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Engineering geological investigation of highway pavement failure in basement complex terrain of southwestern Nigeria

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Abstract :*Many highways are in deplorable states in Nigeria thereby limiting national socio-economic development. Incessant road failure is oftenattributed to construction defects because of the level of corruption in the country. Index and engineering properties of subgrade soils along a major highway linking the southwestern Nigeria to the Federal Capital Territory were evaluated to establish the scientifically defensible cause of the perpetual failure of sections of the pavement.Investigative tests followed the British (BS: 1377) and ASTM-D4318 Standards. Casagrande classification charts indicated the subgrade soils below stable and unstable portions of the pavement had low plasticity and medium to high plasticity respectively. The Optimum Moisture Contents of subgrade soils were lower at stable portions (12.2 to 16.8 %) than unstable parts (13.2 to 18.9 %). Maximum Dry Densities were higher at stable portions (1775 to 1964 kg/m^2) than unstable portions (1688 to 1923 kg/m^2). The Unconfined Compressive Strength values were greater for soils underlying stable locations (50.21 to 209.62 kPa) than unstable segments (23.98 to 49.87 kPa). Cohesion was higher in subgrade soils from stable sections (42.2 to 110.7 kPa), indicating higher shear strength, than unstable sections (19.0 to 59.9 kPa). Soils below stable pavements exhibited relatively higher soaked and un-soaked CBR values (11 to 15 and 16 to 59 % respectively), an indication of higher load bearing capacity and strength, than soils beneath unstable sections (3 to 10 and 6 to 59 % respectively). Hence, it may be concluded that the failure of sections of the flexible highway pavement was largely a functionof the geotechnical properties of the subgrade soils.*

Keywords: *Geotechnical properties, lateritic soils, road failure, subgrade, MDD.*

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I. INTRODUCTION

Lateritic soils are common tropical weathering products developed on various rock types in Nigeria. They are commonly derived from both sedimentary and crystalline basement rocks across the nation and, constitute major resources in the construction industry. Their formation is greatly enhanced by seasonal fluctuations in groundwater table, under alternating distinct wet and dry seasons. This phenomenon often leads to mobility, redistribution and concentration of soil chemical constituents thereby promoting the formation of lateritic soils in the tropics. The major chemical constituents of lateritic soils are silica (SiO_2), alumina (Al_2O_3) and Iron oxide (Fe_2O_3), in order of abundance. Other associated minor constituents include MnO, MgO, CaO, Na_2O and K_2O. Some lateritic soils may also have TiO_2, P_2O_5 and H_2O [1]. These characteristically reddish natural geomaterials occur in abundance in Nigeria especially where there is deep weathering. Their use as engineering soil materials include but not limited to road construction, block molding, ceramic making, foundation filling, and dam embankment. Also, the subgrade material for most flexible highway pavements in Nigeria is made up of these lateritic soils.

Many highways and roads are in deplorable states in Nigeria thereby limiting national socio-economic development [2], [3], [4], [5]. It is common that road failure in parts of the investigated region had been attributed to construction defects consequent upon alleged diversion of funds meant for proper execution of projects by many contractors. This speculation needed to be proved scientifically and technologically, more so that several factors could be responsible for the degradation and eventual failure of any highway pavements. Such factors may include: (1) seasonal moisture and volume changes in expansive soils resulting in soil volumetric changes [6]; (2) Poor engineering properties of subgrade soils which fall short of highway subgrade standard specifications; (3) Poor drainage conditions; (4) construction defects and (5) excessive traffic/vehicular load. Road failure can take different forms, such as, waviness, potholes, soil movement by creep, slides, settlement and compressibility. This study was embarked upon with the goal to evaluate the geotechnical properties of subgrade lateritic soilsunderlying sections of the major highway that links the southwestern Nigeria to Abuja, the Federal Capital Territory, which are in deplorable state of perpetual failure. This is with a view to determining the geotechnical basis, if any, for the failure of the affected portions of the highway.

II. Geomorphologicaland Geological Setting

The study area lies within latitudes 7°00' N and 7°45'N of the equator and longitudes 5°30'E and 6° 00'E of the Greenwich meridian. The highway under investigation is the major link from southwestern Nigeria to Abuja (Fig. 1), the Federal Capital Territory (FCT). The topography is generally characterized by hills of varying heights ranging from about 300m to 400m above the mean sea level. The climate is of the West African monsoonal type, characterized by distinct wet and dry seasons typical of West African tropical regions. The wet season spans between April to September while the dry season period is between October and March. Average temperatures reach 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. Typically, the vegetation of the study area is the tropical rain forest with thick undergrowth but had in many parts been modified by human activities such as urbanization, construction, land cultivation and deforestation.

The regional geology of the area had been described in [7] and [8]. The dominant lithologic units encountered in the study area are basically schist with granite gneiss belonging to the Gneiss-Schist assemblages, and migmatised biotite-gneiss of the Migmatite-Gneiss assemblages of the Precambrian Basement Complex rocks of southwestern Nigeria (Fig. 2). The rock units exhibited varied textural characteristics. This was clearly reflected in the textural characteristics of the lateritic weathering products. The grading properties also indicated the degree of leaching and lateritization in the area.

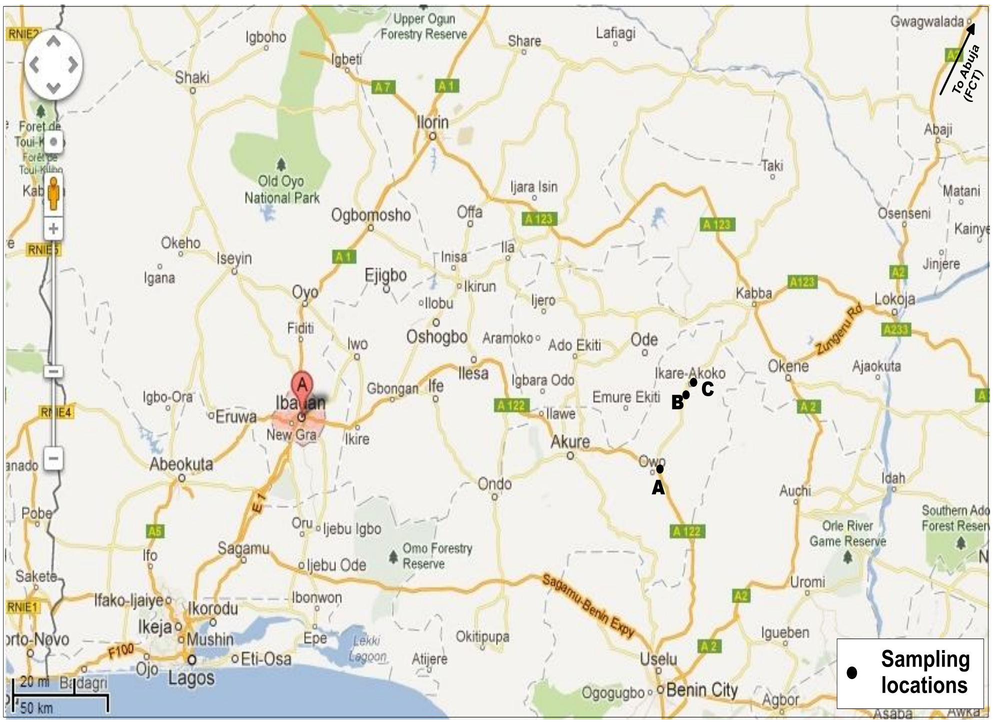

Figure 1: Road map showing sampling locations in southwestern Nigeria (Adapted from Google map Inc., 2018)

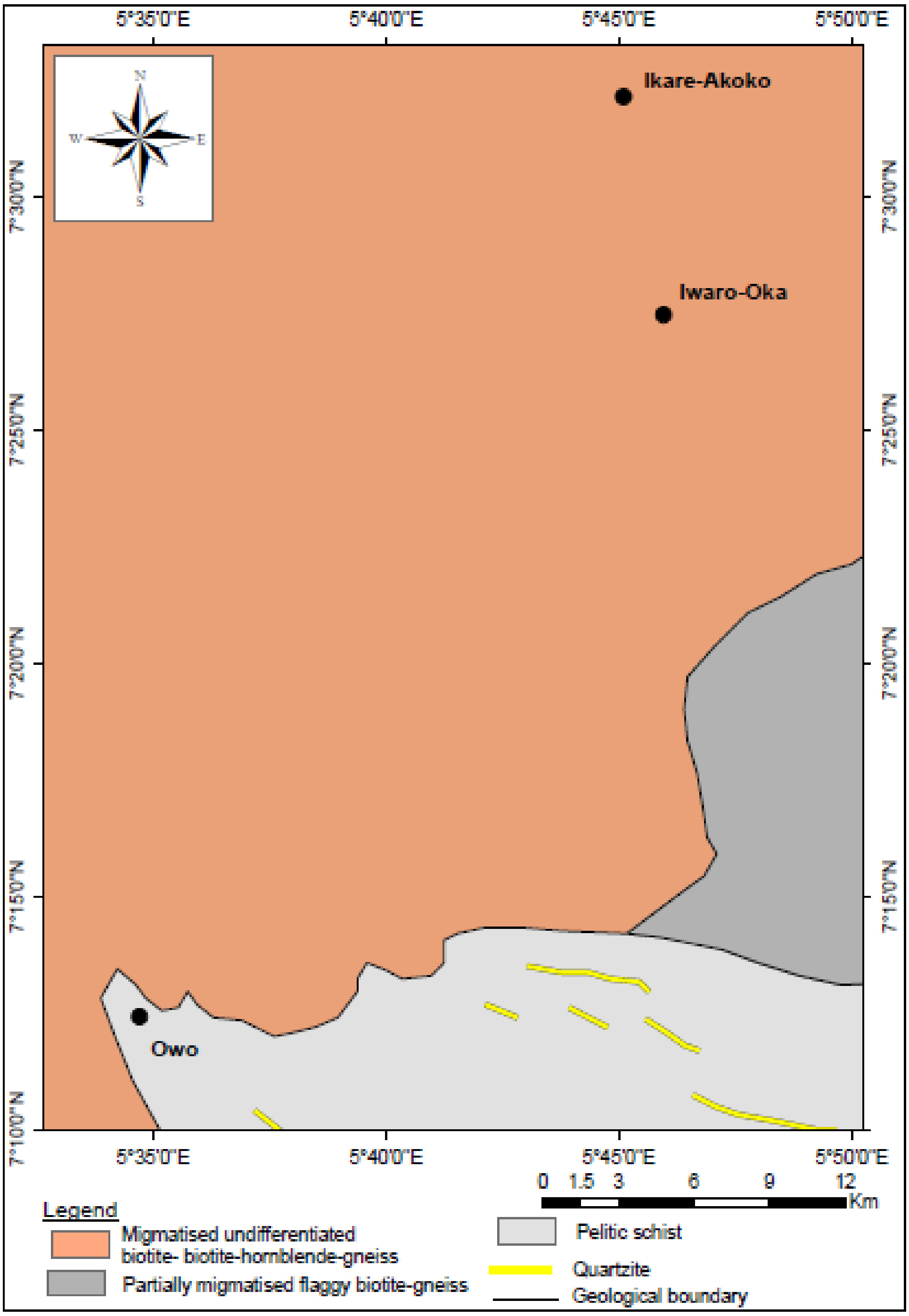

Figure 2: Geological map of the study area.

III. Research Methodology

The research involved field study and laboratory investigations. Field investigation entailed geologic mapping, soil sampling, description and preparation. Surface geologic mapping was carried out to ascertain the parent rocks on which the residual lateritic soils were developed. The rocks were sampled and identified by visual inspection on the field. Disturbed bulk soil samples were collected from trial pits at reasonable depths, generally not less than 1meter below the stable and failed sections of the flexible pavements (Fig. 3). This ensured a representative sampling of the subgrade materials. The soils were identified and described by visual inspection. The soil samples were prepared in the laboratory prior to analyses. The preparation included air-drying at room temperature. Investigative laboratory tests conducted on the soil samples include specific gravity of soil grains, particle size distribution, consistency limits, compaction, Californian bearing ratio, unconfined and triaxial compression. The analyses followed the procedures outlined in the British (BS: 1377-2) and ASTM-D4318 Standards [9] and [10]. The particle size distributions were determined by textural analyses involving both dry (mechanical) and wet (hydrometer) sieving techniques. The consistency limits (plastic limit and liquid limit) were determined at natural moisture contents using the Atterberg approach. Microsoft Excel software package was used for data analysis and presentation. Arc GIS version 10.2 was employed in map preparation.

(i) Location A1 (Stable) (ii) Location A2 (Unstable)

(iii) Location B1 (Stable) (iv) Location B2 (Unstable)

(v) Location C1 (Stable) (vi) Location C2 (Unstable)

Figure 3: Stable and failed road sections adjacent to sampling locations in Owo [i] and [ii]; Iwaro [iii] and [iv]; and Ikare-Akoko [v] and [vi].

IV. RESULTS AND DISCUSSION

Specific gravity

From Table 1, the specific gravity of soil grains at stable locations variedfrom 2.70 to 2.75 whereas the values are between 2.64 and 2.71 for soils at unstable locations. Since the degree of maturity and specific gravity are directly related, the results showed that subgrade soils below the stable locations which possessed higher specific gravity values, have higher degree of soil maturity and laterization than those underlying failed sections exhibiting lower values. This may have contributed to a largely to the trend observed in the strength characteristics of the soils.

Textural Attributes

Generally, the soils were fairly well graded (Fig. 4). However, soils from the unstable locations exhibited relatively higher percentage fines than soils underlying the stable road sections (Table 2). The implication of this is that the observed poor engineering behaviour of the failed portions of the pavements is possibly a reflection of the relatively higher amounts of fines since the amount of fines is inversely proportional to the engineering performance of many lateritic soils [11], [12].

Table 1 Natural moisture content and specific gravity of soil grains

Properties	A1	A2	B1	B2	C1	C2
Natural moisture content (%)	6.30	14.30	8.20	15.30	11.20	15.10
Specific gravity	2.75	2.66	2.70	2.64	2.75	2.71

A1, B1, C1 (Stable locations); A2, B2, C2 (Unstable locations)

Table 2 Grain size distribution characteristics

Properties	A1	A2	B1	B2	C1	C2
% Fines (Clay + Silt)	21.5	35.5	15.1	17.0	9.9	29.5
% Sand	50.3	41.7	50.1	43.8	47.4	51.4
% Gravel	28.2	22.8	34.8	39.2	42.7	19.1

A1, B1, C1 (Stable locations); A2, B2, C2 (Unstable locations)

Consistency Indices

The results of consistency limit tests are presented on Table 3a. The Casagrande classificationcharts (Fig.5) indicated that the subgrade soils are all inorganic, plotting above the A-line. From the chart, the three soil samples from the stable locations exhibited very low to low plasticity. Conversely, soil samples from beneath unstable pavements indicated medium to high plasticity. Comparing these with Whitlow’s classification (Table 3b) [13], all the samples from the stable locations (samples A1, B1 and C1) fall within low plasticity class. However, samples A2 and C2 from unstable segments exhibited intermediate plasticity with liquid limits of 37.2% and 37.8% respectively while sample B2 indicated high plasticity with liquid limits of 53%. The values of the consistency limits observed may be reflecting the varied amounts of fines present in the soils. This may have contributed to the instability of the failed segments of the pavements.

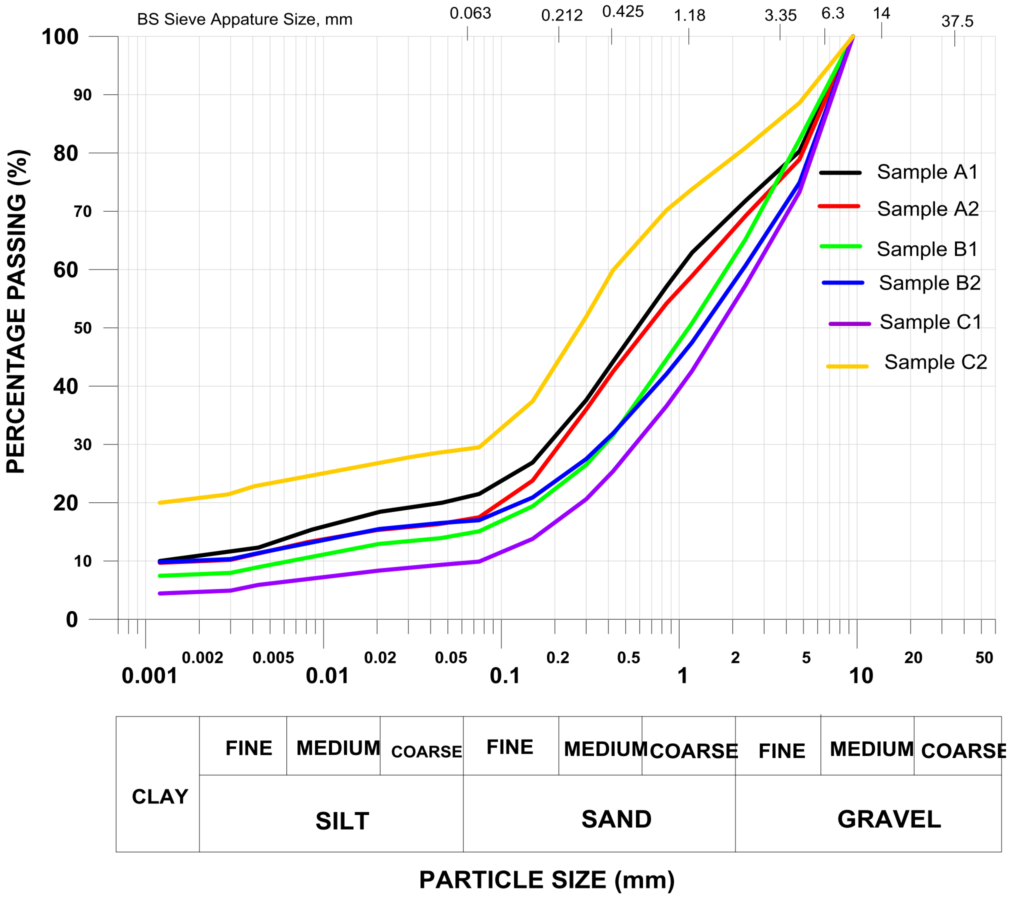

Figure 4: Grain size distributions

Table 3a Results of consistency limit test

Sample code	LL(%)	PL (%)	PI(%)	SL(%)
A1	34.6	17.1	17.53	9.3
A2	37.2	17.9	19.28	10.7
B1	27.6	16.7	10.92	6.4
B2	53.0	25.0	28.0	15.0
C1	19.7	NP*	0.00	7.1
C2	37.8	17.4	20.44	12.1

LL = Liquid limit; PL = Plastic limit; PI = Plasticity index; SL = Shrinkage limit; NP* = Non plastic; A1, B1, C1 (Stable locations); A2, B2, C2 (Unstable locations)

Table 3b Plasticity level of soils from liquid limit values (Whitlow, 1995)

Liquid limit (%)	Plasticity class
< 35	Low
35 – 50	Intermediate
50 – 70	High
70 – 90	Very high
> 90	Extremely high

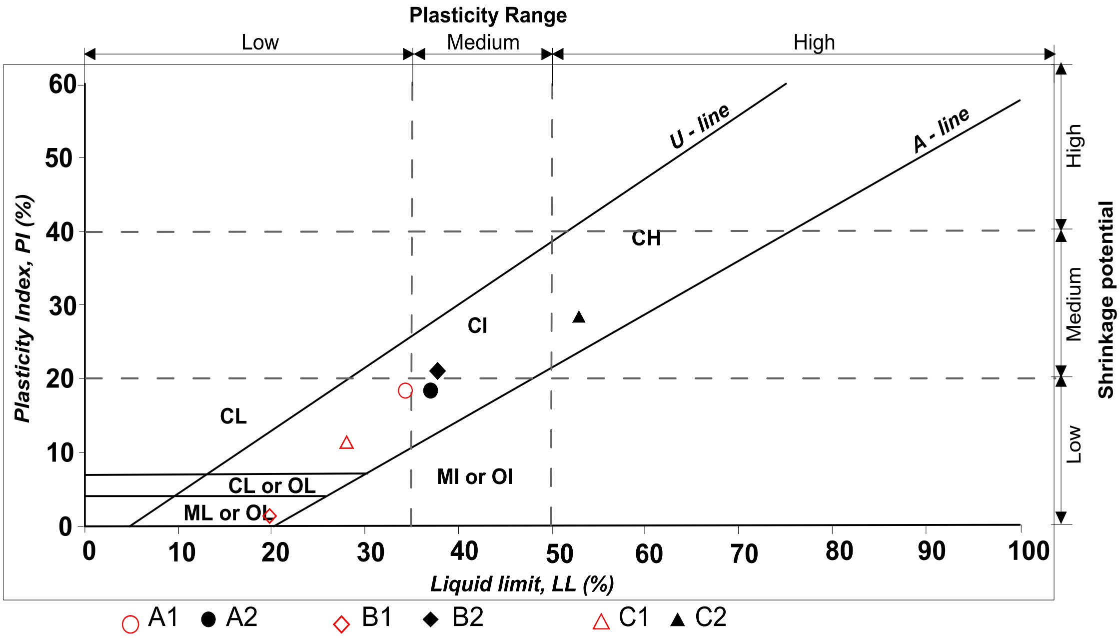

Figure 5: Casagrande chart for the soil under investigation

Compaction Characteristics

The results of compaction test are shown on Table 4. The maximum dry density (MDD) for soils below stable sections were higher at stable locations, with values ranging from 1775 to 1964 kg/m^2, than unstable locations where MDD values varied from 1688 to 1923 kg/m^2. Similar behavioural trend was observed with the Optimum Moisture Contents (OMC) of the soils below stable sections exhibiting lower values (that is 12.2 to 16.8 %) than their counterparts beneath unstable sections (that is 13.2 to 18.9 %) of the pavement (Fig. 6). From these observations, the subgrade soils underlying the stable sections possessed better compaction characteristics than those associated with unstable portions of the flexible pavements.

Strength Characteristics

The Californian Bearing Ratio (CBR), Unconfined as well as triaxial shear strengths of the soils are presented on Fig. 6. The soaked and un-soaked CBR values for subgrade soils at stable sections varied from 11 to 15 % and 26 to 59 % respectively. The soaked and un-soaked CBR values for subgrade soils at unstable sections varied from 3 to 10 % and 6 to 23 % respectively. Both the un-soaked and soaked CBR of samples from unstable sections are lower than the CBR values of samples from stable sections. The Unconfined Compressive Strength (UCS) for soils underlying stable locations ranged from 50.21 to 209.62 KPa while the UCS values ranged from 25.19 KPa to 62.85 KPa for failed portions. The shear strength characteristics in terms of angle of internal friction (φ) and cohesion (C) indicated better values in favour of engineering performance by subgrade soils from stable sections of the pavement. Both the compressive and shear strength values for soils in stable areas are relatively higher than those for unstable locations. The grading characteristics of the soils are not unconnected with the pattern of strengths exhibited by the soils. These are indications that the subgrade soils beneath the stable segments of the highway possess better load bearing capacity and higher strength characteristics than those beneath unstable sections of the pavement.

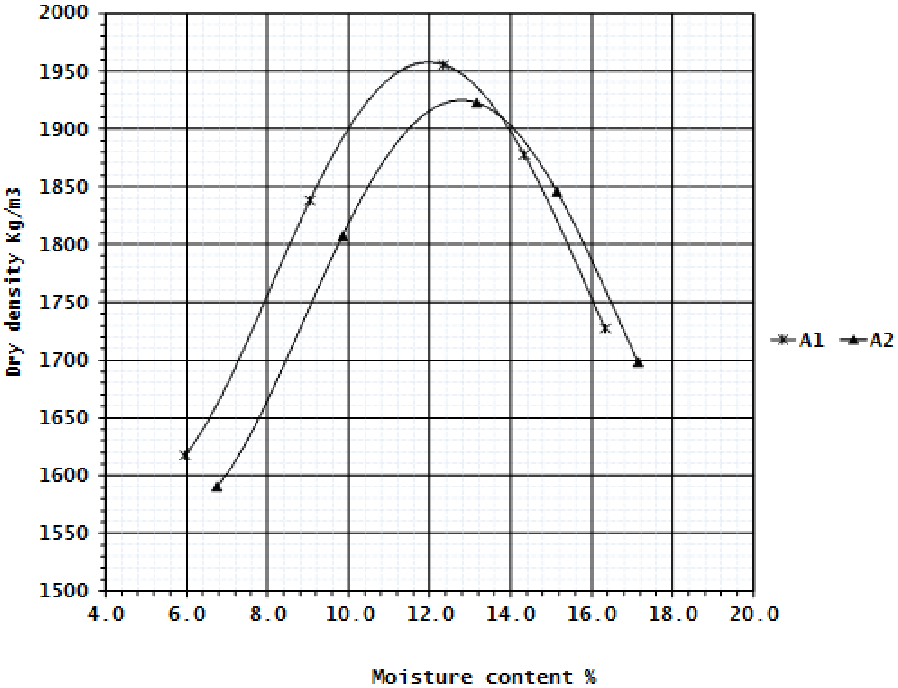

Figure 6a: Compaction Characteristics of soil samples A1 and A2.

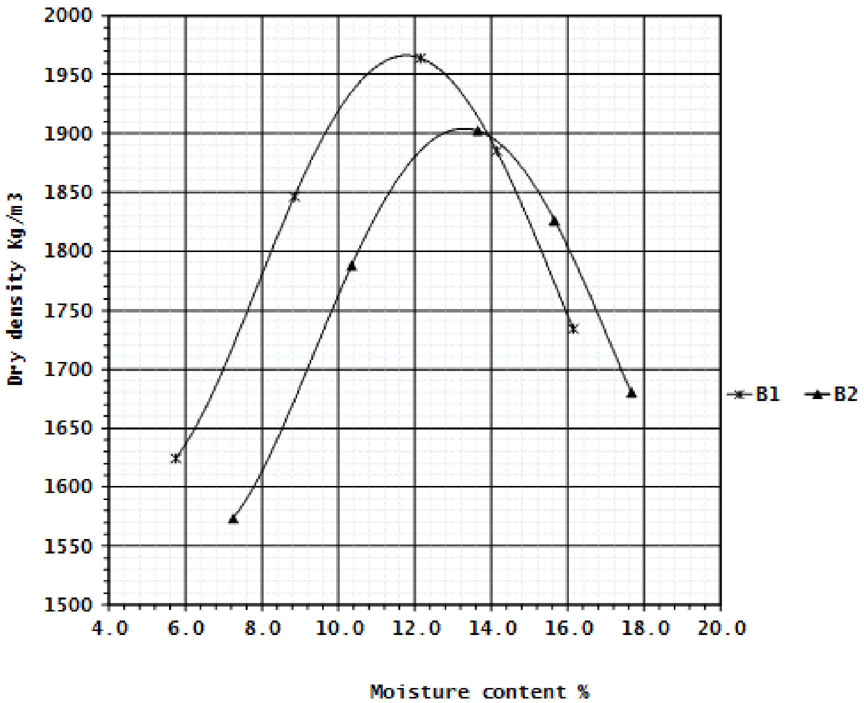

Figure 6b: Compaction Characteristics of soil samples B1 and B2.

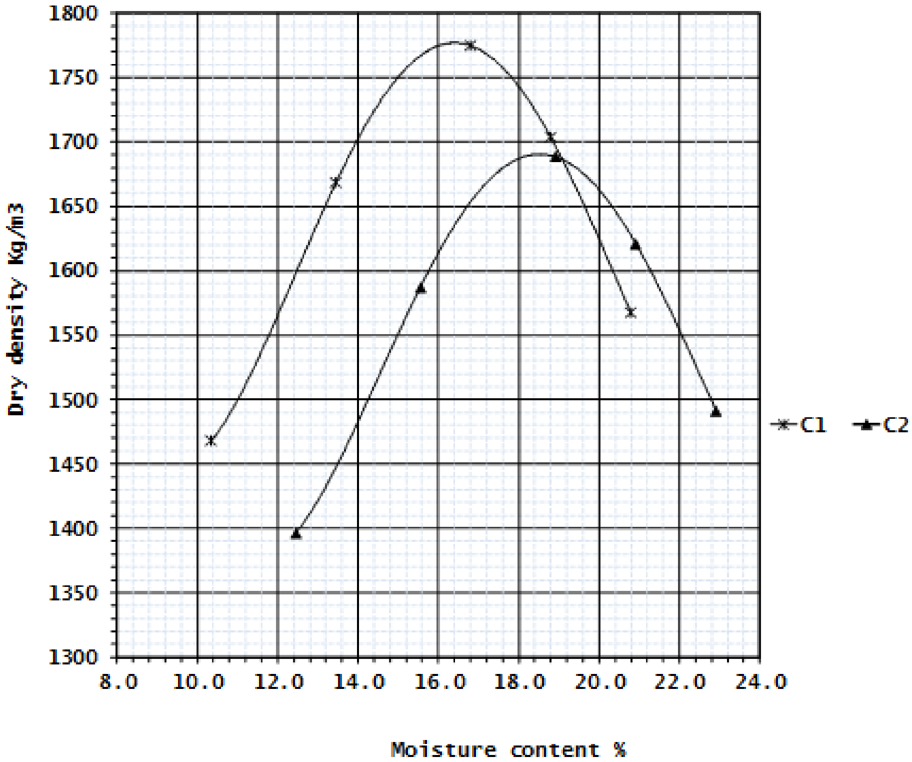

Figure 6c: Compaction Characteristics of soil samples C1 and C2.

V. Conclusion

The specific gravity values gave indication of higher degree of maturity and laterization for subgrade soil underlying stable locations than those from unstable locations. Although all the subgrade soils were generally well-graded, textural analyses indicated that soils below stable pavements exhibited generally lower proportions of fines than the soils underlying unstable sections of the flexible pavements. Both the Casagrande and Whitlow classification schemes agreed that the plasticity of the soils underlying stable sections of road pavement were relatively lower than that of the soils below the failed sections. Moreover, the subgrade soils below stable pavements exhibited relatively higher CBR, UCS and shear strength values than their counterparts below unstable sections. Furthermore, soils from stable locations showed better compaction characteristics than their counterparts from unstable locations. These results indicate that the contrasting engineering performances of the lateritic soils reveal their plasticity and strength characteristics. From the foregoing therefore, the failure of the sections of the flexible highway pavement investigated is largely a function of the geotechnical properties of the subgrade soils.

VI. Acknowledgments

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