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Index and Strength Characteristics of Residual Lateritic Soils from South-Western Nigeria

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Authors' contributions

This study was undertaken in collaboration with all authors. Author NOA designed and conducted the investigation, performed the statistical analysis and wrote the first draft of the manuscript. He also directed the literature searches. Authors DK and FOA managed the analyses of the study and literature searches as well as producing the subsequent drafts. All authors read and approved the final manuscript.

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ABSTRACT

Aim: To test consistency and strength of residual lateritic soil of Migmatite Gneiss of the Gneiss Complex from Abeokuta and Ibadan of South-western Nigeria for utilisation as sustainable road construction materials.
Study Design: A reconnaissance survey was carried out for location and identification of major outcrops around the area. The test pit investigative method was adopted by profiling the subsoil 3 m below the ground surface. Disturbed soil samples were used for the determination of the index properties, while shear strength parameters were determined on undisturbed soil specimens.
Place and Duration: The study was undertaken in Ibadan and Abeokuta, Southwest, Nigeria between Dec 2011 and March 2012.
Methodology: All the procedures adopted for the tests were in accordance with the British Standard 1377.The specific gravity of the samples was determined using the pycnometer method. The sieve analysis and hydrometer methods were employed to study the particle size distribution of coarse and fine soils respectively, while the Atterberg tests were performed to investigate the

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consistency limits of fine grained soils.
Results: The lateritic soils are predominantly well-graded silty, clayey sands with average specific gravity and clay content of 2.72 and 31.8% respectively. The colloidal activity of the clay ranged up to 2.25, signifying considerable volume change when wetted and large shrinkage when dried. Kaolinite and Ca montmorillonite are the principal clay minerals present in the soils. The fines are silty clays of low to medium plasticity.
Conclusion: Fairly strong inverse relationship was established between undrained cohesion and flow index, implying that the rate of loss of shearing stress of the soils is comparatively a function of increase in their moisture content.

Keywords: Residual lateritic soil; clay; consistency; strength; flow index; gneiss.

1. INTRODUCTION

Residual lateritic soils are abundant in Abeokuta and Ibadan, South-western Nigeria. This is as a result of the action of water and other weathering agents including tropical climate on the Precambrian rocks of the basement complex in the gneiss complex area of the region, which are mainly gneisses [1,2]. Lateritic soils are commonly used as subbase and base materials in road construction works due to their engineering properties. Abeokuta is 78 km on the older trunk road from Lagos to Ibadan, while Ibadan is located at 128 km inland northeast of Lagos.

Many studies have been carried out to relate the engineering properties of residual lateritic soils to the geological formation of the parent rock in South-western Nigeria. It has been reported that geological factors needed due consideration when searching for suitable soils for road projects [3]. Studies have also shown that the clay content, as well as its mineralogical composition, controlled the engineering performance of laterised soils [4,5].

This investigative study carried out in Abeokuta established that the origin of the parent rock strongly affects the strength properties of laterised soils stabilised with lime [6]. Well-graded reddish brown, sandy-silt-clay of medium plasticity and compressibility with some little contents of clay of inorganic origin and higher plasticity index was reported from the various tests carried out on quartz schist and granite derived lateritic soils of the area [7].

Clay-sized particles constitute a vital portion of lateritic soils and play an important role in their plasticity and cohesive strength. This study was therefore carried out to determine the relationship between flow index and cohesive strength of residual lateritic soils in the South-western Nigeria.

2. METHODOLOGY

2.1 Field Mapping and Sample Collection

A reconnaissance survey was carried out for location and identification of major outcrops around the study area (see Fig. 1). The positions of the investigation pits were then established after pedological mapping to identify profiles with appreciable thicknesses for sampling. The test pit, as an investigation technique, was selected because it provided a very quick and economical method of obtaining substantially reliable samples and information, making it very suitable in profiling the pits. In addition, the soils were competent enough for the pit side-walls to remain stable during excavation and profiling. Each test pit was dug using a chisel-like digger and excavating the underlying material to a depth of 3.0 m. In the process, soil samples were obtained whenever pit materials changed. At applicable depths, both disturbed and undisturbed soil samples were redeemed from the pit using a hand auger and U-tube core cutters (100 mm in diameter) respectively. This was done taking cognizance of change in nature of the profile. Undisturbed samples were sealed with wax (on either end of the cutter) to avoid any loss of moisture before being transported carefully to the laboratory avoiding any disturbance to the soil structure.

2.2 Laboratory Testing

Disturbed soil samples were used for the determination of the index properties, while shear strength parameters were determined on undisturbed soil specimens. All the procedures adopted for the tests were in accordance with the British Standard 1377 [8]. The specific gravity of the samples was determined using the pycnometer method. The sieve analysis and hydrometer methods were employed to study the particle size distribution of coarse and fine soils respectively, while the Atterberg tests were performed to investigate the consistency limits of fine grained soils. Consistency limits, which included liquid limit (L_L) and plastic limit (L_p),were determined on air-dried soil samples passing through the British standard sieve no. 40 (slot size of 0.425 mm)as highlighted by [9]. The Casagrande method was used for L_L tests as well as the measurement of the consistency index (I_c).

Undrained cohesion (C_u) and angle of shearing resistance (ϕ_u) were both obtained using the undrained triaxial compression apparatus on undisturbed specimens. In each case, the triaxial procedure was followed at different three cell pressures of 50 k/Nm^2, 100 kN/m^2 and 200 kN/m^2 in order to obtain the failure envelope on the Mohr-Coulomb graph.

2.3 Site Geology and Soil Profile

From published geological data, the terrain of South-western Nigeria was known to be underlain by a varying thickness of lateritic profile strata, which emanated from the Precambrian crystalline rocks in the Migmatite-Gneiss Complex and the Older Granites Suite areas [10]. The variable cover of weathered residual soils was confirmed by the sub-surface investigation on the site upon the digging of 3 test pits (1 and 2 from Abeokuta and Ibadan respectively). It revealed uniform sub-soil conditions across the investigation area, that is, there were no significant differences in the depth and thickness of the residual material within the respective lateral distances. Based on visual inspection of the test pits and more specifically, examination of the undisturbed core, the overall consistency of the material was found to be relatively high (medium dense to dense) over the area.

The tropically-weathered residual material occurred as a dense deposit, the bottom of which was established at about 3 m below ground level. The deposit represented an upper silty clayey zone approximately 0.3 m thick, underlain by a sandy silty clay zone and finally into slightly weathered rock. The soil profile generally, comprised sub-rounded weathered, very soft largely intact clayey silt towards the ground level and completely weathered very stiff consolidated brown reddish sandy silty clay. Groundwater was not encountered at all the depths investigated. A full description of the material layers is illustrated in Fig. 2.

3. RESULTS AND DISCUSSION

A typical set of grading curves for the studied soils is shown in Figs. 3a, 3b and 3c. The observed range of soil particles sizes present is indicative of a well-graded residual material. On the basis of the British Standard BS 5930 for the Unified Soil Classification System (1981) the studied soils are silty clays, silty sand gravels and clayey silty sands in Pits 1,2 and 3 respectively. It is apparent that these laterites contain a considerable amount of fines, i.e. silt and clay. Specifically, the average clay contents of 31.8%, 12% and 20.6% are realised in Pits 1, 2 and 3 respectively. This is peculiar to lateritic soils in parts of South-western Nigeria.

The specific gravity, activity and grading characteristics of the soil are given Table 1. Grain specific gravity (Gs) of the studied soils ranges between 2.64 and 2.76 with a wide range of overlap. It falls within those of gravel, sand, silt and clay sizes. This is consistent with established variations in specific gravity values for lateritic soils of the tropical region [11-13].

In the assessment of lateritic a soil for construction purposes, the colloidal activity (Ac) of its clay content is important to determine. This is evident when considering the manner in which plasticity index relates to the percentage finer than 0.002 µm of such soil. Therefore, it is possible to infer the clay mineralogical composition of a soil from the value of colloidal activity of clay content in a lateritic soil. In Table 1, the Ac values generally range between 0.18 and 2.25 in all the studied soils. On the basis of the standard established by [14], kaolinite and Ca montmorillonite are inferred to be the principal clay minerals that could be present in the soils, with illite only present in those samples obtained from pit 2. In laterite literature, kaolinite has been established to be the dominant clay mineral with subordinate amount of illite, while montmorillonite is rarely identified in lateritic soils of the Basement Complex. However, [1] identified smectite, of the montmorillonite group in lateritic soils developed over granite and gneiss at depth of 3.0 m, where differential settlement of a small magnitude may occur if employed as foundation material. On the other hand, likely unfavourable engineering performances of such soils are swelling and flow [15]. The implication is that the studied soils may undergo foundation settlement when loaded by structures.

A detailed consistency limits characteristics of the studied soils is presented in Table 2. Plots of plasticity index (I_P) against corresponding liquid limit (L_L) values on a Casagrande chart [16] show that fines are present as silt and clay of low to nearly high plasticity. The derived consistency limits, which include plasticity index (I_P), consistency index (I_C), liquidity index (I_L), toughness index (I_T) and flow index (I_F),were also estimated and presented in the same Table 3.

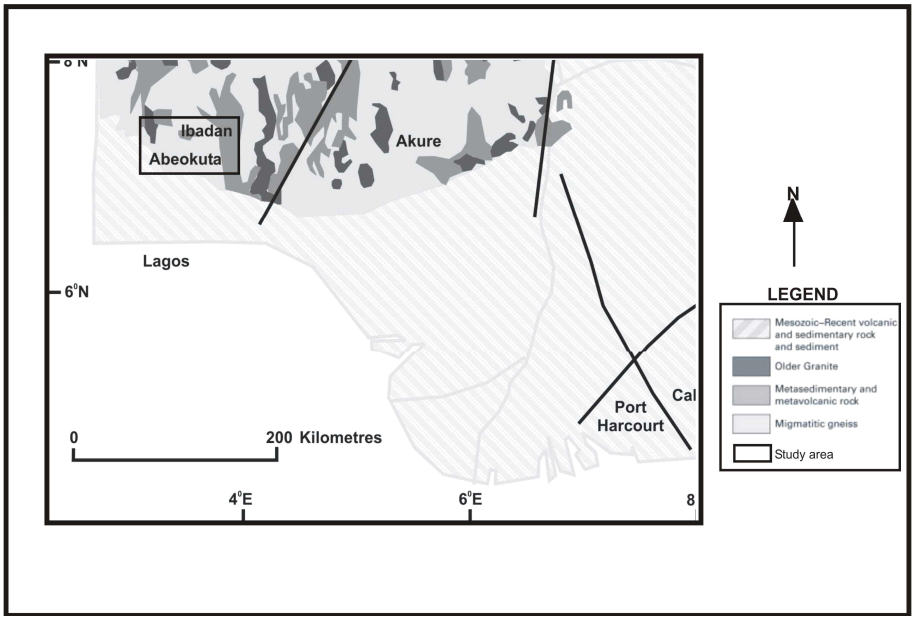

Fig. 1. Geological map of South-western Nigeria showing the study area [11]

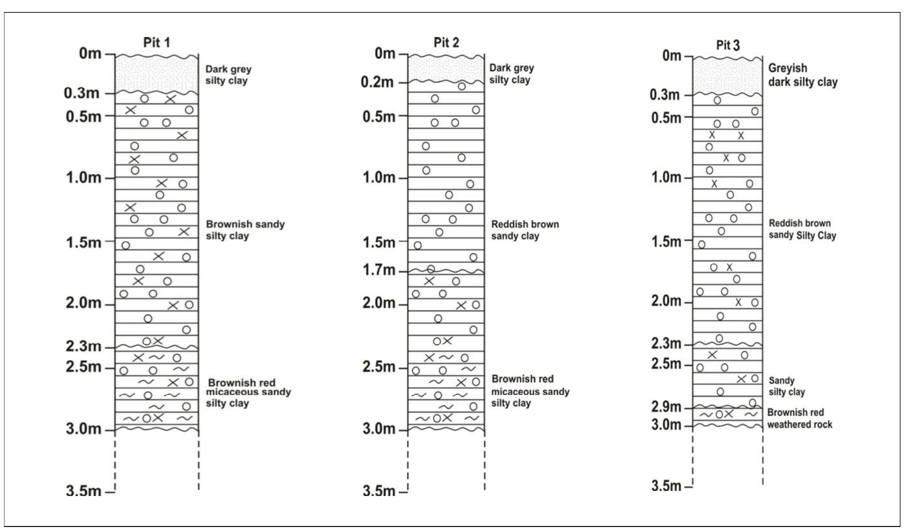

Fig. 2. Test pit and soil profiles from the study area

Table 1. Grain-size distribution, activity and specific gravity of the studied soils

Pit no.	Depth (m)	Depth range (m)	% clay	% clay range	Colloidal activity of clay (A_c)	A_c range	Inferred clay mineral(s)	% silt	% silt range	% sand	% Sand range	% gravel	% gravel range	Specific gravity (G_s)	G_s range
1	0.5	0.5–2.8	51	9 – 51	0.18	0.18 -1.67	Kaolinite, Illite and Ca Montmorillonite	27	26 – 44	18	18 – 42	4	3 – 5	2.72	2.70 – 2.76
	1.0		49		0.27			26		20		5		2.72	
	1.3		28		0.25			38		30		4		2.70	
	2.4		22		0.23			43		32		3		2.71	
	2.8		9		1.67			44		42		5		2.76	
2	0.2	0.2–2.0	12	9 – 15	2.25	1.0 – 2.25	Illite and Ca Montmorillonite	24	13 – 28	19	18 – 25	45	45 – 54	2.64	2.62 – 2.71
	0.8		15		1.27			13		18		54		2.68	
	1.2		9		2.0			16		22		53		2.62	
	1.5		12		1.67			19		19		50		2.71	
	2.0		12		1.0			28		25		35		2.64	
3	0.3	0.3–2.5	18	15 - 28	1.28	0.5 – 1.45	Kaolinite, Illite and Ca Montmorillonite	28	28 – 40	44	28 - 44	10	10 - 16	2.67	2.64 – 2.69
	1.0		20		0.6			34		31		15		2.69	
	1.6		28		0.5			26		35		11		2.71	
	2.0		22		1.45			32		28		18		2.64	
	2.5		15		1.33			40		29		16		2.68	

Table 2. Natural moisture content and consistency limits of the studied soils

Pit no.	Depth (m)	Natural moisture content (%)	Liquid limit (%)	Plastic limit (%)	Plasicity index (%)
1	0.5	12	52	34	17
	1.0	11	47	27	20
	1.3	13	42	21	21
	2.4	17	46	27	19
	2.8	10	40	35	5
2	0.2	10	28	15	13
	0.8	10	38	17	21
	1.2	10	29	18	11
	1.5	8	27	14	13
	2.0	8	35	15	20
3	0.3	9	47	34	13
	1.0	13	33	23	10
	1.6	15	44	30	14
	2.0	12	40	12	28
	2.5	14	31	20	11

Table 3. Derived limits and undrained cohesion of the studied soils

Pit no.	Depth(m)	Consistncy index (I_C)	I_C Range	Liquidity index (I_L)	I_L Range	Swell index (I_S)	I_S range	Toughness index (I_T)	I_T range	Flow index (I_F)	Undrained cohesion (kN/m^2)
1	0.5	2.29	0.36 – 2.29	-1.29	-5 - -0.38	23	23 – 39	1.16	0.38 – 1.21	14.71	10
	1	1.8		-0.8		32		0.88		22.68	9
	1.3	1.38		-0.38		33		1.21		17.42	14
	2.4	1.53		-0.53		39		0.73		25.92	12
	2.8	0.36		-5		25		0.38		13.15	16
2	0.2	1.38	1.33 – 1.73	-0.38	-0.73 - -0.33	36	23 -36	0.8	0.75 – 3.67	16.35	12
	0.8	1.33		-0.33		26		3.67		5.72	19
	1.2	1.73		-0.73		34		0.75		14.6	8
	1.5	1.46		-0.46		30		2.39		5.44	13
	2	1.33		-0.35		23		1.57		12.76	11
3	0.3	2.92	1 – 2.92	-1.92	-1.92 - -0.55	26	10 – 57	1.44	0.46 – 1.36	9.01	18
	1	2		-1		57		0.46		21.61	13
	1.6	2.07		-1.07		50		1		14.01	23
	2	1		0		10		1.36		17.94	16
	2.5	1.35		-0.55		70		0.6		18.43	10

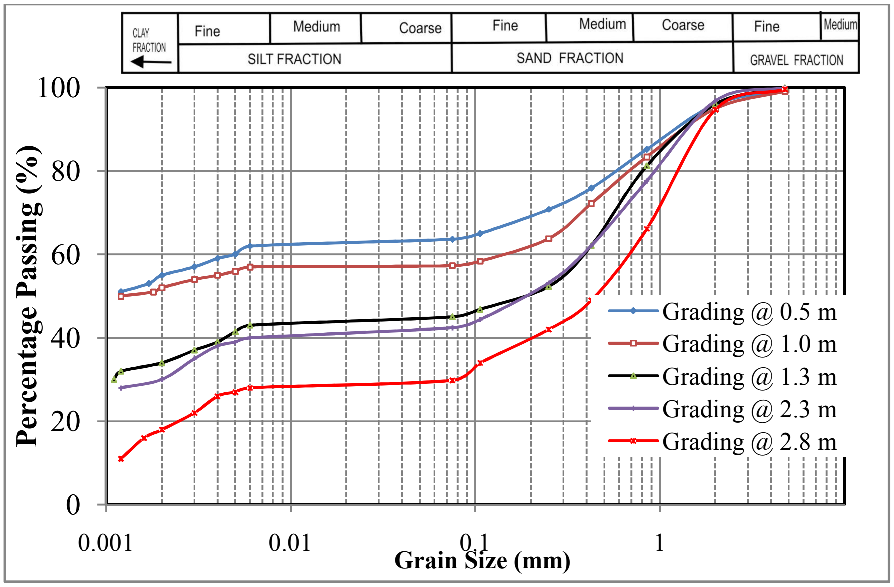

Fig. 3a. Grain-size distribution curves for soils from Pit 1

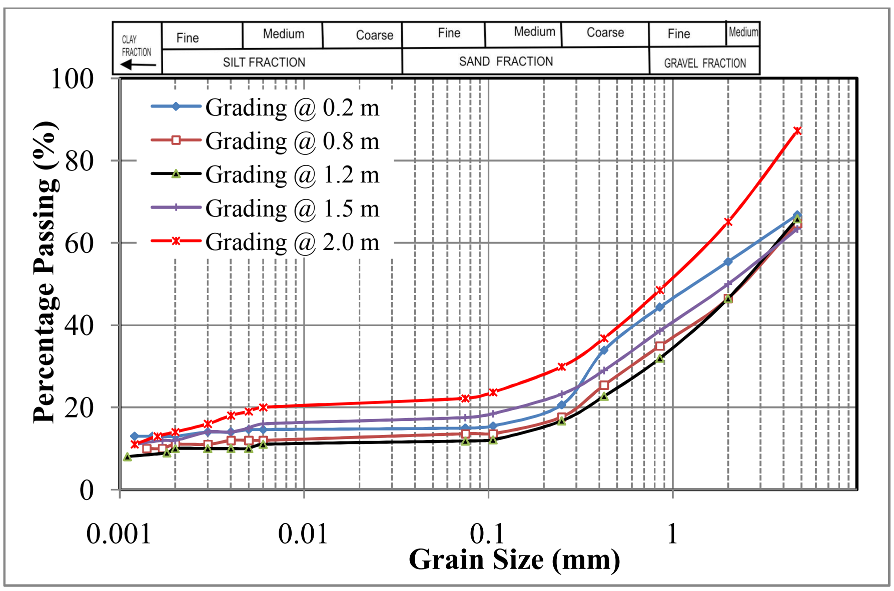

Fig. 3b. Grain-size distribution curves for soils from Pit 2

The consistency index (I_C) values for the studied soils range between 0.36 and 2.92 in the three pits, showing a combination of soft, stiff, solid and hard characteristics. Majority of the studied soils have I_C value less than 2.5, indicating that they are structurally unstable. It follows that virtually 90% of the soils are susceptible to weathering and erosion. Values of liquidity index (I_L) of the residual laterised soils are generally less than zero (-5 to-0.33). Soils with I_L values within this range are semi-plastic to solid in nature. Toughness index (I_T) of the studied soils fall between 0 and 3, while few of them have I_T values less than 1, indicating friable soils at plastic limit. The swell index (I_S) was greater than 15, which is indicative of low swell soils.

The undrained cohesion (C_U) values which measure the rate of shearing strength also vary greatly within each of the sampled pits. They range from 9 kN/m^2 to 16 kN/m^2 in Pit 1, 8 kN/m^2 to 19 kN/m^2 in Pit 2 and 10 kN/m^2 to 23 kN/m^2 in

Pit 3. The rate of loss of shearing strength upon increase in moisture content of the soils in this study can be related to flow index (I_F). This is considered necessary so as to establish a relationship between C_U and I_F of the soils and make a categorical statement on how the two parameters vary with each other. A regression plot of I_F against C_U for soils in each of the sampled pits is shown in Fig. 4. Fairly strong inverse correlation exists between I_F and C_U of the soils with coefficient of correlation (r) equals - 0.71 in Pit 2 and - 0.62 in Pit 3. The best line of fit in each case is defined by C_u = -0.632 I_F + 26.24 for soils from pit2 and C_u =-0.566 I_F+18.81 for soils from pit3. Beyond all doubts, cohesion increases with decreasing flow index, except that r' values are not reliable enough to suggest the determination of one property in absence of the other. Bye and large, the soils will increase in shearing strength only when there is decrease in water content as revealed by the flow index. The problems likely to be caused by such soils in engineering construction will range from swell to flow, leading to foundation settlement.

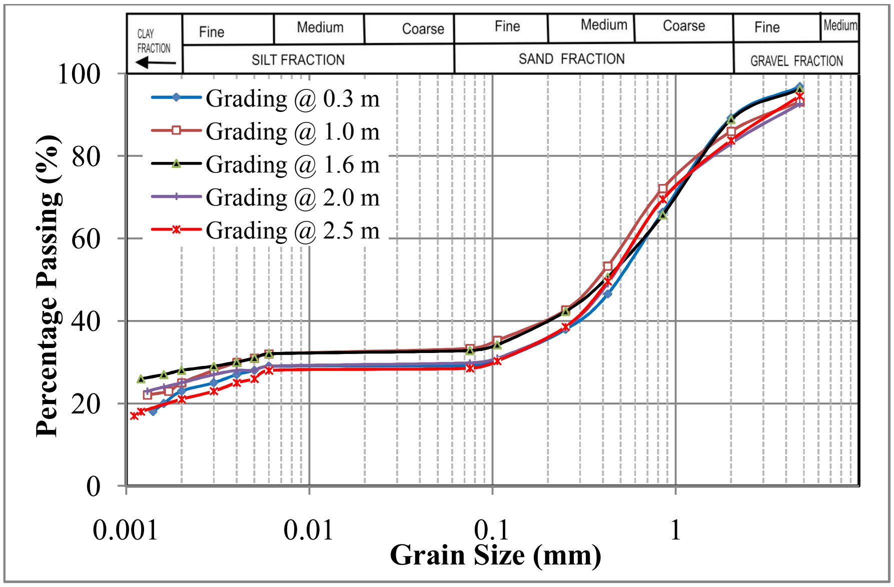

Fig. 3c. Grain-size distribution curves for soils from Pit 3

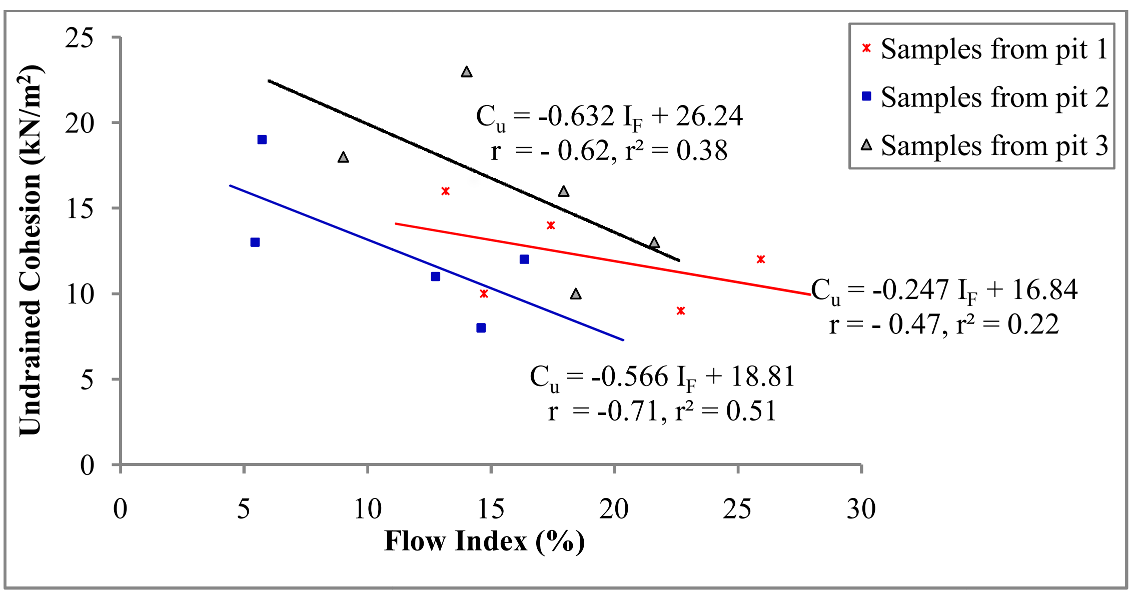

Fig. 4. Regression plots of cohesion and flow index of the studied soils

4. CONCLUSION

The study showed that the lateritic soils developed over gneisses and widespread all over the Basement Complex Terrain of South-western Nigeria. These soils are well graded silty clay sands with an average specific gravity of 2.72 and clay content of 31.8%. The colloidal activity of the clay in the soils is high and generally ranges between 0.18 and 2.25. The generally high activity demonstrated potential substantial volume changes when the soils are wetted and large shrinkages when dried. It also revealed likely presence of kaolinite and Ca montmorillonite as the principal clay minerals in the residual soils. The fines in the weathered laterites were largely silty clays exhibiting low to nearly high plasticity. The montmorillonitic clay predicted to be present could be instrumental to the soils' tendency to swell as clay absorbs water, lowering the bearing capacity of the composite. The greatest engineering threat to the lateritic soils will come from their strength characteristics generated by their clay content, which most often contains minerals especially montmorillonite.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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