in all cases except in relation to specific gravity, permeability and compressibility.

1. Introduction

Laterites and lateritic soils are the most common soils occurring in the tropical and subtropical regions of the world. Blight (2012: p. 14) described them as 'highly weathered and altered residual soils, low in silica, that contain a sufficient concentration of the sesquioxides of iron and aluminum to have been cemented to some degree. Depending on the extent of the emplacement, the material could be described as lateritic or as laterite'. The properties or geotechnical behaviour of laterite and lateritic soils depend largely on the mineralogical composition of parent rock they develop from, micro-fabric and geochemical environmental conditions in addition to climate, topography and weathering time. In Nigeria and the most tropical world, they serve as common construction and foundation materials (Adeyemi *et al.*, 2015; Gidigasu, 1976). The link between the mineralogy of parent rocks and engineering properties of the derived lateritic soils in the southwestern part of Nigeria has been studied (Adebisi, 2010; Adeyemi *et al.*, 1999; Badmus, 2010; Bayewu *et al.*, 2012). However, most of these works, according to Adeyemi (1995), placed little emphasis on the quantitative aspect of the influence of the parent rock on the engineering behaviour of lateritic soils, which is more important in the foundation design of structures. In addition, the north central part of Nigeria has a drier and warmer climate than the southwest, hence the necessity to study soils from this climatic zone.

To investigate the quantitative aspect of the influence of parent rock on the engineering behaviour of lateritic soils in climatic zones that are drier and warmer than what is observed in southwestern Nigeria, a series of tests was conducted (such as index tests, engineering tests, X-ray diffraction (XRD) and X-ray fluorescence (XRF)) on the lateritic soils employed as construction materials (sub-grade and base material) in Ilorin and Mokwa, north central Nigeria. In addition, an attempt was made to link the petrological and textural characteristics of the two major rocks from which these lateritic soils were derived with the geotechnical properties of the lateritic soils. This paper presents and compares the influence the different parent rocks might have on the index and mechanical properties of lateritic soils derived from them using the statistical *t*-test.

1.1 Study area

Two locations were selected for this study. The first location is situated at Tungaruwa, a community about 2 km away from Mokwa on latitude 9°12′ 29·04″N and longitude 4°52′ 27·54″E. The second location was at Shao near Ilorin on latitude 8°33′ 16·12″N and longitude 4°30′ 43·80″E. Figure 1 shows the locations and geology of the two sampling locations. The studied soils were developed over the Sandstone Formation of the Northern Bida Basin and

migmatite–gneiss (MG) of the Precambrian Basement Complex (Figure 1).

1.2 Method

The two locations selected for this study have similar topography and relief but varying bedrocks. In addition, they both fall within the same climatic zone (Figure 2). The locations belong to the hot humid subclimate (zone 3), with an average annual rainfall between 1183 and 1787 mm (FMW, 2013). Choosing locations with similar topography and climate will help eliminate the possibility of attributing the observed differences in the geotechnical characteristics (if any) of these residual soils to pedogenic factors other than their parent rocks. Petrographic studies of the rocks were undertaken in order to determine whether there is a link between the properties of the rocks and those of the derived soils. Thin sections of the collected rock samples were prepared. Petrographic study was carried out in accordance with the standard procedures for petrographic examination of rocks given by the International Society for Rock Mechanics (ISRM, 1987). Mineralogical and textural properties were investigated by using a polarising microscope and analysing the images. The modal composition was obtained using the point counting method.

Thirty-two bulk disturbed samples were collected systematically within an area of 525 m^2 at each location from abandoned borrow pits. Index and engineering tests including specific gravity, consistency limits, grain-size analysis, California bearing ratio (CBR), compaction test, permeability test and consolidation test were carried out on all samples taken from both locations. The moisture dry density relationship was determined after the samples were compacted using modified American Association of State Highway and Transportation Officials (Aashto) energy at optimum moisture content (OMC). The permeability test was performed under falling head conditions using a rigid-wall compaction mould permeameter. All tests were carried out following the procedure of BS 1337 (BSI, 1990). XRF spectroscopy was used to quantitatively determine the major elements in the soil samples. Soil samples from both parent rocks were pulverised in a tungsten-carbide milling pot to achieve particle sizes <75 μm. The samples were dried at 100°C and roasted at 1000°C to determine loss on ignition (LOI) values. 1 g of the sample was mixed with 6 g lithium teraborate flux and fused at 1050°C to make a stable fused glass bead. The mineralogical analysis of the studied soils was carried out using a PANalytical X'Pert Pro powder diffractometer in θ–θ configuration with an X'Celerator detector and variable divergence and fixed receiving slits with iron (Fe)-filtered Co-Kα radiation ($\lambda = 0{\cdot}1789$ nm). The samples were prepared according to the standardised Panalytical back-loading system identifying different phases with X'Pert High score plus software.

Some chemical weathering indices, which have proved effective on residual soils for weathering intensity prediction (Duzgoren-Aydin *et al.*, 2002), were calculated using the equations given below. ba_3 refers to the ratio of potassium (K)–sodium (NA)–magnesium (Mg) to aluminium (Al), CIA is the chemical index of alteration, while bases:R_2O_3 refers to the bases/sesquioxide ratio (Nesbitt and Young, 1982; Harrassowitz, 1926 (cited in Rocha Filho *et al.* (1985)); Colman, 1982).

$$1.\quad \mathrm{CIA} = \frac{100 \times \mathrm{Al_2O_3}}{\mathrm{Al_2O_3} + \mathrm{K_2O} + \mathrm{Na_2O} + \mathrm{Na_2O} + \mathrm{CaO}}$$

$$2.\quad \mathrm{ba_3} = \frac{\mathrm{K_2O} + \mathrm{Na_2O} + \mathrm{MgO}}{\mathrm{Al_2O_3}}$$

$$3.\quad \mathrm{Bases{:}R_2O_3} = \frac{\mathrm{K_2\,O} + \mathrm{K_2O} + \mathrm{CaO} + \mathrm{MgO}}{\mathrm{Al_2O_3} + \mathrm{Fe_2O_3} + \mathrm{TiO_2}}$$

The ratios of silica (SiO_2) to sesquioxide (Fe_2O_3, Al_2O_3) of the studied soils were computed using Equation 4 (Bell, 1993; Gidigasu, 1976). The molecular weights used in this work are silicon dioxide (SiO_2): 60, ferric oxide (Fe_2O_3): 160 and aluminium oxide (Al_2O_3): 102

$$4.\quad \mathrm{Silica{:}sesquioxide\ molar\ ratio} = \frac{(\%\ \mathrm{SiO_2/wt\ of\ SiO_2})}{(\%\ \mathrm{Al_2O_3/wt\ of\ Al_2O_3}) + (\%\ \mathrm{Fe_2O_3/wt\ of\ Fe_2O_3})}$$

where wt denotes the molecular weight.

The average values of each determined parameter were compared in order to determine whether there is an influence of the parent rocks on their index and engineering properties. This was done using the statistical Student's *t*-test. This test helps to decide if the observed difference in two sets of measurements is legitimate or just due to randomness. When

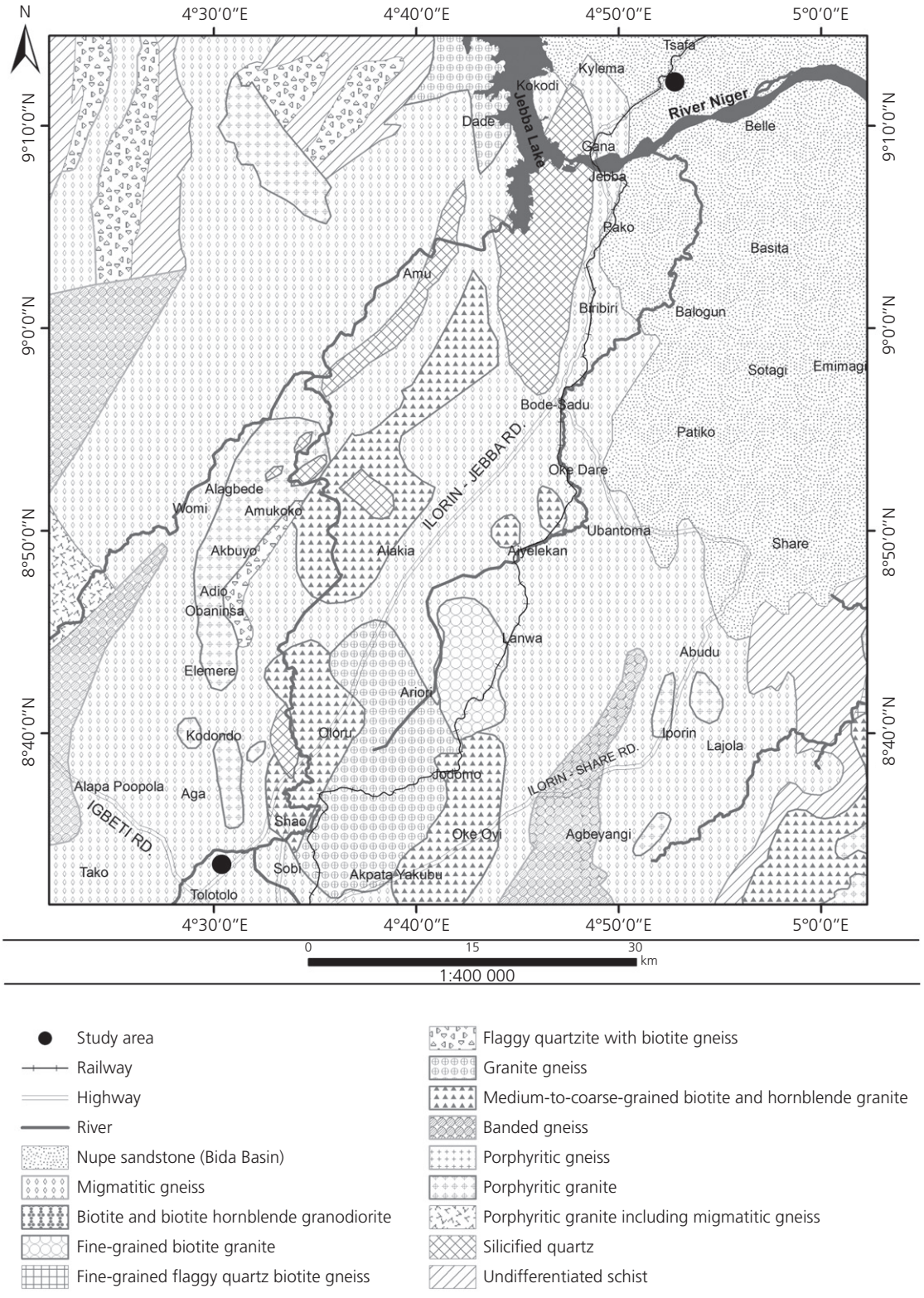


Figure 1. Geological map of the study areas source: modified from NGSA (2007)

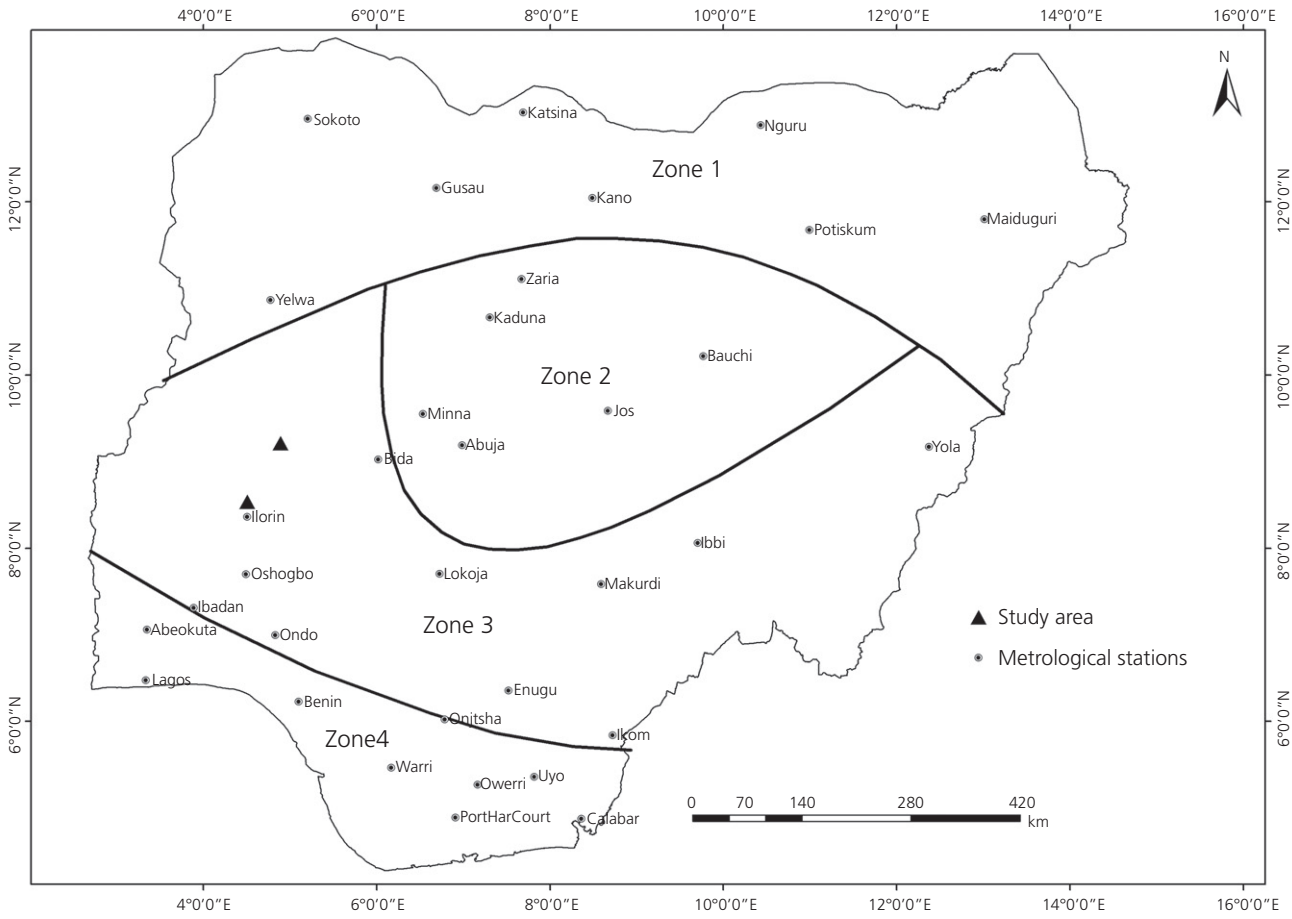


Figure 2. Map of Nigeria showing the climatological zones of the two sampling locations (source: modified from FMW (2013))

the calculated '*t*' is higher than the '*t*' in the table, the difference is judged to be significant.

2. Petrography

The MG hand specimen consists of mafic gneissic bands that are more pronounced than the grey colour granitic bands. The granitic portion in order of abundance consists of quartz, feldspars, biotite and muscovite, while the gneissic portion consists of hornblende, biotite and plagioclase. Modal analysis of the two parent rocks presented in Table 1 reveals quartz as the predominant mineral. The MG samples are rich in feldspars, micas and hornblende while the sandstone samples consist essentially of medium-grained, sub-angular to sub-rounded monocrystalline quartz grains with traces of accessory minerals.

3. Mineralogy

Quantitative interpretation of patterns (Figures 3 and 4) obtained from XRD analysis showed that the dominant clay mineral in the two genetically different soils is kaolinite. It ranges from 38·78 to 68·92% in the MG-derived soil (MGS) samples and from 27·99 to 58·1% in the sandstone-derived soil (SS) samples. Other identified minerals in the MGS listed in order of their abundance are quartz, goethite, muscovite and traces of microcline and anatase. Those identified in the SS samples are quartz, microcline and traces of haematite and anatase. A few samples of MGS contain traces of haematite and gibbsite, while some of the SS samples contain zircon, muscovite and goethite. Hydrated iron oxides in the form of goethite and gibbsite are prevalent in the MGS, while the non-hydrated purer form of iron is prevalent in the SS soil. This difference suggests that the MGS is more lateritised than the SS one (Remillon, 1967). Tables 2 and 3 present the relative portions of mineral components of soils derived from the two parent rocks, while Table 4 presents the result of a statistical *t*-test of the mineral content of the studied soils. It shows that there is a significant difference in mineral contents of soils derived from the two parent rocks.

Table 1. Modal composition of migmatite and sandstone samples

	MG samples				Sandstone samples		
Mineral constituent: %	M1	M2	M3	M4	SS1	SS2	SS3
Quartz	25	30	30	40	95	96	95
Microcline	10	8	5	15	—	—	—
Plagioclase	15	20	30	25	—	—	—
Biotite	25	15	15	5	—	—	—
Muscovite	—	5	—	15	—	—	—
Hornblende	25	22	20	—	—	—	—
Accessory mineral					5	4	5

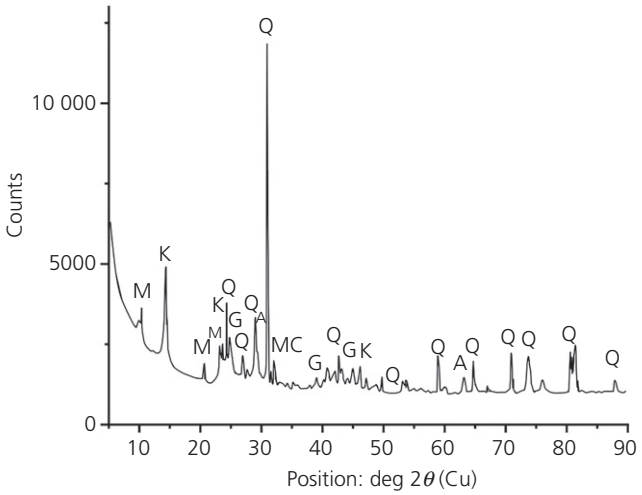


Figure 3. XRD of a MGS sample (muscovite (M), kaolinite (K), quartz (Q), anatase (A), goethite (G), microcline (MC))

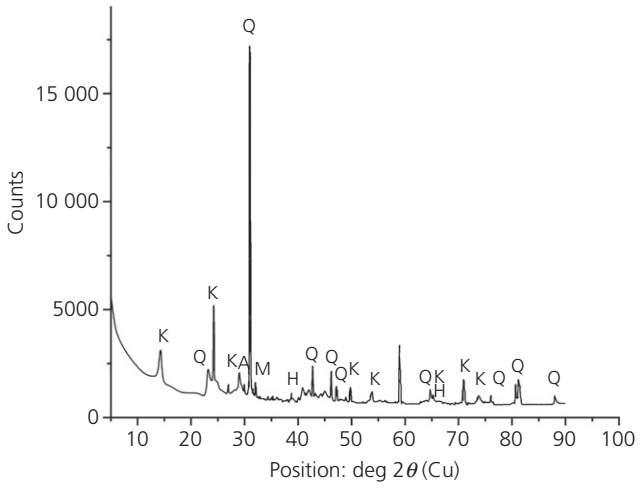


Figure 4. XRD of SS sample (kaolinite (K), quartz (Q), anatase (A), muscovite (M), haematite (H))

3.1 Geochemistry and weathering indices of the studied soils

The soil samples are products of weathering of sandstone and MG. Tables 5 and 6 present the chemical composition of soils derived from the two parent rocks. The main compositions of the SS samples are silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), ferric oxide (Fe_2O_3), potassium dioxide (KO_2) and titanium oxide (TiO_2), whereas the MGS samples consist mainly of silicon dioxide, aluminium oxide, ferric oxide, titanium oxide and potassium oxide (K_2O). Other oxides including manganese oxide (MnO), magnesium oxide (MgO), calcium oxide (CaO), sodium oxide (Na_2O), phosphorus pentoxide (P_2O_5), chromium (III) oxide (Cr_2O_3), nickel oxide (NiO), vanadium pentoxide (V_2O_5) and zirconium dioxide (ZrO_2) were detected in minor quantities in both genetically different soils. The sum of these minor oxides is about 0·5% in the SS sample and about 1% in the MGS one. Table 7 presents the summary of the Student's statistical *t*-test on the chemical composition of the studied soils. There is significant difference in the elemental abundance of the set of two soils, except for titanium oxide.

Chemical weathering indices are principally based on the basic assumption that distributions of chemical elements as well as LOI along profiles are mainly regulated by the degree of weathering (Duzgoren-Aydin *et al.*, 2002). In general, as the intensity of weathering increases, calcium (Ca), sodium (Na), potassium (K) and silicon (Si) decrease, whereas aluminium (Al), iron (Fe), titanium (Ti), manganese (Mn) and LOI increase. Tables 8 and 9 present the weathering indices of the soils derived from the two parent rocks. The LOI of sandstone and MG-derived lateritic soil ranges from 7·55 to 11·5% and 8·52 to 15·64%, respectively. The average sesquioxide content of MGS is 42·27% while that of the SS sample is 28·73%. It is obvious from a comparison of the weathering indices for the two soils that the MGS sample appears to be more laterised than the SS soil. However, this decision might be misleading because the two studied soils do not have the same parent rock and the observed differences in their weathering indices might just be due to differences in the parent rock mineralogy. For

Table 2. Quantitative interpretation of the XRDs of MGS samples

Sample number	Kaolinite: %	Quartz: %	Goethite: %	Muscovite: %	Microcline: %	Anatase: %
BMB 1	59·73	15·87	15·30	2·74	4·09	2·26
BMB 2	60·43	13·85	12·85	6·50	4·05	2·31
BMB 3	61·99	11·95	7·71	10·78	6·65	0·93
BMB 4	46·17	22·85	13·50	11·84	0·00	5·63
BMB 5	44·94	24·08	12·29	11·68	1·87	5·14
BMB 6	39·17	40·98	8·76	0·00	7·12	3·96
BMB 7	47·07	21·04	11·66	10·53	4·82	4·88
BMB 8	66·45	11·25	9·42	5·28	4·85	2·74
BMB 9	38·75	22·83	8·97	9·08	3·85	4·11
BMB 10	45·27	17·77	14·52	12·46	4·31	5·67
BMB 11	46·21	14·04	10·37	12·49	1·49	5·18
BMB 12	62·25	17·58	9·82	4·09	2·85	3·41
BMB 13	53·74	24·46	6·23	1·50	2·35	1·84
BMB 14	53·08	17·98	7·44	3·24	4·46	2·94
BMB 15	44·98	22·00	10·62	11·59	6·03	4·78
BMB 16	66·10	12·33	7·30	7·30	3·54	3·43
BMB 17	64·64	9·67	10·14	5·03	3·33	3·37
BMB 18	62·43	14·16	8·43	6·25	4·46	2·87
BMB 20	55·60	16·74	8·86	3·91	0·00	2·84
BMB 21	56·74	22·64	8·34	5·66	3·86	2·77
BMB 22	61·35	13·33	10·78	7·51	2·64	3·30
BMB 23	68·92	9·04	12·28	4·12	2·54	3·11
BMB 24	59·44	22·81	11·50	0·00	1·63	2·72
BMB 25	68·15	12·55	10·18	1·56	4·31	3·24
BMB 26	66·65	11·80	10·80	4·82	2·77	3·16
BMB 27	63·24	14·73	11·63	4·51	2·90	2·99
BMB 28	65·22	13·20	11·89	4·41	2·13	3·14
BMB 29	63·80	13·36	11·77	4·01	3·93	3·13
BMB 30	64·48	12·76	11·32	3·83	4·42	3·19
BMB 31	62·89	12·09	10·56	6·03	5·44	2·99
BMB 32	60·17	14·60	11·41	6·28	0·00	3·38
Range	38·75–68·92	9·04–40·98	6·23–15·3	0–12·49	0–7·12	0·93–5·67
Average	57·42	16·91	10·54	6·10	3·44	3·40

instance, the studied sandstone samples consist essentially of quartz (SiO_2) grains with no ferromagnetic minerals. The only source of other aluminosilicates in sandstones is feldspar pebbles embedded in the matrix of the lithified sandstone. The expected residual weathering products are quartz sand and clay (Huat *et al.*, 2004). The silica–sesquioxide ratio for the MGS sample ranges from 1·7 to 3·2 while that of the SS sample is from 2·9 to 6·6. This indicates that the MGS sample is ferruginous in nature, while the sandstone-derived one classifies as clay and quartz-rich soil (Fookes, 1997). Only few of the MGS samples classify as lateritic soils, while all of the SS samples classify as non-lateritic soil. Since this ratio is an indication of the degree of laterisation, this implies that the MGS is more lateritised than the sandstone-derived one.

3.2 Relationship between geochemistry and mineralogy

Abimbola *et al.* (1999) identified kaolinite as a precursor for iron stone deposit. For the MGS, a strong positive correlation was found between the amount of iron oxide and amount of kaolinite; the equation for the relationship is

$$\%Fe_2O_3 = 0{\cdot}17\%\ \text{kaolinite} + 7{\cdot}16 \quad (5)$$

For the SS, a weaker correlation was found between the amount of iron oxide and the kaolinite content; the equation for the relationship is

$$\%Fe_2O_3 = 0{\cdot}03\%\ \text{kaolinite} + 7{\cdot}19 \quad (6)$$

This result is in agreement with the work of Adebisi (2010).

A strong positive correlation was also found between the amount of iron and aluminium sesquioxide and the amount of kaolinite in the studied soils. The equation for the relationships

Table 3. Quantitative interpretation of the XRDs of SS samples

Sample number	Kaolinite: %	Quartz: %	Microcline: %	Anatase: %	Haematite: %
BMS1	45·47	42·61	7·80	2·85	1·27
BMS 2	46·42	40·83	8·03	3·01	1·71
BMS 3	51·99	35·76	7·47	2·63	1·59
BMS 4	51·46	34·60	8·36	2·35	2·70
BMS 5	43·66	47·01	6·14	2·04	1·15
BMS 6	57·74	30·32	7·44	3·00	1·51
BMS 8	53·89	34·98	7·15	2·65	1·34
BMS 9	46·93	42·95	6·20	2·16	1·76
BMS 10	47·00	43·44	6·30	2·18	1·08
BMS 11	49·27	42·39	3·80	2·38	2·16
BMS 12	51·98	39·75	4·38	2·64	1·25
BMS 13	58·10	31·36	5·90	2·79	1·85
BMS 14	49·07	42·59	4·48	2·24	1·63
BMS 15	49·23	43·37	3·58	2·18	1·65
BMS 16	51·26	40·63	3·88	2·45	1·78
BMS 17	50·47	34·99	2·90	2·39	2·18
BMS 18	47·68	43·71	4·23	2·34	2·05
BMS 19	45·50	40·40	7·10	4·06	2·90
BMS 20	44·80	40·11	4·80	2·06	1·65
BMS 21	36·29	34·55	5·32	3·69	3·53
BMS 22	38·79	42·95	3·99	1·81	6·46
BMS 23	49·18	42·38	0·00	4·68	3·77
BMS 24	57·02	38·65	0·00	2·77	1·56
BMS 25	57·48	31·20	0·00	2·60	1·69
BMS 26	43·55	47·63	5·71	2·06	1·04
BMS 27	56·01	30·34	8·57	3·18	1·90
BMS 28	37·20	44·50	11·80	3·50	3·04
BMS 29	37·23	46·08	4·74	2·33	2·10
BMS 30	32·64	49·04	4·54	2·44	2·02
BMS 31	27·99	60·81	7·85	2·23	1·12
BMS 32	37·18	54·78	5·26	1·54	1·24
Range	27·99–58·1	30·32–60·81	0–11·8	1·54–4.68	1·04–6·46
Average	46·85	41·12	5·41	2·62	2·02

Table 4. Results of statistical *t*-test of the mineral content of the studied soils

Mineral	*t*-test parameter	Value	Nature of difference
Kaolinite	*t*-calculated	4·99	Significant
	t-table	1·67	
Quartz	*t*-calculated	14·39	Significant
	t-table	1·67	
Microcline	*t*-calculated	3·47	Significant
	t-cable	1·67	
Anatase	*t*-calculated	3·43	Significant
	t-table	1·68	

for the migmatite and SS are

$$\%\text{sesquioxide} = 0{\cdot}24\%\ \text{kaolinite} + 28{\cdot}36(\text{MGS}) \quad (7)$$

$$\%\text{sesquioxide} = 0{\cdot}26\%\ \text{kaolinite} + 18{\cdot}9(\text{SS}) \quad (8)$$

It is observed that a stronger correlation exists between MGS and its geochemistry and mineralogy. These results support the fact that iron oxide and sesquioxide content increase with increasing kaolinite content; however, the weaker correlation coefficient associated with the SS may be as a result of its lower iron oxide content. According to Roa and Mahashary (1981), the degree of laterisation of a soil is usually dictated by the amount of iron oxide present in it, therefore it can be said that kaolinite content increases with increasing degree of laterisation. An inverse relationship was found between the silica–sesquioxide ratio and the amount of kaolinite present in the studied soils

$$\text{Silica/sesquioxide ratio} = -0{\cdot}012\%\ \text{kaolinite} + 1{\cdot}9(\text{MGS}) \quad (9)$$

$$\text{Silica/sesquioxide ratio} = -0{\cdot}04\%\ \text{kaolinite} + 4{\cdot}04(\text{SS}) \quad (10)$$

This implies that kaolinite content decreases with increase in silica–sesquioxide ratio. This is an indication that weathering

Table 5. Chemical composition of some MGS samples

Amount of oxide: %	BMB 22	BMB 23	BMB 24	BMB 25	BMB 26	BMB 27	BMB 28	BMB 29	BMB 30	BMB 31	BMB 32
Silicon dioxide	39·36	40·28	42·51	40·77	38·36	39·29	39·22	41·23	40·45	40·39	38·17
Titanium oxide	1·44	1·46	1·14	1·61	1·39	1·33	1·40	1·35	1·52	1·46	1·30
Aluminium oxide	24·15	28·51	21·03	26·39	26·44	24·73	25·55	26·24	25·12	25·86	25·61
Ferric oxide	20·61	20·66	21·98	17·01	18·50	20·17	20·05	17·23	18·59	17·04	20·31
Manganese oxide	0·69	0·21	1·35	0·31	0·74	0·91	0·61	0·56	0·69	0·56	0·67
Magnesium oxide	0·32	0·41	0·23	0·49	0·45	0·41	0·41	0·37	0·55	0·54	0·31
Calcium oxide	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01
Sodium oxide	0·03	0·02	0·04	0·02	0·04	0·05	0·03	0·02	0·03	0·03	0·03
Potassium oxide	0·63	0·67	0·58	0·83	0·75	0·72	0·70	0·65	0·87	0·88	0·59
Phosphorus pentoxide	0·03	0·02	0·04	0·03	0·02	0·02	0·02	0·02	0·03	0·03	0·03
Chromium (III) oxide	0·03	0·03	0·03	0·02	0·02	0·03	0·03	0·04	0·03	0·02	0·03
Nickel oxide	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·02	0·01	0·01	0·01
Vanadium pentoxide	0·05	0·05	0·05	0·05	0·05	0·05	0·05	0·04	0·05	0·04	0·05
Zirconium oxide	0·09	0·06	0·12	0·08	0·07	0·08	0·08	0·08	0·09	0·08	0·06
Copper oxide	0·003	0·004	0·004	0·003	0·004	0·005	0·003	0·003	0·004	0·003	0·003
LOI	11·61	7·47	10·46	11·48	12·72	11·49	11·49	11·32	11·44	11·46	11·90
Total	99·05	99·88	99·60	99·12	99·57	99·30	99·65	99·18	99·49	98·43	99·07

Table 6. Chemical composition of some SS samples

Amount of oxide: %	BMS 22	BMS 23	BMS 24	BMS 25	BMS 26	BMS 27	BMS 28	BMS 29	BMS 30	BMS 31	BMS 32
Silicon dioxide	55·26	52·92	57·98	52·06	65·79	53·03	56·87	55·95	61·58	68·96	68·00
Titanium oxide	1·26	1·43	1·38	1·37	1·35	1·49	1·36	1·46	1·79	1·69	1·45
Aluminium oxide	19·06	22·10	20·04	23·06	15·98	22·26	19·21	21·60	19·34	14·08	13·97
Ferric oxide	12·59	10·91	9·41	11·55	7·66	9·96	10·26	8·56	6·76	5·93	7·21
Manganese oxide	0·04	0·04	0·03	0·06	0·04	0·04	0·03	0·03	0·04	0·04	0·05
Magnesium oxide	0·16	0·21	0·18	0·20	0·13	0·21	0·17	0·21	0·18	0·12	0·10
Calcium oxide	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01	0·01
Sodium oxide	0·05	0·04	0·06	0·05	0·06	0·07	0·05	0·05	0·07	0·08	0·07
Potassium oxide	1·09	1·10	1·12	0·98	1·18	1·06	1·12	1·11	1·35	1·53	0·37
Phosphorus pentoxide	0·03	0·03	0·03	0·02	0·02	0·04	0·04	0·04	0·05	0·03	0·03
Chromium (III) oxide	0·02	0·02	0·01	0·02	0·01	0·02	0·01	0·01	0·02	0·01	0·01
Nickel oxide	0·00	0·01	0·00	0·01	0·00	0·01	0·00	0·01	0·01	0·01	0·00
Vanadium pentoxide	0·03	0·03	0·03	0·03	0·02	0·03	0·03	0·03	0·03	0·02	0·02
Zirconium oxide	0·10	0·11	0·13	0·09	0·23	0·10	0·12	0·12	0·14	0·19	0·17
Copper oxide	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001
LOI	9·77	10·14	9·11	10·04	7·39	10·70	9·75	10·17	8·75	6·80	6·87
Total	99·47	99·10	99·53	99·55	99·90	99·02	99·03	99·35	100·11	99·51	99·33

in the study area causes more of ferruginisation than bauxinisation (Adebisi, 2010; Adeyemi, 1992; Bolarinwa and Elueze, 2005; Gidigasu, 1976).

3.3 Influence of parent rock on the Atterberg indices and engineering classification of the studied soils

Since the mineral composition and texture of pre-existing rocks determine the characteristics of the soil formed, the petrographic characteristics of the rocks can be related to the geotechnical characteristics of the soils (Shafique *et al.*, 2012). Compared with MGS, SS has lower liquid limit and flow index. According to Mitchell and Soga (2005), this implies that the MGS samples are softer soils with lower remoulded strength and lower shear strength compared with SS samples (Table 10). A plasticity classification chart (Figure 5) indicates that the MGS samples are of medium plasticity, while the SS are of low to medium plasticity.

Table 11 presents the results of the statistical *t*-test conducted on the Atterberg indices data of the studied soils. Student's

Table 7. Influence of parent rock on the geochemical properties of the studied soil

Oxide	*t*-test parameter	Value	Nature of difference
Silicon dioxide	*t*-statistic	13·47	Significant
	t-critical	1·67	
Titanium oxide	*t*-statistic	1·56	Insignificant
	t-critical	1·67	
Aluminium oxide	*t*-statistic	9·18	Significant
	t-critical	1·67	
Ferric oxide	*t*-statistic	13·06	Significant
	t-critical	1·68	
Sesquioxide	*t*-statistic	14·17	Significant
	t-critical	1·67	

Table 8. Some weathering indices of MGS samples

Sample number	LOI	ba_3	CIA	R_2O_3 ratio	SS ratio
BMB 1	9·62	0·07	95·86	0·04	2·8
BMB 2	10·33	0·09	94·79	0·05	2·2
BMB 3	10·64	0·08	95·06	0·05	2·0
BMB 4	11·16	0·06	96·33	0·03	2·1
BMB 6	9·39	0·06	96·35	0·03	2·1
BMB 7	10·87	0·06	95·37	0·04	3·2
BMB 8	11·42	0·08	94·96	0·05	2·1
BMB 9	10·23	0·06	96·21	0·04	1·8
BMB 10	11·03	0·07	95·38	0·05	2·2
BMB 11	11·84	0·06	96·09	0·04	2·0
BMB 12	11·94	0·07	96·03	0·04	1·9
BMB 14	11·21	0·05	97·18	0·03	1·8
BMB 15	10·67	0·09	93·58	0·06	3·0
BMB 16	11·21	0·06	96·09	0·04	2·0
BMB 17	15·64	0·07	95·48	0·05	2·1
BMB 18	11·05	0·06	96·54	0·03	1·9
BMB 20	10·40	0·03	97·85	0·02	1·7
BMB 21	10·11	0·08	95·54	0·05	2·0
BMB 22	11·61	0·08	95·40	0·05	2·3
BMB 24	10·46	0·07	95·82	0·04	2·3
BMB 25	11·48	0·04	97·33	0·02	1·8
BMB 26	12·72	0·04	97·60	0·02	1·6
BMB 27	11·49	0·04	97·09	0·02	2·1
BMB 28	11·49	0·05	96·83	0·03	1·9
BMB 29	11·32	0·05	97·08	0·03	1·7
BMB 30	11·44	0·05	96·95	0·03	1·8
BMB 31	11·46	0·04	97·22	0·02	1·7
BMB 32	11·90	0·04	97·49	0·02	1·9

t-test was used to check if the observed differences in the index properties of this soil are significant. The result showed that the observed differences are significant in all cases except for specific gravity (Table 11). The lower plasticity and linear shrinkage of the SS is due to the fact that the parent rock is rich in sandstone. This parent rock is expected to produce coarse-grained material, which will not exhibit plastic behaviour even when ground to clay-size particles as a result of prolonged weathering. This can also be related to the type and amount of clay mineral present in them. XRD results show that, on average, kaolinite and quartz make up about 80% of the sandstone soils but are much lower in the MGS sample. Kaolinite is known to exhibit lower plasticity and shrink and swell potential, while quartz is non-plastic.

Table 9. Some weathering indices of SS samples

Sample number	LOI	ba_3	CIA	R_2O_3 ratio	SS ratio
BMS 1	9·42	0·05	94·99	0·04	3·6
BMS 2	10·08	0·04	95·78	0·04	2·9
BMS 3	8·60	0·06	94·50	0·05	3·9
BMS 4	8·61	0·05	95·54	0·04	3·4
BMS 5	7·55	0·08	92·25	0·06	5·0
BMS 6	9·40	0·05	95·43	0·04	3·1
BMS 8	9·29	0·06	94·44	0·05	3·7
BMS 9	7·67	0·07	93·31	0·05	4·7
BMS 10	8·89	0·06	93·91	0·05	4·6
BMS 11	8·37	0·06	93·99	0·05	4·5
BMS 12	8·84	0·06	93·91	0·05	4·2
BMS 13	9·10	0·05	95·16	0·04	3·3
BMS 14	8·25	0·07	93·41	0·05	4·8
BMS 15	8·37	0·07	93·26	0·05	4·8
BMS 16	9·06	0·07	93·87	0·05	4·3
BMS 18	9·11	0·06	94·24	0·05	3·7
BMS 19	10·01	0·08	92·71	0·05	4·9
BMS 21	11·15	0·06	94·78	0·04	3·2
BMS 22	9·77	0·07	93·44	0·05	4·0
BMS 23	10·14	0·05	95·17	0·04	2·9
BMS 24	9·11	0·06	94·34	0·04	3·5
BMS 25	10·04	0·05	95·06	0·04	3·1
BMS 26	7·39	0·06	94·40	0·04	3·8
BMS 27	10·70	0·05	95·69	0·03	2·9
BMS 28	9·75	0·08	92·73	0·06	5·4
BMS 29	10·17	0·05	95·15	0·04	3·2
BMS 30	8·75	0·06	94·23	0·04	3·8
BMS 32	6·87	0·05	94·87	0·04	3·5

The MGS samples have higher natural moisture content than the SS ones. This can also be related to the fine contents of these soils. The amount of fine-grained materials in the MGS ranges from 20 to 54%, while the fine content of the SS ranges from 11 to 35%. The higher amount of fines in the MG soil can be attributed to the high feldspar and ferromagnetic minerals in the parent rock, which are expected to weather into fine-grained materials. The linear shrinkage of the SS ranges from 1·5 to 7·3%, while that of the MGS ranges from 2·2 to 10·1%. According to Ola (1980), the SS samples classify as soils with a marginal degree of expansion, while the MGS ones classify as soils with marginal to critical degree of expansion. On average, the MGS has slightly higher linear shrinkage than the SS and this can be attributed to a higher amount of kaolinite in the MGS.

Table 10. Average values of the Atterberg indices of the two set of soils

	Sandstone soil		Migmatite soil	
Atterberg Indices: (%)	Average	Range	Average	Range
Liquid limit	33·20	4·20–20·76	40·18	28·38–48·8
Plastic limit	20·09	10·92–27·66	23·43	17·38–29·58
Plasticity index	16·68	11·03–19·09	18·47	7·31–26·61
Linear shrinkage	4·03	1·5–7·3	6·63	2·2–10·1
Specific gravity	2·63	2·55–2·70	2·63	2·60–2·70
Flow index	16·85	7·36–24·90	20·25	15·30–32·4

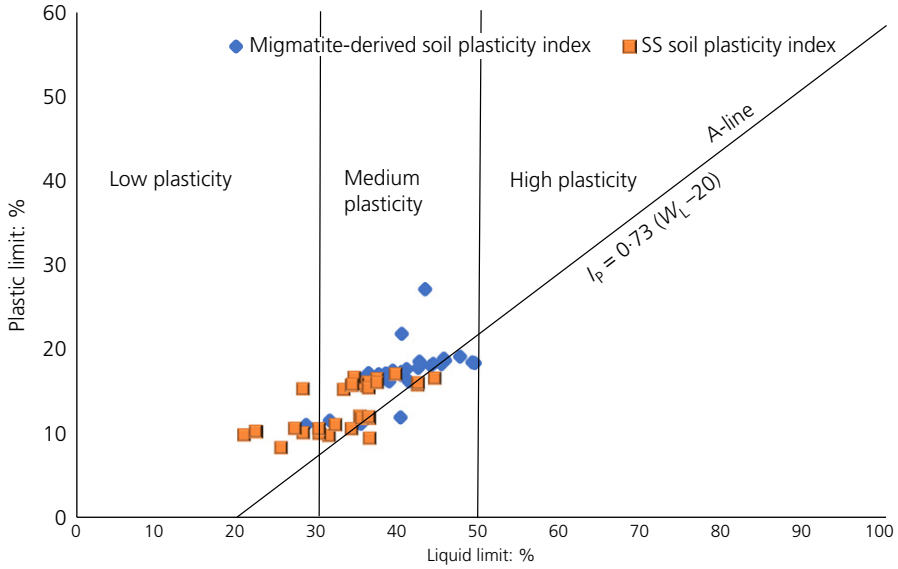


Figure 5. Casagrande chart comparing the plasticity of the studied soil

Table 12 presents the classes of the studied soil according to the unified soil classification system (USCS) and the Aashto classification. The SS samples mostly belong to group A-2 of the Aashto classification. The group index for this soil ranges from 0 to 1. These soils consist of transitional granular materials, all of which contain fines that are less than 35% silty fines. This group is rated as good-to-fair road subgrade. The MGS classifies as A-7 soil and possesses a group index higher than 20. Soil belonging to this class is usually very elastic and plastic, and subject to high volume change with variations in moisture content. Strength can be low to high, but all A-7 soils are quite impermeable. This type of soil should be utilised only where nothing else is available.

It is obvious from these results that the MGS samples have poor index properties. This can be attributed to the mineralogy of the parent rocks from which these lateritic soils were derived. Sandstone-generated soils that are rich in quartz sand produces non-plastic mixtures with water even when ground to clay size. The presence of quartz grains as the main part of a soil lowers its plasticity and activity values.

Table 11. Results of the statistical *t*-test conducted on the Atterberg indices data of the studied soils

Atterberg indices	*t*-statistic	*t*-critical	Nature of difference
Liquid limit	5·69	1·67	Significant
Plastic limit	3·00	1·67	Significant
Plasticity index	5·42	1·67	Significant
Linear shrinkage	4·67	1·67	Significant
Specific gravity	0·45	1·67	Insignificant
Flow index	3·40	1·67	Significant

Table 12. Aashto and USCS classification of the studied soils

Sample number	USCS group name	Aashto classification	Sample number	USCS group name	Aashto classification
BMS1	Silty sand	A-2-4(0)	BMB1	Silty clay	A-7-6(18)
BMS2	Silty gravel	A25(0)	BMB2	Silty clay	A-6(5)
BMS3	Clayey sand	A-2-4(0)	BMB3	Silty clay	A-7-6(21)
BMS4	Clayey sand	A1B(0)	BMB4	Silty clay	A-7-6(20)
BMS5	Clayey sand	A26(0)	BMB5	Clayey sand	A-2-6(0)
BMS6	Clayey sand	A26(1)	BMB6	Clayey sand	A-2-6(0)
BMS7	Clayey sand	A26(0)	BMB7	Silty clay	A-6(7)
BMS8	Clayey sand	A26(1)	BMB8	Silty clay	A-6(11)
BMS9	Clayey sand	A26(1)	BMB9	Silty clay	A-7-6(23)
BMS10	Silty sand	A26(0)	BMB10	Silty clay	A-7-6(22)
BMS11	Silty sand	A-2-4(0)	BMB11	Silty clay	A-7-6(10)
BMS12	Silty sand	A-2-4(0)	BMB12	Silty clay	A-6(10)
BMS13	Clayey sand	A26(0)	BMB13	Clayey sand	A-2-6(1)
BMS14	Clayey sand	A26(0)	BMB14	Clayey sand	A-2-6(0)
BMS15	Clayey sand	A26(0)	BMB15	Silty clay	A-6(4)
BMS16	Clayey sand	A-2-6(0)	BMB16	Silty clay	A-7-6(15)
BMS17	Silty gravel and sand	A-2-4(0)	BMB17	Silty clay	A-7-6(20)
BMS18	Silty gravel and sand	A-2-4(0)	BMB18	Silty clay	A-7-6(3)
BMS19	Clayey sand	A-2-6(0)	BMB19	Silty clay	A-7-6(21)
BMS20	Clayey sand	A-2-6(1)	BMB20	Silty clay	A-7-6(21)
BMS21	Clayey sand	A-2-6(1)	BMB21	Clayey gravel with sand	A-2-6(0)
BMS22	Clayey sand	A-2-6(1)	BMB22	Clayey gravel with sand	A-2-7(0)
BMS23	Clayey sand	A-2-6(0)	BMB23	Silty clay	A-7-6(8)
BMS24	Clayey sand	A-2-6(1)	BMB24	Silty clay	A-7-6(10)
BMS25	Silty sand	A-2-6(1)	BMB25	Silty clay	A-7-6(18)
BMS26	Silty sand	A-2-6(0)	BMB26	Silty clay	A-7-6(16)
BMS27	Silty sand	A-2-6(0)	BMB27	Silty clay	A-7-6(8)
BMS28	Silty sand	A-2-4(0)	BMB28	Silty clay	A-7-6(8)
BMS29	Clayey sand	A-2-6(1)	BMB29	Clayey sand	A-2-6(1)
BMS30	Silty sand	A-2-6(0)	BMB30	Clayey sand	A-2-6(0)
BMS31	Clayey sand	A-2-6(0)	BMB31	Clayey sand with gravel	A-2-7(1)
BMS32	Clayey sand	A-2-6(1)	BMB32	Silty clay with gravel	A-7-6(16)

3.4 Influence of parent rock on the grain-size distribution

Although soils from both parent rocks are well graded, MGS samples are richer in fine-grained materials than the SS ones, which are richer in sand-sized materials. This is a direct reflection of their parent rock mineralogy. The abundant feldspars and micas in the MG are expected to weather faster into fine-grained silt and clay-sized materials, while quartz in the sandstone is expected to weather into sand grains. The results of the grain-size distribution analyses of the studied soil were treated using the statistical Student's *t*-test and the result is presented in Table 13. It is observed that the coefficient of curvature, which is descriptive of soil texture, is not significantly different based on the parent rock factor. Moreover, the coefficient of uniformity, which is descriptive of soil grading and percentage composition of different grain sizes, varies significantly with the parent rock factor. This indicates that keeping other pedogenic factors such as climate and topography constant, a significant difference in the grain-size distribution parameters of residual soils can be caused by difference in parent rocks.

3.5 Effect of parent rock factor on consolidation parameters of the studied soils

Table 14 presents the summary of the statistical treatment of the coefficient of volume compressibility (m_v) data. Although, comparison of the average m_v values for both parent rocks shows that the sandstone samples exhibit higher compressibility than the MGS ones, Student's statistical *t*-test, however, shows that the observed difference is not significant at any pressure range. Since m_v is a measure of soil compressibility, this implies that the parent rock factor does not have a significant influence on the compressibility of the studied soils. This could also be due to the prevalence of kaolinite in all the soil samples, irrespective of their parent rock. Kaolinite is generally of lower plasticity and compressibility than illites and smectites.

Table 15 shows the result of Student's statistical *t*-test of the coefficient of consolidation of the studied soils. Despite the seemingly observed higher rate of consolidation in the SS soil, the statistical *t*-test shows that there is no significant difference in the coefficient of consolidation for soils of both origins.

Table 13. Result of the statistical treatment of the grain-size distribution parameters of the studied soils

Parameter	*t*-calculated	*t* in table	Nature of difference
Amount of gravel-sized particles	3·36	1·67	Significant
Amount of sand-sized particles	10·65	1·68	Significant
Amount of silt-sized particles	6·42	1·67	Significant
Amount of clay-sized particles	1·30	1·67	Insignificant
Amount of fine particles	7·25	1·67	Significant
Coefficient of uniformity	3·89	1·70	Significant
Coefficient of curvature	0·72	1·68	Insignificant

Table 14. Summary of the results of Student's statistical *t*-test of the coefficient of volume compressibility values of the studied soils

Pressure range: kPa	*t*-calculated	*t* in table	Nature of difference
32–64	1·19	1·70	Insignificant
64–128	1·21	1·71	Insignificant
128–256	0·39	1·70	Insignificant
256–512	0·79	1·70	Insignificant

Table 15. Summary of the results of Student's statistical *t*-test of the coefficient of consolidation values of the studied soils

Pressure: kPa	*t*-calculated	*t* in table	Nature of difference
32	0·23	1·70	Insignificant
64	0·45	1·70	Insignificant
128	0·81	1·70	Insignificant
256	1·57	1·70	Insignificant
512	0·74	1·70	Insignificant

Since coefficient of consolidation is a measure of rate of consolidation, this implies that the parent rock factor does not have a significant impact on the rate of consolidation of the studied soils.

3.6 Influence of parent rock factor on the compaction parameters, CBR and permeability coefficients of the studied soils

The SS samples possess higher maximum dry density (MDD) and lower OMC than the MGS ones. The OMC and MDD values of the studied soil samples were compared with the classification of Krebs and Walker (1972), which classified compacted densities and OMC according to the Aashto classification system. Based on this classification, the MGS soil exhibits OMC and MDD typical of silty sands and gravels of low plasticity belonging to class A-4 of the Aashto classification system, while the SS exhibits OMC and MDD typical of silty or clayey gravel and sand mixture belonging to class A-2 of the same classification system. The unsoaked CBR of the SS samples ranges from 43 to 127%, while the soaked CBR ranges from 17 to 46%. The unsoaked CBR value for the MGS ranges from 22 to 89%, while the soaked CBR ranges from 13 to 36%. The permeability coefficient of the MGS ranges from $9{\cdot}2 \times 10^{-9}$ to $3{\cdot}5 \times 10^{-8}$ m/s, while that of the SS ranges from $1{\cdot}0 \times 10^{-8}$ to $3{\cdot}4 \times 10^{-8}$ m/s. According to Terzaghi and Peck (1967) and Kedi (1974), the permeability coefficients of soils of both origins are typical of very low-permeability fine sand, sandy silt and silt. Their drainage properties are described as poor.

Table 16. Statistical *t*-test results of the OMC, MDD, CBR and permeability of the studied soils

Parameter	*t*-calculated	*t* table	Nature of difference
OMC	9·47	1·70	Significant
MDD	1·81	1·75	Significant
Unsoaked CBR	9·73	1·71	Significant
Soaked CBR	4·02	1·69	Significant
Permeability	0·40	1·70	Insignificant

Table 16 presents the statistical *t*-test results of the OMC, MDD, CBR and permeability coefficients of the studied soils. These results indicate that the parent rock factor has control over the OMC, MDD, soaked and unsoaked CBR of the studied soils. Although the average permeability values of the SS are slightly higher than that of the MGS, the statistical *t*-test indicates that the observed difference is not significant. This implies that the parent rock factor does not have a significant impact on the permeability coefficients of the studied soils. The presence of more fines and clay minerals in the MGS samples, which can be linked with the feldspar and ferromagnetic minerals present in its parent rock, might be responsible for their significantly lower OMC and higher MDD and CBR.

4. Conclusion

A quantitative approach was employed in the investigation of the influence of parent rock on the engineering behaviour of lateritic soils in a climatic zone drier and warmer than what is

observed in southwestern Nigeria. The studied soil samples are products of weathering of sandstone and MG. The MG samples are rich in feldspars, micas and hornblende, while the sandstone samples are essentially quartz grains. This has direct impact on the plasticity and other engineering properties of soils derived from them. The MG soils rated as fair-to-poor subgrade materials while sandstone soils rated as excellent-to-good subgrade soils based on the Aashto classification. Geochemistry in terms of major elements and weathering indices indicated that the soil developed on sandstone has higher silica content and lower amount of iron and aluminium oxide enrichment. Student's *t*-test confirmed that there is a significant difference between the mineralogical and geotechnical properties of the two soil sets. Despite the relatively warmer and drier climate operative in north central Nigeria, the parent rock still has a significant influence on the engineering behaviour of lateritic soils formed in this region. This implies that these soils should not be treated in the same way, especially when they are derived from different parent rocks.

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