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Compressibility Characteristics of Remoulded Residual Soils under Loading

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Abstract: *The compressibility characteristics of residual soils derived from different crystalline basement rocks underlying Ado-Ekiti metropolis in south-western Nigeria were assessed using one-dimensional loading. Parameters like particle size distribution, relative compaction and hydraulic conductivity were also assessed. Results of tests carried out on the remoulded soils indicate spatial variation in parameters defining the soils' compressibility. Regression analyses indicate that compression index C_c of the soil is moderately affected by initial void ratio e_0 with correlation coefficient value of 0.53. Regression plots of coefficient of consolidation C_v against initial void ratio e_0 and also against hydraulic conductivity k respectively suggest that compressibility of the soils is due to reduction in initial volume of void and drainage characteristics of the soil under loading. Settlement of the soil is mainly due to deformation of soil grain structure during loading; this reflects in high correlation coefficient of 0.96 between compression indices C_c and settlement of soils. Spatial distribution of settlement in soils across the study area shows that settlement is dependent on the type and nature of parent rock.*

Keywords: *Compressibility, Consolidation, Residual Soils, and Settlement*

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I. Introduction

Most engineering design methods have been developed on ideal soils (Tembe *et al*, 2010), whereas, characteristics which define an ideal soil cannot be generalized for residual soils. Residual soils mostly retain the anisotropy and heterogeneity of the parent rocks, thus variation in compressibility characteristics of residual soils is therefore expected over short distance posing major concern to stability and safety of built structures.

When a soil layer is subjected to vertical stress, change in volume (consolidation) through rearrangement of soil grains can be achieved by removal of water from the voids and destruction of grains structures. The removal of water takes time and it is controlled by soil hydraulic conductivity and the locations of free draining boundary surfaces. This processes result in the densification of soil and improved soil strength. However, during consolidation of soils, it is necessary to determine the uniformity, the magnitude, the volume change per time and the differential behaviour in volume change over an area; these will help determine the nature of settlement in soils. The magnitude of settlement is dependent on the magnitude of the applied stress, thickness of the soil layer, and the resultant compressibility of the soil.

Parameters that describe soil's compressibility include: **(i) pre-consolidation stress/maximum past pressure** (**σ'_{vm}** or σ_c**)**. It is the consolidated nature of soil or the maximum effective stress experienced by the soil prior to consolidation test; **(ii) Initial Void Ratio (e_0),** defines the amount of void space at the start of the loading. It is this initial void space that will be reduced as the water is squeezed out of the voids with time; **(iii) Compression Index (C_c),** is a measure of the load-deformation characteristic of the soil during "virgin" compression; **(iv) Recompression Index (Cr),** measures the load-deformation characteristic of the soil upon reloading after some amount of load release; **(v) Coefficient of Consolidation (C_v),** is an indicator of the rate of drainage during consolidation, or a measure of the time rate of primary consolidation and; **(vi) Secondary Compression Index (C_α)** accounts for majority of settlement that takes place over a long period of time beyond the time required for primary consolidation.

Effect of soil compressibility becomes more profound in built structures when differential settlement in foundation is high (Chummer, 1984). Several studies have been carried out to determine the compressibility behaviour of different soils. Malomo (1981) examined the compressibility characteristics of a compacted lateritic soil, at three moisture contents chosen along the moisture-density (compaction) curve and found that the soil is most compressible when compacted at the optimum moisture content which he termed as an unusual behaviour since the density was highest at the optimum moisture content. Malomo *et. al* (1983) compared two methods, namely Cassangrade and Constrained Modulus methods, in the determination of the pre-consolidation pressure of a lateritic soil. They showed that Constrained Modulus method is more preferred and recommended for the pre-consolidation pressure determination. The method requires less manipulation and is less manipulation and is less subjective in its consolidation and pre-consolidation tests results. Different soil parameters, such as void ratio, porosity, hydraulic conductivity, particle size distribution, and grain packing, have been found to influence the compressibility behaviour of soils (Otoko, 2014). This present work presents the compressibility characteristics of residual soils derived from different rock types underlying Ado-Ekiti metropolis in south-western Nigeria and predicts settlement behaviours of built structures on these soils.

II. Study Area

The study area is Ado-Ekiti metropolis, within Longitude 7^0 34ˈ and 7^0 41ˈ E, and latitude 5^0 11ˈ and 5^0 16ˈ N. It covers approximately 119.79 square kilometres (Figure 1).

The area is characterized by humid tropical climate of the West African Monsoon type with distinct wet and dry seasons. Annual rainfall reaches mean value of about 1350 mm coupled with high temperatures reaching a peak of about 32°C around February and a threshold of about 21°C around August. Relative humidity ranges from about 70% around January to about 90% in July. Vegetation in the study area is of re-growth rainforest type which consists largely of grasses and shrubs. Soils underlying the area are of residual type.

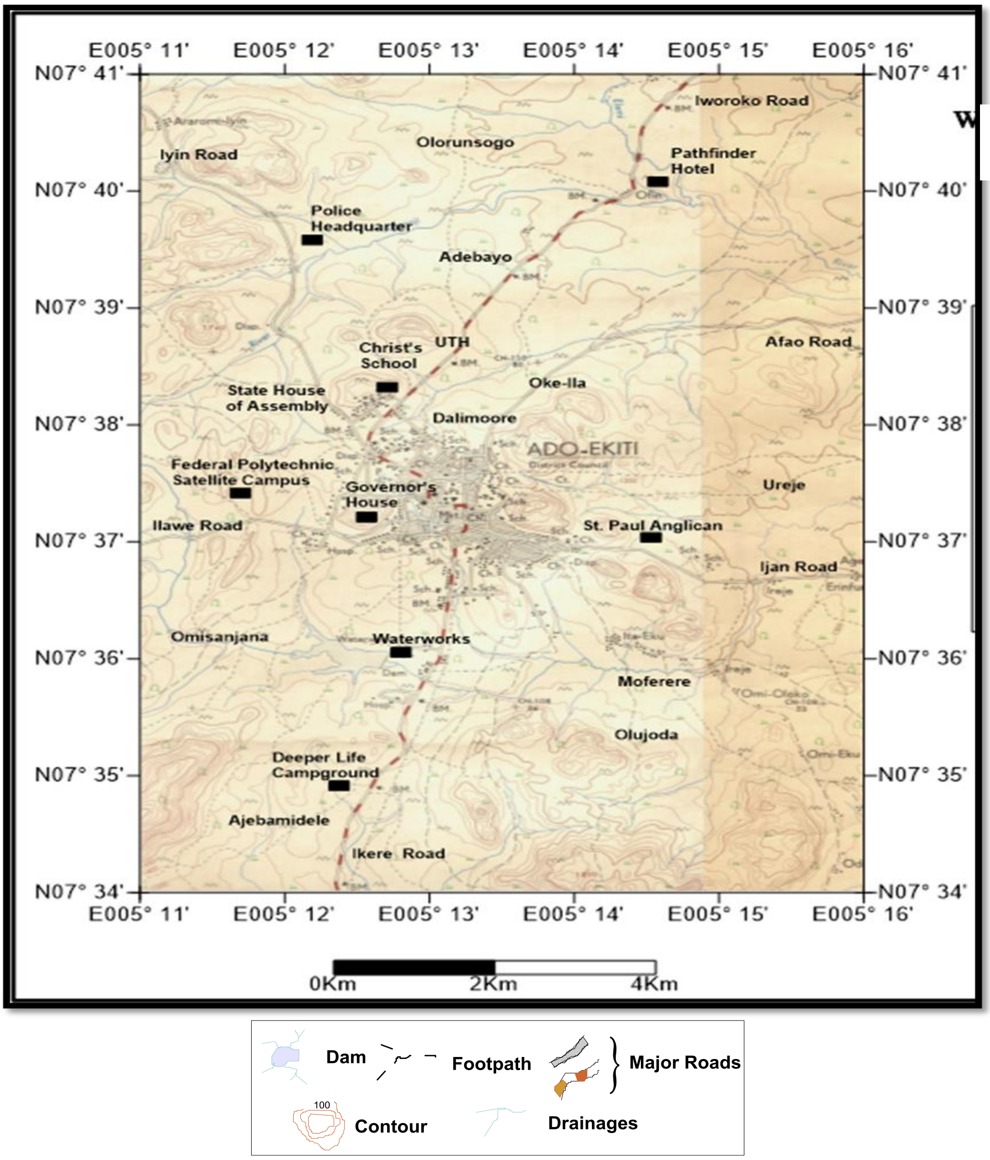

Figure 1: Location Map of the Study Area, South-western Nigeria

III. General Geology

The area is underlain by crystalline rocks typical of the Basement Complex of Nigeria. The rock units are migmatized granite-gneiss, foliated quartzite, medium-grained biotite-granite, charnockite, porphyritic plagioclase-granite and porphyritic orthoclase-granite (Olanrewaju, 1981 and Rahaman, 1988). Some of the rock units have been highly weathered in some places, producing relatively thick layers of residual soils.

IV. Methodology

Disturbed soil samples were collected from thirty-two test pits which were distributed over the area of study but using rock distribution as a slightly biased guide. The depth of sampling was about 2 meters below the ground surface. Grain size analysis and compaction tests were carried out on the soil samples. Hydraulic conductivity and one-dimensional consolidation tests were carried out on soil samples remoulded at optimum moisture contents for each soil. These tests were carried out in the Engineering Geology laboratory of the Federal University of Technology Akure in accordance to BSI 1377 (1990).

V. Results And Discussion

Grain Size Analysis, Soil Compaction and Hydraulic Conductivity

Table 1: Summary of Grain Size analysis, Soil Compaction and Hydraulic Conductivity test

Sample No	Soil grading	Relative Compaction	Hydraulic Conductivity k (cm/s)
1	Well graded silty sand with fines	0.99	1.43×10^{-4}
2	Well graded silty sand with fines	0.94	1.54×10^{-5}
3	Sand with silt and fines.	1.08	5.90×10^{-5}
4	Well graded silty sand with gravel and fines	1.00	1.09×10^{-4}
5	Well graded sand with gravel, silt and fines	1.03	1.49×10^{-5}
6	Gravelly sand with silt and low amount of fines	1.29	5.27×10^{-4}
7	Sandy gravel with silt and low amount of fines	1.02	1.63×10^{-3}
8	Silty sand with gravel and fines	1.31	2.78×10^{-5}
9	Well graded clay, sand, silt and gravel	0.89	3.66×10^{-6}
10	Well graded clayey sand with silt and gravel	0.97	2.49×10^{-6}
11	Well graded clayey sand with gravel and silt	0.97	5.73×10^{-7}
12	Poorly graded silty sand with fines	1.02	5.64×10^{-6}
13	Gravelly sand with silt and fines	0.95	2.04×10^{-4}
14	Well graded clayey sand with silt	1.07	2.73×10^{-6}
15	Well graded clayey sand with silt	1.026	7.52×10^{-6}
16	Well graded silty sand with fines	0.90	1.68×10^{-4}
17	Poorly graded gravel with sand, silt and fines	1.09	3.56×10^{-4}
18	Well graded clayey sand with silt	0.96	9.61×10^{-7}
19	Well graded sandy clay with silt and gravel	0.86	1.41×10^{-3}
20	Poorly graded gravel with sand, silt and fines	0.97	1.56×10^{-3}
21	Well graded clayey sand with silt and gravel	0.87	1.22×10^{-4}
22	Well graded clayey sand with silt and gravel	0.89	3.75×10^{-7}
23	Well graded sandy clay with silt ad gravel	0.87	1.90×10^{-5}
24	Poorly graded gravel with silt, sand and fines	1.07	3.83×10^{-3}
25	Well graded clayey sand with silt and gravel	1.03	1.42×10^{-5}
26	Well graded sandy clay with silt and gravel	0.88	3.14×10^{-5}
27	Well graded clayey sand with silt and gravel	0.95	4.58×10^{-5}
28	Well graded gravel with sand, silt and fines	0.91	5.11×10^{-6}
29	Well graded silty sand with fines and gravel	0.94	1.41×10^{-3}
30	Well graded clayey sand with silt and gravel	0.88	8.15×10^{-6}
31	Poorly graded gravel with silt, sand and fines	1.21	3.92×10^{-3}
32	Well graded sandy clay with silt and gravel	0.99	2.57×10^{-6}

Results from particle size analysis show that 69% of the soil samples are well graded type; 75% of the soils possessed fine contents above 10%. The well graded soils are expected to possess high relative stiffness, low permeability and resultant reduced compressibility compared to the poorly graded soils.

Values of relative compaction of the tested soils show that 59% of soil samples possess improved density after compaction while 41% showed reduced density. The improved soils will have reduced hydraulic conductivity and compressibility due to reduced void spaces; the soil samples with reduced density (mass to volume ratio) will have increase in inter-connected void spaces and consequently, increase in soils' compressibility. According to Carter and Bentley (1991), remoulded residual soils are generally of very low hydraulic conductivity. As a result, the soils will possess poor drainage capacities.

One-dimension Consolidation Tests

Table 2: Summary of Results of One-dimensional Consolidation Test

Sample No.	c_v (m^2/yr)	e	σ'_{vm} (MPa)	C_s	C_c	C_r	m_v (MPa^{-1})	a_v (MPa^{-1})	S (mm)
1	0.1785	0.5790	0.0621	-0.0073	0.2777	0.1310	0.6881	1.0869	2.8530
2	0.2320	0.4350	0.0553	-0.0043	0.1331	0.0650	0.4537	0.6509	1.5750
3	0.2049	0.6730	0.0452	-0.0078	0.1027	0.0660	0.4361	0.7296	1.0530
4	0.2065	0.5620	0.0360	-0.0047	0.1148	0.0650	0.6363	0.9939	1.2390
5	0.2728	0.5440	0.0458	-0.0050	0.1051	0.0670	0.4774	0.7370	1.1670
6	0.2995	0.3760	0.0499	-0.0038	0.0774	0.0350	0.3114	0.4283	0.9780
7	0.1569	0.6380	0.0380	-0.0076	0.1672	0.1610	1.0141	1.6608	1.6440
8	0.2477	0.4120	0.053	-0.0071	0.1369	0.0650	0.4950	0.6988	1.6470
9	0.1972	0.6780	0.0489	0.0047	0.1835	0.1010	0.6724	1.1285	1.8180
10	0.1325	0.7050	0.0219	0.0006	0.1542	0.1360	1.2517	2.1346	1.4730
11	0.1790	0.7850	0.0461	-0.0061	0.1774	0.0990	0.6597	1.1777	1.6620
12	0.2530	0.3150	0.0514	-0.0024	0.0791	0.0430	0.3433	0.4513	1.0410
13	0.1460	0.6670	0.0386	-0.0141	0.1832	0.1920	1.1181	1.8842	1.770
14	0.2453	0.5370	0.0615	-0.0020	0.2743	0.0890	0.6088	0.9360	2.9370
15	0.2160	0.6060	0.0377	-0.0050	0.0992	0.1020	0.6343	1.0189	1.0470
16	0.2097	0.4770	0.0576	-0.0021	0.2368	0.0680	0.6031	0.8910	2.6490
17	0.2856	0.5320	0.0490	-0.0054	0.1396	0.0580	0.5025	0.7699	1.5510
18	0.2088	0.5550	0.0391	-0.0051	0.1019	0.1030	0.6495	1.0010	1.1100
19	0.2548	0.6160	0.0487	-0.0016	0.1250	0.0920	0.5411	0.8744	1.3170
20	0.2220	0.6150	0.0495	-0.0066	0.1670	0.0880	0.6119	0.9882	1.7340
21	0.0907	0.9490	0.0528	-0.0048	0.3726	0.2230	1.1024	2.1482	3.0150
22	0.1087	0.8530	0.0248	0.1741	0.4586	0.2120	2.3914	4.4300	3.7590
23	0.2355	0.7020	0.0494	0.0024	0.1122	0.0760	0.4417	0.7518	1.1370
24	0.2674	0.3860	0.0513	-0.0081	0.0967	0.0480	0.3777	0.5233	1.2000
25	0.1684	0.9100	0.0458	-0.0062	0.1729	0.1280	0.6760	1.2910	1.1515
26	0.1847	0.7250	0.0434	0.0042	0.1925	0.1030	0.7864	1.3564	1.8390
27	0.1918	0.7120	0.0625	-0.0061	0.3359	0.0760	0.5557	0.9515	3.2340
28	0.1834	0.7510	0.0407	-0.0014	0.1704	0.1250	0.8178	1.4323	1.6140
29	0.1693	0.5690	0.0433	0.0007	0.1745	0.1220	0.8640	1.3556	1.8360
30	0.1610	0.8110	0.0344	-0.0079	0.2187	0.0990	1.0317	1.8683	1.9650
31	0.2970	0.3150	0.0607	-0.0027	0.1535	0.0370	0.3629	0.4770	1.9890
32	1.3140	0.7180	0.0487	0.0003	0.1335	0.116	0.5894	1.0125	1.3140

C_v- coefficient of consolidation,. e- void ratio, σ'_{vm} – pre-consolidation pressure, C_s- swelling index, C_c- compression index, C_r- recompression index, m_v- coefficient of volume compressibility, a_v- coefficient of compressibility, S- settlement.

Compressibility characteristics of soils underlying the study area range from high to very high. Compressibility of the soils is a function of both the void spaces and clay content of the soil. Based on Bell (2007) scale of compressibility, 97% of the samples have a high compressibility characteristic and 3% have a very high degree of compressibility. According to Bell's (2007) grouping of soils based on soil compression index, 9% of the samples fall within soft, organic alluvial clays and peats; 47% of the samples falls within the normally consolidated alluvial clays and 44% of the samples falls within the silty-laminated firm to stiff clays.

Settlement is relatively high in soils derived from migmatized granite-gneiss and charnockitic rocks than soils derived from the porphyritic granite and foliated quartzite. This may be caused by the deep weathering of locally enriched zones of feldspars in the original parent rocks as proposed by Asiwaju-Bello (2007). Settlement differential due to differential compressibilities is largely expected in the northeastern and western parts of the study area which corresponds to areas around Iworoko road, Afao road, Ureje quarters and Olujoda.

Generally, settlement characteristics of the soils are bellow 6cm/s proposed as acceptable limit of 6cm/s proposed by Chummer (1984). However, for sensitive structures, this degree of settlement must be taken into consideration.

Regression Analyses

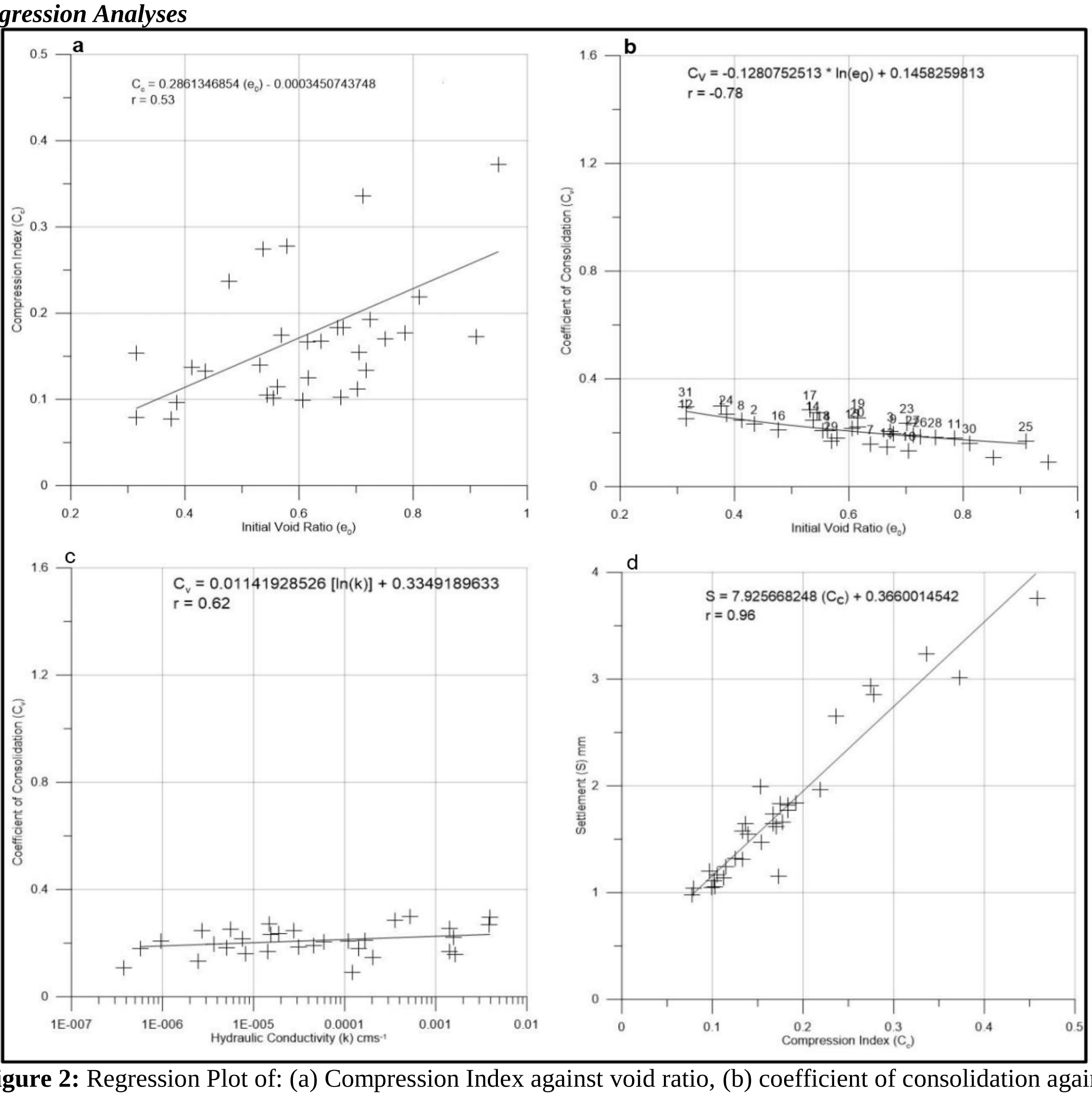

Figure 2: Regression Plot of: (a) Compression Index against void ratio, (b) coefficient of consolidation against initial void ratio, (c) coefficient of consolidation against hydraulic conductivity, (d) Settlement against compression index

Regression analyses (Figure 2) indicate that compression index, C_c, of the soil is moderately affected by initial void ratio, e_0, with correlation coefficient of 0.53 (Figure 2). Logarithmic relationship between coefficient of consolidation, C_v, and initial void ratio, e_0, indicates that the coefficient of consolidation, C_v, of the soil is less affected by initial void ratio, e_0, but increases with increase hydraulic conductivity, *k*; this is an indication that virgin compression is a function of hydraulic conductivity rather than void spaces. Strong correlation coefficients of -0.78 and 0.62 for coefficient of consolidation, C_v, against initial void ratio, e_0, hydraulic conductivity, k, respectively imply that compressibility of the soils is due to reduced initial volume of void and increase hydraulic conductivity of the soil. The soils with low and medium compressibility will not pose problems on the field while those of high compressibility will pose significant problem. Coefficient of regression of 0.96 between settlement and compression indices shows that settlement is mainly due to virgin compression than pre-consolidation stress and secondary compression of the soils.

VI. Conclusion

The compressibility characteristics of residual soils underlying Ado Ekiti, Nigeria is a function of both initial void ratio and hydraulic conductivities of the soils. Settlement is mainly by virgin compression at a low rate due to low drainage potential of the soils and will span over a longer time due to low drainage potential of the soils. Low drainage potential is due to low hydraulic conductivity values recorded in the soils. Differential settlements in the soils are less than $6cms^{-1}$ recommended by Chummer, 1984.

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