Geotechnical and Mineralogical Evaluation of Soils Underlying a Failed Highway Section in South Eastern Nigeria

Akaha Celestine Tse and Oghenekevwe Efobo

Department of Geology, University of Port Harcourt, Port Harcourt, Nigeria

Abstract: The Port Harcourt Enugu expressway is part of a national road grid that links parts of southern and northern Nigeria. The severe pavement failure between Umuahia and Okigwe section of the expressway covering a distance of about 30 km was investigated by geotechnical and mineralogical assessment of disturbed and undisturbed samples of the underlying soils. Also vertical electrical sounding was performed at the failed sections. Results indicate that the section is underlain by shales of the Imo Formation, and soils are composed of 27% and 74% sand and fines respectively. The Atterberg limit values are moderate to high, with liquid limit in the range of 49-54%, plasticity index 11.1-24.4% and linear shrinkage 17.86-23.57% respectively. Abrasion test results of 0.58 to 16% indicate shales of low durability. The 24 hour free swell tests results range from 33-70% implying soils of moderate to high hydro-affinity and volume change. These data corroborate the X-ray diffraction analyses results which show montmorillonite and kaolinite as the main clay minerals present in the soils. Undrained cohesion range from 9 to 54 kPa and frictional angle from 13° to 29°. High settlement amounts and field observation of intense failure correlated well with the engineering properties and the clay minerals. The soils indicate mainly MI-MH and A-7-5 soils on the USC and AASHTO classification system respectively, implying poor quality soils as subgrade materials. The engineering properties may be modified and upgraded by stabilisation. Result of the study will be useful in remedial works on the failed sections of the road and future pavement design in areas underlain by the shales.

Key words: Geotechnical, mineralogical, highway, Imo Formation, clay minerals.

1. Introduction

The Port Harcourt-Enugu highway which is a segment of a major national road network that links the Niger Delta petroleum rich parts of southern Nigeria with northern Nigeria, is a flexible pavement built over terrains underlain by sedimentary to pyroclastic rocks deposited during the Cretaceous to Tertiary periods. Flexible pavements are constructed of several layers of natural granular material covered with one or more waterproof bituminous surface layers. Many sections of the road are underlain by argillaceous rocks. The segment between Umuahia and Okigwe, corresponds to the road alignment with the most pervasive and recurrent pavement failure

(Fig. 1). Despite repeated remedial rehabilitation strategies including removal and resurfacing of the failed sections, pavement distress occurs soon afterwards. Geologically, this segment is underlain by the Imo Formation which consists of thick fine textured, dark grey to bluish grey clayey shale, with occasional admixture of clay ironstone and thick sandstone beds [1]. A review of the factors influencing the performance of a pavement has been described by Ref. [2] including the different types of road failure ranging from cracks, pot-hole to road-cut leading to differential heave. Shales possess variable engineering problems which cause damage to civil structure founded on them such as heave on pavements, cracks on buildings, settlement and shear failure, thus reducing the lifespan of the structures. Thus they are usually unsuitable as construction

Corresponding author: Akaha Celestine Tse, Ph.D., research fields: engineering geology and environmental geology.

Fig. 1 Types of pavement failure in the study area.

material in foundations, buildings, highways, water retaining structures, dams etc. [3] due to clay mineral composition, physical properties such as particle size distribution, non-clay mineral composition, organic matter content and geologic history [4]. For example, the heterogeneity of the subgrade materials [5, 6], and presence of expansive clays have impaired civil infrastructure such as transportation networks [7], residential, industrial and commercial facilities and water supply and sewage collection systems [8-11]. The unsatisfactory behaviour of shales as construction materials has been locally studied in the Lower Benue Trough [12-18]. Generally, these studies conclude that in south eastern Nigeria, Tertiary Shales in the Lower Benue Trough exhibit varying degrees of poor engineering performance as subgrade materials on account of their geological and engineering properties. Sometimes highways are built with inadequate geotechnical studies of neither the soils along the alignments nor the borrow pits which provide the construction materials resulting in subgrade and subbase materials which fall short of

engineering specifications. The presence of clay minerals derived from underlying shales is a major contributory factor to the behaviour and performance of roads built over shale subgrades. This is similar to the swelling behaviour of expansive shales from the middle region of Saudi Arabia which causes severe and widespread damage in residential buildings, sidewalks and pavements due to the development of heave and swelling pressure in the expansive shales [19]. Also in south-western Nigeria underlain by basement rocks, pavement distress due to poor subgrade performance in addition to poor engineering construction has been reported [20-23]. This work is an attempt to determine critical factors in the pavement performance by correlating the mineralogical and the geotechnical index properties of soils developed over the underlying Imo Shale between Umuahia and Okigwe to the pervasive road failure in the section. The study area is located along Umuahia-Okigwe road between longitude $7^{\circ}08' E$ and $7^{\circ}30' E$ latitude $5^{\circ}35' N$ and $5^{\circ}49' N$ within which the Imo Shale outcrops (Fig. 2). A more recent

2. Materials and Methods

procedures in Refs. [26, 27].

Organic content of the soil was determined by the ignition method whereby a known weight of the soil was heated to temperature as high as 700-800 °C in a furnace. The loss of soil due to the heating at high temperature was determined and reported as the organic matter content to the nearest 0.1% based on the total oven dried weight of the soil. The slake durability test was performed as described in Ref. [27] to determine quantitatively the durability in terms of the SDI (Slake Durability Index). Oven-dried samples of rock were placed in a wire mesh drum partially immersed in water and the drum rotated at 20 r.p.m. for approximately 10 mins over two cycles. The slake durability index was afterwards determined as the percentage by dry mass retained of a collection of shale pieces on a 2 mm mesh sieve. For the quick undrained unconsolidated triaxial test, the stress path method as describe by Ref. [28] which gives a continuous

Table 1 Sampling locations and coordinates.

S/N	Locations	Latitude	Longitude	Elevation (m)	Sample Type
1	Ohuhu I	5°36'40" N	7°26'37" E	111	Disturbed/Undisturbed
2	Ohuhu II	5°36'40" N	7°26'30" E	105	Disturbed/Undisturbed
3	Nkpa I	5°39'18" N	7°25'19" E	113	Disturbed/Undisturbed
4	Nkpa II	5°38'10" N	7°25'18" E	76.1	Disturbed/Undisturbed
5	Nunya I	5°41'55" N	7°25'02" E	120	Disturbed/Undisturbed
6	Nunya II	5°42'21" N	7°25'40" E	135	Disturbed/Undisturbed
7	Ezinachi I	5°44'23" N	7°22'10" E	129	Disturbed/Undisturbed
8	Ezinachi II	5°45'01" N	7°22'04" E	159	Disturbed/Undisturbed
9	Umuna I	5°45'46" N	7°15'22" E	115	Disturbed/Undisturbed
10	Umuna II	5°46'06" N	7°14'52" E	126	Disturbed/Undisturbed

Table 2 Laboratory tests and standards.

S/N	Test	Method/Standard	Sample
1	Natural Moisture Content	BS 1377:1990 Part 2 Section 3	Disturbed sample
2	Liquid Limit	BS 1377:1990 Part 2 Section 4.5	Disturbed sample
3	Plastic Limit	BS 1377:1990 Part 2 Section 5.3	Disturbed sample
4	Linear Shrinkage	BS 1377:1990 Part 2 Section 6.5	Disturbed sample
5	Bulk Density	BS 1377:1990 Part 2 Section 6.7	Disturbed sample
6	Specific Gravity	BS 1377:1990 Part 2 Section 8	Disturbed sample
7	Particle Size Analysis	BS 1377:1990 Part 2 Section 9	Disturbed sample
8	Organic Matter Content	BS 1377:1990 Part 3 Section 3.4	Disturbed sample
9	Free Swell Test	IS 2720:1985 Part 40	Disturbed sample
10	Slake Durability Index	ASTM D4644:1987	Disturbed sample
11	Triaxial Compression Test	BS 1377:1990 Part 7 Section 8	Undisturbed sample
12	Consolidation Test	BS 1377:1990 Part 5 Section 3	Undisturbed sample
13	X-ray Diffraction Analysis	Bragg's Law (1913)	Whole rock

representation of the relationship between the components of stress at a given point as they change was used to determine the undrained cohesion and frictional angle. Each specimen of 35 mm diameter and 110 mm height was prepared from the undisturbed samples obtained with U-4 tubes of 120 mm diameter and tested in quick unconsolidated-undrained compression using cell pressures of 100, 200 and 300 kN/m² respectively. Clay mineral species were determined using whole rock and clay fraction soil samples for X-ray diffraction with a PW 1800 automated diffractometer with a Cu-K α radiation source (30 kV, 55 mA). During the field investigation, the VES method of electrical resistivity survey was employed to determine the geoelectric characteristics of the underlying soils. The VES data were acquired with an ABEM SAS 300 terrameter using the

Schlumberger electrode array with maximum current electrode separation (AB/2) of 200 m. A total of 10 VES points were occupied. Field curves were generated by plotting the apparent resistivity values against the electrode spacing (AB/2). The curves were interpreted using the partial curve matching technique. The manually derived geoelectric parameters were further refined using a forward modeling software, RESIST version 1.0 and the VES data were interpreted based on the approach of Ref. [29].

3. Results and Discussion

3.1 Index Properties

Results of the various tests are summarised in Table 3. Particle size analysis of the samples gave average values of sand and fines (silt and clay) content as 26.5% and 74.3% respectively. Typical size

Table 3 Summarising the engineering properties of the soils.

Property	Ohuhu I	Ohuhu II	Nkpa I	Nkpa II	Nunya I	Nunya II	Ezinachi I	Ezinachi II	Umuna I	Umuna II	Range	Average
Liquid Limit (%)	53.5	56	42.6	55	53.6	40.4	63.04	64.8	40.9	57.4	40-64.80	52.76
Plastic limit (%)	37.3	31.6	27.3	38	36.6	23.7	39.6	41.2	29.8	35.1	23.7-41.20	34.02
Plasticity Index (%)	16.2	24.4	15.3	17	17	16.7	23.8	23.6	11.1	22.3	11.1-24.4	18.74
Linear Shrinkage (%)	23.57	20	17.86	20	18.57	20	22.86	21.43	20.36	20	17.86-23.57	20.47
Specific Gravity	2.37	2.49	2.64	2.45	2.55	2.45	2.5	2.53	2.53	2.56	2.37-2.64	2.51
Organic Content (%)	4.5	5	3.5	6.5	5	4	4	4.5	5	5	3.50-6.50	4.70
Natural Moisture Content (%)	34.94	30.59	29.76	46.75	37.90	33.33	44.57	36.00	36.11	34.57	29.76-46.75	36.45
Bulk Density (kN/m ³)	18.74	18.84	18.74	18.15	19.33	19.13	18.35	17.85	18.54	19.52	17.85-19.52	18.72
Free Swell (%)	55.67	66.67	55.56	70	33.33	47.37	42.86	52.34	44.44	50	33.33-70.00	51.82
USCS	MI-MH	MI-MH	MI-MH	MI-MH	MI-MH	CI	MI-MH	MI-MH	MI-MH	MI-MH	-	-
ASSHTO	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	A-7-5	-	-
Grain Size	Sand (%)	15	16	43	10	34	30	3	12	43	12-59	26.50
	Silt/Clay (%)	85	84	57	90	66	70	97	88	65	41-97	74.30

Fig. 3 Typical particle size gradation curves.

distribution curves are represented in Fig. 3. The high fines content suggests a high water retention capability. The natural moisture content ranges from 29.76-46.75% with an average of 36.45%. These values are higher than the average range (5-15%) specified by Ref. [30] for engineering specification. The moisture content indicates a high water adsorption capability of the shale material. It is used as an indicator for the shear strength of soils, as increase in the moisture content results in a decrease in the shear strength of the material. Natural moisture content also influences the shrink-swell potential of soils [31] and also clay bulk density and consistency [32]. With an average bulk density of 18.72 kN/m³, the shale may be classified as dense. The organic

matter content ranges from 3.5-6.5% with an average of 4.7%. The amount of soil organic matter significantly affects index, physico-chemical and engineering properties of soils, including compressibility and strength. Generally, organic matter in soils increases soil compressibility and reduces strength. The liquid limit range from 40.4-64.8% with an average of 52.76% while the plasticity index range from 11.1-24.4% with an average of 18.74%.

When the textural characteristics and consistency results were evaluated, the soil samples classified as organic clay of intermediate to high plasticity, MI-MH (Fig. 4) according to the Unified Soil Classification scheme, and as A-7-5 soils using the AASHTO

Fig. 4 Position of the soils on the plasticity chart.

classification system, all implying that they are of poor quality as subgrade materials in pavement construction.

This classification also is in agreement with Refs. [33, 34] soil expansivity classification system. All the samples have a group index of more than 20 which reinforces the poor subgrade quality rating of the soil. The index properties of these highly organic silt and clayey soils exceed the general specification [35] for roads and bridges which states that liquid limit and plasticity index should not exceed 50 and 30% respectively, and particle size passing sieve number 200 (0.074 mm) should not be greater than 35%. The linear shrinkage ranges from 17.86-23.57% with an average of 20.47% which is rated as non-critical to marginal. With a free swell index range from 33.33 to 70% and an average value of 51.80%, the shale material is considered to have moderate to high swelling potential at Nunya, Ezinachi I, Umuna I and very high swelling potential in the rest of the study locations. This portends damage to engineering structures founded in the soils due to potential large volume changes in wet and dry conditions.

The slake durability index of the shales range from 0.58 to 16.20% (Table 4). This falls within the range of 10-20% for shales which should be treated like soil after excavation in contrast to shale rating with SDI

range of 70-80% which indicate that shales should be treated as rock.

Slake durability is often used to differentiate between durable and non-durable rocks. The shales in this study disaggregated in water which is an indication of weathered and relatively weak soils, thus they are not suitable for use in pavement constructions. Poor subgrade materials are characterised by low stiffness and resistance to deformation which results in pavement failure due to inability to support a high amount of loading [36].

3.2 Shear Strength and Settlement Characteristics

The shear resistance parameters (Table 5) were obtained from the undrained unconsolidated triaxial

Table 4 Slake durability index results.

Locations	Slake Durability Index Test
Ohuhu I	1.77
Ohuhu II	10.87
Nkpa I	1.81
Nkpa II	3.09
Nunya I	15.39
Nunya II	4.89
Ezinachi I	6.27
Ezinachi II	16.20
Umuna I	0.58
Umuna II	5.74

Table 5 Shear strength characteristics.

Locations	Depth of Samples (m)	Unit Weight γ (kN/m ³)	Undrained Cohesion (kPa)	Angle of friction Φ (degree)
Ohuhu I	1	15.97	24	16
Ohuhu II	1	17.11	25	17
Nkpa I	1	16.12	52	26
Nkpa II	1	15.8	9	10
Nunya I	1	16.9	53	27
Nunya II	1	17.21	54	26
Ezinachi I	1	14.37	16	13
Ezinachi II	1	14.6	14	14
Umuna I	1	14.92	23	21
Ununa II	1	17.27	14	23

Fig .5 Typical stress-strain path in triaxial test.

test using the stress path plot (Fig. 5). The undrained cohesion ranges from 9 to 54 kPa and frictional angles from 13 to 29°. These values are relatively low and correlate well with the durability index test results. The low strength will cause pavement failure under sustained axial loading. Generally, the permeability values of the order of 10^{-11} m/s indicate practically non-permeable soils. The ranges of values of coefficient of volume compressibility, m_v (0.0123 to

0.0128 m²/MN) and coefficient of compressibility C_v , (1.64×10^{-8} to 5.47×10^{-8} m²/s) obtained from the consolidation tests (Fig. 6) give an indication of the large volume changes that are associated with the soils with settlement as high as 138 mm.

3.3 Mineralogical Characteristics

The X-ray diffractograms of the whole rock samples (Fig. 7) show that the main clay minerals present are

Fig. 6 Typical e-p curve.

Table 6 Settlement characteristics of the soils.

Locations	e_o	Δe	$\Delta \sigma$	k_v (m/s)	M_v (m ² /MN)	C_v (m ² /s)	S_c (cm)
Ohuhu I	1.196	1.122	40	2.1×10^{-11}	0.0128	$1.64E^{-8}$	10.19
Ohuhu II	1.054	1.02	40	3.4×10^{-11}	0.0124	$2.74E^{-8}$	9.37
Nkpa I	1.084	1.072	40	4.2×10^{-11}	0.0128	$3.28E^{-8}$	13.66
Nkpa II	1.37	1.22	40	3.6×10^{-11}	0.0128	$2.81E^{-8}$	9.89
Nunya I	1.125	1.06	40	4.3×10^{-11}	0.0125	$3.44E^{-8}$	10.02
Nunya II	1.080	1.024	40	2.9×10^{-11}	0.0123	$2.36E^{-8}$	9.11
Ezinachi I	1.406	1.235	40	3.3×10^{-11}	0.0128	$2.58E^{-8}$	12.09
Ezinachi II	1.460	1.26	40	4.7×10^{-11}	0.0128	$3.67E^{-8}$	10.02
Umuna I	1.371	1.215	40	7×10^{-11}	0.0128	$5.47E^{-8}$	13.79
Ununa II	1.127	1.042	40	7×10^{-11}	0.0123	$5.69E^{-8}$	10.41

Note: e_o = Initial void ratio, Δe = Change in void ratio, $\Delta \sigma$ = Change in stress, k_v = Coefficient of Permeability, M_v = Coefficient of Volume Compressibility, C_v = Coefficient of Consolidation and S_c = Consolidation Settlement.

Geotechnical and Mineralogical Evaluation of Soils Underlying a Failed Highway Section in South Eastern Nigeria

Fig. 7 Typical diffractograms (a = Ohuhu, b = Nkpa).

montmorillonite and kaolinite (Table 7). Sections of the road along Nkpa and Ohuhu which contain relatively more montmorillonite in the soil structure exhibit the most severe form of pavement failure. This is expected because montmorillonite is an active clay mineral with high hydroaffinity which causes cyclic soil swelling and shrinking resulting in pavement distress and damages. The high clay mineral content

correlates well with the high values of liquid limit, plasticity index and high natural moisture content. Sections of the road at Nunya, Ezinachi and Umuna where the soils contain mainly kaolinite as the clay mineral experience less severe pavement failure since kaolinite is a relative more stable clay mineral than montmorillonite in terms of differential volume changes.

Table 7 Clay mineral composition of the soils.

Locations	Quartz	Kaolinite	Montmorillonite
Ohuhu I	36.94	63.13	-
Ohuhu II	18.96	68.44	12.60
Nkpa I	33.60	32.62	33.78
Nkpa II	18.94	68.75	12.32
Nunya I	23.45	76.55	-
Nunya II	34.99	65.01	-
Ezinachi I	22.92	77.08	-
Ezinachi II	33.64	66.36	-
Umuna I	23.27	76.73	-
Ununa II	22.46	77.54	-

3.4 Geoelectric Characteristics

The AK curve type identified within the study area is the predominant curve type (Fig. 5). Five geological subsurface layers comprising mainly sand and clay were delineated. The top soil is composed of sandy clay or clayey sand or laterite with resistivity values of 62 to 130 Ωm . It has a thickness of about 1.45 to 1.99 metres. The second layer is a clay with resistivity values that vary between 418 Ωm and thickness of between 2.86 to 3.43 metres. These low resistivity values are typical of expansive clay which is thought to be a major contributor to the instability of the road. The electrical resistivity characteristics corroborate the poor geotechnical properties of the soils obtained in this study, and are in agreement with the results of [15] which underscore the unsuitability of the soils to transmit axial loads for long periods without failure. In addition, the lack of drainage results in collection of water from run-off on the shoulders of road which also promotes failure by lowering the soil strength. The 3rd, 4th and 5th layers are composed of sand up to 80 metres deep. The high resistivity of the 3rd layer (644 to 11,720 Ωm) suggests saturated sand.

The poor geotechnical properties of the soils imply that they are unsuitable for use as foundation materials in engineering structures. This is evident in the widespread failure of the pavement such as elastic deformation which indicates the generation of excess pore water pressures in one or more of the underlying

layers. Options for dealing with these weak shales include removal and replacement of the soils with desirable engineering properties during construction, design of structures to fit into the soil properties, or modification of the properties. The clayey and organic nature of the soils will not yield any significant improvement if mechanical compaction is employed. However, stabilisation by chemical methods using cement, lime or their admixtures will achieve desired results of reducing the hydroaffinity, increasing the soil strength and restrict the volume change potential of the weak, fine grained, highly plastic and compressible shales by causing a reduction of void spaces and binding the particles of soil together. It is recommended that for soils to be stabilized with cement, proper mixing requires that the soil have a PI of less than 20% and a minimum of 45% passing the 0.425 mm sieve [37]. Therefore the study soils satisfy this condition because the average PI is 18%. A cement-modified soil reduces plasticity and expansive characteristics. However, the presence of organic matter will affect soil cement by inhibiting the normal hardening process unless the PH is brought to least 12. Alternative to cement is the use of lime which achieves rapid strength gain, reduces plasticity and accomplishes long-term pozzolanic cementing when mixed with fine grained soils. This implies that soils classified as CH, CL, MH, ML, SC, and GC with a plasticity index greater than 12 and with 10% passing the 0.425 mm (No. 40) sieve are potentially suitable

Geotechnical and Mineralogical Evaluation of Soils Underlying a Failed Highway Section in South Eastern Nigeria

Fig. 8 Typical computer modeled curves (a=Ohuhu, b=Nkpa).

for stabilization with lime. Lime has been found most effective in improving workability and reducing swelling potential with highly plastic clay soils containing montmorillonite, illite, and kaolinite. Generally therefore, the weak shales underlying the road alignment in this study may be modified by stabilization with cement or lime to obtain desirable strength for engineering applications.

4. Conclusion

The aim of this work was to determine the mineralogical and geotechnical index properties of soils developed over the Imo Shale underlying the highway between Umuahia and Okigwe and relate the properties to the pervasive pavement failure in the section. Data from this study suggest that the geotechnical properties and the mineralogical composition of the shale are major factors responsible for road failure in the area. The index properties of these organic silty and clayey soils exceed the general specification for roads and bridges in Nigeria. However, stabilisation using cement or lime will improve the strength. Results of this study will be useful in remedial works on the rehabilitation of the failed sections of the road and may guide future pavement design in other areas underlain by the shale.

References

- [1] Kogbe, C. A. 1989. "The Cretaceous and Paleogene Sediments of Southern Nigeria." In *Geology of Nigeria*, edited by Kogbe, C. A. Rock View, Jos., 325-34.
- [2] Adlinge, S. S., and Gupta, A. K. 2010. "Pavement Deterioration and Its Causes." *International Journal of Innovative Research and Development* 2 (4): 437-50.
- [3] Ola, S. A. 1982. "Mechanical Properties of Concretionary Laterites from Rainforest and Savannah Zones of Nigeria." *Bull. of Int. Assoc. of Eng. Geol.* 21: 21-6.
- [4] Grim, R. E. 1968. *Clay Mineralogy*, 2nd edition. New York: McGraw-Hill Book Company, p. 596.
- [5] Adeleye, A. O. 2005. "Geotechnical Investigation of Subgrade Soil along Sections of Ibadan-Ile Highway." Unpublished M.Sc. Project, Obafemi Awolowo University, Ile-Ife, 181.
- [6] Adeyemi, G. O., Oloruntola, M. O., and Adeleye, A. O. 2014. "Geotechnical Properties of Subgrade Soils along Sections of the Ibadan-Ife Expressway, South-Western Nigeria." *Journal of Natural Sciences Research* 4 (23): 67-75.
- [7] Mesida, E. A. 1987. "The Relationship between the Geology and the Lateritic Engineering Soils in the Northern Environs of Akure, Nigeria." *Bulletin of the international Association of Engineering Geology* (35): 65-9.
- [8] Azam, S., Ito, M., and Chowdhury, R. 2013. "Engineering Properties of an Expansive Soil." In *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris.
- [9] Ito, M., and Azam, S. 2010. "Determination of Swelling and Shrinkage Properties of Undisturbed Expansive Soils." *Geotechnical and Geological Engineering* 28: 413-22.
- [10] Hu, Y., and Hubble, D. W. 2005. "Failure Conditions of Asbestos Cement Water Mains." *Canadian Geotechnical Journal* 34: 608-21.
- [11] Kelly, A. J., Sauer, E. K., Barbour, S. L., Christiansen, E. A., and Widger, R. A. 1995. "Deformation of the Deer Creek Bridge by an Active Landslide in Clay Shale." *Canadian Geotechnical Journal* 32: 701-24.

- [12] Aghamelu, O. P., Odoh, B. I., and Egboka, B. C. E. 2011. "A Geotechnical Investigation on the Structural Failures of Building Projects in Parts of Awka, Southeastern Nigeria." *Indian Journal of Science and Technology* 4 (9): 1119-24.
- [13] Aghamelu, O. P., and Okogbue, C. O. 2011. "Geotechnical Assessment of Road Failures in the Abakaliki Area, Southeastern Nigeria." *Intl. J. Civil & Environ. Engg.* 11 (2): 12-24.
- [14] Ekeocha, N. E. 2012. "The Engineering Geological and Mineralogical Properties of Cretaceous and Tertiary Shales in the Lower Benue Trough, South Eastern Nigeria." Unpublished Ph.D. thesis, 278.
- [15] Ekeocha, N. E., and Akpokodje, E. G. 2012. "Assessment of Subgrade Soils of Part of the Lower Benue Trough Using California Bearing Ratio (CBR)." *The Pacific Journal of Science and Technology* 13 (1): 572-9.
- [16] Ekeocha, N. E., and Akpokodje, E. G. 2014. "Cement Stabilization Characteristics of Shale Subgrade of Parts of the Lower Benue Trough, Southeastern Nigeria." *International Journal of Science and Technology* 3 (1): 78-84.
- [17] Onuoha, D. C., and Onwuka, S. U. 2013. "The Place of Soil Geotechnical Characteristics in Road Failure, a Study of the Onitsha-Enugu Expressway, Southeastern Nigeria." *Civil and Environmental Research* 6 (1): 55-67.
- [18] Onyeobi, T. U. S., Imekparia, E. G., Ilegieuno, O. A., and Egbuniwe, I. G. 2013. "Compositional, Geotechnical and Industrial Characteristics of Some Clay Bodies in Southern Nigeria." *Journal of Geography and Geology* 5 (2): 73-84.
- [19] Abdullah, I. A. 1998. "Swelling Behaviour of Expansive Shales from the Middle Region of Saudi Arabia." *Geotechnical and Geological Engineering* 16: 291-309.
- [20] Abam, T. K. S., Osadebe, C. C., and Omange, G. N. 2005. "Influence of Geology on Pavement Performance: A Case Study of Shagamu-Benin City Road, Southwestern Nigeria." *Global Journal of Geological Sciences* 3 (1): 17-24.
- [21] Jegede, G. 2004. "Highway Pavement Failure Induced by Poor Soil Geotechnical Properties at a Section along the F209 Okitipupa-Igbokoda Highway, Southwestern Nigeria." *Ife Journal of Science* 6 (1): 41-4.
- [22] Adeyemo, I. A., and Omosuyi, G. O. 2012. "Geophysical Investigation of Road Pavement Instability along Part of Akure-Owo Express Way, Southwestern Nigeria." *Am. J. Sci. Ind. Res.* 3 (4): 191-7.
- [23] Adams, J. O., and Adetoro, A. E. 2014. "Analysis of Road Pavement Failure Caused by Soil Properties along Ado Ekiti-Akure Road, Nigeria." *International Journal of Novel Research in Engineering and Applied Sciences (IJNREAS)* 1 (1).
- [24] Nwajide, C. S. 2013. *Geology of Nigeria's Sedimentary Basins*. Lagos: CSS Bookshops Limited, 565.
- [25] Akande, S. O., Ojo, O. J., Adekeye, O. A., Egenhoff, S. O., Obaje, N. G., and Erdmann, B. D. 2011. "Stratigraphic Evolution and Petroleum Potentials of the Middle Cretaceous Sediments in the Lower and Middle Benue Trough, Nigeria, Insights from New Source Rock Facies Evolution." *Petroleum Technology Journal* 1: 1595-9104.
- [26] BS, British Standards. 1990. "Methods of Testing for Soils for Civil Engineering Purposes." BS 1377, British Standards Institution. London.
- [27] ASTM. 1992. *Standard Method for Classification of Soils for Engineering Purposes (Unified Soil Classification System): ASTM Standard D2487*. American Society for Testing and Materials, West Conshohocken, Pa.
- [28] Lambe, T. W. 1967. "The Stress Path Method." *Journal of the Soil Mechanics and Foundation Division. ASCE*, 93(SM6): 309-31.
- [29] Zohdy, A. A. R. 1989. "A New Method for the Automatic Interpretation of Schlumberger and Wenner Sounding Curves." *Geophysics* 54 (2): 245-56.
- [30] Underwood, L. B. 1967. "Classification and Identification of Shales." *J. Soil Mech. Found. Div., ASCE*, 93 (11): 97-116.
- [31] Nelson, D., and Miller, D. J. 1992. *Expansive Soils Problems and Practice in Foundation and Pavement Engineering*. New York: John Wiley, 259.
- [32] Bell, F. G. 2000. *Engineering Properties of Soils and Rocks*, 4th Ed. Oxford: Blackwell Science, 482.
- [33] Chen, F. H. 1975. *Foundations on Expansive Soils*. 2nd Ed., Amsterdam, The Netherlands: Elsevier Scientific Publishing Co.
- [34] Holtz, W. G., and Gibbs, H. J. 1956. "Engineering Properties of Expansive Clays." *Transactions of ASCE* 121: 641-77.
- [35] Federal Ministry of Works and Housing (FMWH). 1997. *General Specification for Roads and Bridges*.
- [36] Amer, R., Saad, A., Elhafeez, T. A., Kady, H. E., and Madi, M. 2014. "Geophysical and Geotechnical Investigation of Pavement Structures and Bridge Foundations." *Austin J Earth Sci.* 1 (1): 6.
- [37] FHWA. 2005. "Geotechnical Aspects of Pavements Reference Manual." *Chapter 7.0 Design Details and Construction Conditions Requiring Special Design Attention*. Publication No. FHWA NHI-05-037. Federal Highway Administration, Washington, DC.