2D Electrical Resistivity Surveys and Geotechnical Studies for Pavement Failure Evaluation, North-Central, Nigeria

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Abstract- A 2D resistivity survey was combined with geotechnical tests to gain an insight into the influence of the underlying subgrade soils on the failed Ajaokuta-Anyigba Highway. Resistivity data from twelve (12) 2D traverses using Dipole-Dipole Array were complemented with geotechnical tests on twenty-one (21) subgrade soil samples from the unstable and stable sections of the highway. The geophysical results revealed that the unstable and stable sections are underlain by a continuous stretch of subgrade soils with low (< 100 Ohms.m) and high resistivities (100 – 1000 Ohms.m) interpreted as clayey and silty-sand respectively. Results of Geotechnical tests showed that the subgrade soils of the unstable segment have higher fines (52 – 64%), higher liquid limit (21.3 – 46. 0), higher plasticity index (12.7 – 38.8), a lower amount of sand (36 – 48 %) than subgrade soils of the stable section. Compaction test revealed that subgrade soils of the unstable sections have poorer compaction characteristics: Optimum Moisture Content, OMC (9.62 – 18.7%), and maximum dry density, MDD (1.7 – 2.03 g/cm^3) than the subgrades of the stable section. Unsoaked and soaked California Bearing ratio (CBR) were not only lower than those of the stable section but fell below relevant acceptable standards. The study showed that the low resistivity and poor geotechnical properties of the subgrades are major geological contributors to the instability of the pavement.

Keywords- Resistivity, Subgrade, Highway failure, Clay, Geotechnical properties

I. INTRODUCTION

In the last few centuries till the present, transportation authorities and highway engineers around the globe have been facing different types of challenges more than their counterparts [1]. Some of the challenges outlined by [1] include minor to catastrophic failures of roads and bridges around the world due to natural disasters, extreme weather, and human error. Most of these failures were attributed to the ground supporting the structures and appropriate authorities and agencies all over the world are now challenged with the responsibility of preventing similar future occurrences through better designs. Highway pavement failure is a major experience on Nigerian roads [2] and is known to occur shortly after construction and well before the design age [3]. The failure of highway pavements which is dated back to the colonial period [4] has been attributed to some factors, such as the use of poor construction materials, subgrade conditions, environmental conditions, traffic loading, lack of drainage, and poor workmanship [5],[4],[6] and [7]. However, studies conducted by authors such as [8 – 13] have shown that road failures are not primarily a result of faulty design alone but can also be a result of the influence of geomorphology and geology. For instance, research by [12-16] revealed that clayey soils in the subgrade are major reasons for highway failure. Research by [17] on geotechnical, mineralogical, and geochemical evaluation of soils concluded that the genesis of rocks and climatic factors affect the engineering geological properties of subgrade soils. Authors [e.g., 18-20] have reported the success of geophysical and geotechnical methods in site investigation. In the light of the aforementioned works, it is thus paramount to understand the nature of the subgrade soils which are the product of the geology of an area before designing a highway pavement.

Most studies on highway pavement failure have been skewed to the Southwestern part of Nigeria. Meanwhile, several highways have failed in other regions of Nigeria (e.g., Anyigba – Ajaokutata, Isanlu – Egbe, Kabba – Ekirin Highway) but have received very minimal attention. These highways are potential economic boosters because of their strategic geographical location. The present study is aimed at characterizing the foundation (subgrade) soils underlying the Ajaokuta-Anyigba highway using combined 2D resistivity and geotechnical data.

II. Study Area

The study location has been chosen because of the socio-economic importance of the road to the nation's development. It is delimited within N7^{0}22ˈ30ˈˈ-7^{0}30’0’’ and E06^{0}40ˈ30ˈˈ– 06048’0’’. Also, geologically, the highway is underlain by mica-schist and granite-gneiss [21]. This enables a comparative study of the influence of different rock types on the stability of the highway.

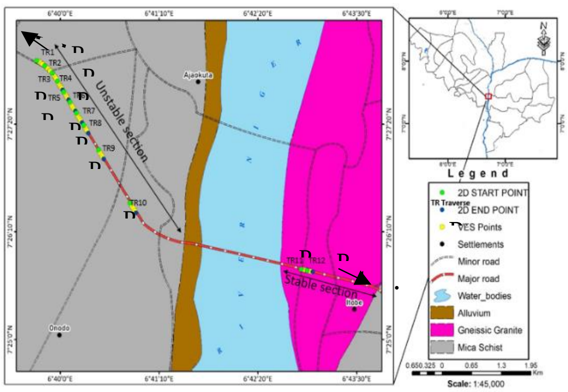

Figure 1: Geologic Map of the study area showing geophysical survey and soil sampling points [Modified from 21]

III. Methodology

Geophysical Study (2D Electrical Resistivity)
As a follow-up to the desk study of the existing maps and literature in the area, a reconnaissance survey involving field geological study and identifying possible 2D profile lines was conducted. This enabled the possibility of characterizing the highway based on geology and stability. The 2D profiles were therefore conducted on varying geology to appreciate the influence of geology on pavement failure.
2D Electrical Resistivity survey using Dipole-Dipole Array Dipole-Dipole was adopted for the 2D survey because it has good horizontal data coverage and can map vertical structures such as cavities [22]. Ten (10) 2D traverses, each approximately 200 m long were occupied on the unstable section underlain by Mica Schist. While two (2) 2D traverses were performed on the stable section with a profile length of 100 m. This was due to barriers caused by the drainage system and outcropping Granite gneiss at the flanks of the road. These profiles were meant to serve as a control. The detailed procedure for data acquisition has been well documented in [22].
Generally, different resistivity values obtained are a reflection of the subgrade soil type, degree of compactness, moisture content, and competency (Table 1).

Table 1. Resistivity range and corresponding inferred lithology

Resistivity range (Ohms-m)	Inferred Lithology	Engineering Implication	Colour code for 2D resistivity
< 100	Clay	Poor subgrade	Yellow
100 - 1000	Weathered basement (silty sand)	Fair – good subgrade	Green
> 2000	Fresh basement	Competent rock	Red

Geotechnical Study
Both index (classification) and strength tests were conducted on 21 subgrade soil samples obtained from the unstable and stable sections at depths ≤ 1 m adjacent to the 2D electrical resistivity lines. The index or classification tests include particle size distribution and the Atterberg limit. The strength tests include the compaction test and the California bearing ratio (CBR) in unsoaked and soaked states. Standard codes according to the American Society for Testing and Materials (ASTM) were used for the laboratory tests. It was however necessary to separate the clays and silts that were tightly bound to the sand using Sodium hexametaphosphate before running the particle size distribution. This procedure has been well reported by works in [23-24].

IV. Results and Discussion

2D Resistivity
Although a depth of up to 10 m was imaged in all the 2D sections, the first 2 m is considered paramount to the highway integrity as this constitutes the subgrade soil and the closest to the pavement [23]. Only three traverses that represent the entire eleven are presented in this paper.

Traverse 1
Within the first 2 m, the resistivity values are generally less than 45 Ohms-m inferred as clay throughout the entire 100 m (Fig. 2).

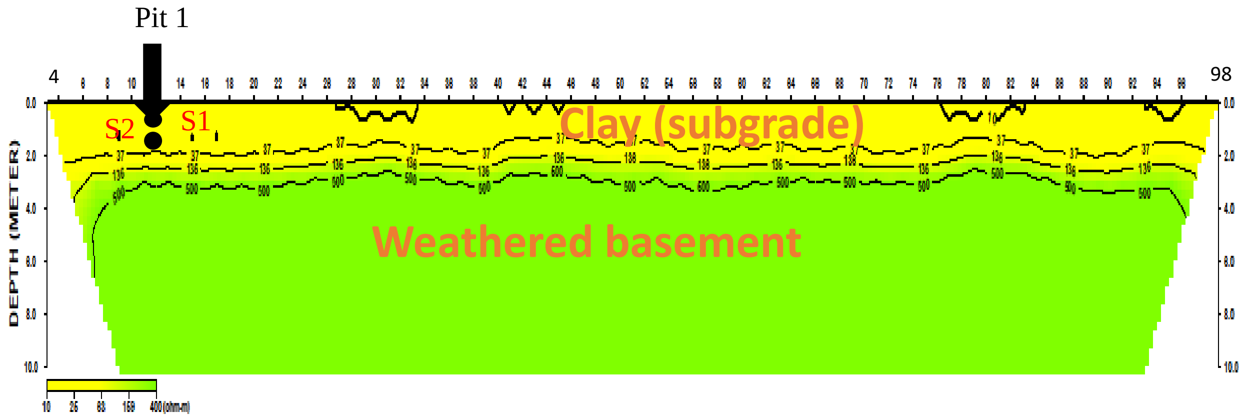

Figure 2. 2D resistivity structure and sampling points along Traverse 1

This clayey unit is the subgrade soil. It is the product of extensive weathering of the parent rock – Mica Schist. This clayey subgrade soil is inimical to highway pavement. This is due to the possibility of varying degrees of shrinking and swelling during dry and wet seasons. The very low resistivity also points to high moisture content and weak compaction. The geotechnical tests also corroborate these. The grain size distribution (Table 2) of the subgrade soils ('S1' and 'S2') obtained along Traverse 1 shows that the amounts of fines (silt and clay) ranged between 61 – 62%; sand: 36 – 38%; Liquid limit: 28.2 – 33.8; Plasticity Index: 12.7 – 15.1. These samples fall under the A-6 soil classification and are described as clayey soils with fair to poor subgrade rating by the American Society of State Highways and Transportation Officials [23]. The compaction test reveals that the OMC and MDD range from 9.62 – 14.7% and 16.5 – 17.8 kN/m^3. These values are within the Federal Ministry of Works and Housing Specification [24]. This implies that upon adequate mechanical stabilization on the field, the density of the soils can be suitable as subgrades. The unsoaked and soaked CBR range from 5 – 6 and 2 – 3% respectively. These values fall below the required CBR value of ≥10% [24]. The soaked CBR showed that there will be a 40 – 60% reduction in the subgrade strength due to the ingress of water. A form of soil improvement is therefore recommended and a drainage system along the flanks of the road to prevent water influx into the subgrade soils upon rainfall or flooding.

Fig. 3 shows the 2D resistivity structure along Traverse 8. The first 6 m is entirely made up of clay with low resistivity less than 100 Ohms-m. This low resistivity substratum is interpreted as clay with high moisture content and it is suspected to facilitate the pavement instability along the traverse. The grain size distribution (Table 2) of the subgrade soils ('S15' and 'S16') obtained along Traverse 8 shows that the amount of fines (silt and clay) is 64%; sand: 36 %; Liquid limit: 38.5 – 46.0; Plasticity Index: 17.4 – 18.6. These samples fall under the A-6 and A-7-6 soil classification respectively. These groups are characterized by clayey soils with fair to poor subgrade ratings [23]. The compaction test revealed that the OMC and MDD range from 18.1 – 18.3% and 16.7 – 17.8 kN/m^3. Although the OMC values are marginally within the less than 18% specification of [24], the MDD values are well above the minimum requirement. This implies that upon adequate mechanical stabilization on the field, the density of the soils can be suitable as subgrades. The unsoaked and soaked CBR range from 6 – 8 and 4% respectively. These values fall below the required CBR value of ≥10% of [24]. The soaked CBR shows that there will be a 33 – 50% reduction in the subgrade strength due to the ingress of water. A form of soil improvement is therefore recommended and a drainage system to prevent water influx into the subgrade soils upon rainfall or flooding.

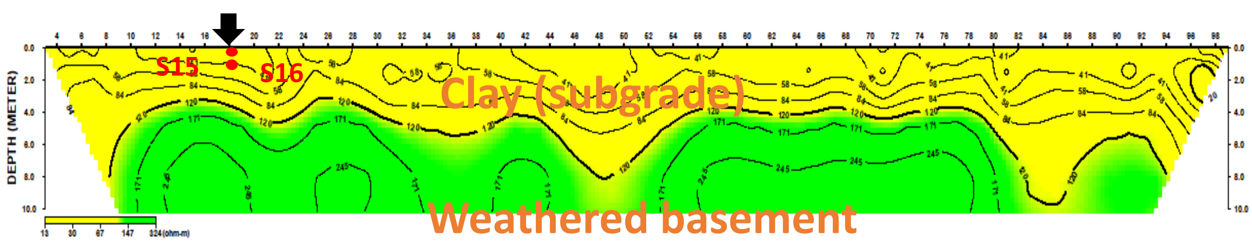

Fig 3. 2D resistivity structure along Traverse 8

Table 2. Summary of subgrade's geotechnical parameters

Subgrade Sample no	Sampling depth (m)	Traverse number	Road characterization	Sand (%)	Fines (%)	PI (%)	LL (%)	OMC (%)	MDD (kN/m^3)	CBR unsoaked (%)	Soaked CBR (%)	% Strength loss
S1 (Pit 1)	0.5	1	Unstable	36	62	12.7	33.8	9.62	16.5	5	3	40
S2 (Pit 1)	1.0	1	Unstable	38	61	15.1	28.2	14.7	17.8	6	2	67
S3 (Pit 2)	0.3	2	Unstable	39	61	24	24	9.95	19.7	9	3	67
S4 (Pit 2)	0.4	2	Unstable	43	57	38.8	38.8	18.7	18.6	4	3	25
S5 (Pit 3)	0.6	3	Unstable	45	55	19.5	32.9	13.2	18.6	6	2	67
S6 (Pit 3)	0.8	3	Unstable	38	62	25.2	34.3	14.9	19.5	6	2	67
S7 (Pit 4)	0.3	4	Unstable	45	55	23.5	29.4	12.1	19.1	8	3	63
S8 (Pit 4)	0.6	4	Unstable	45	55	22.4	31.2	11.4	17.3	8	4	50
S9 (Pit 5)	0.2	5	Unstable	48	52	14.3	21.3	12.9	19.6	4	3	25
S10 (Pit 5)	0.6	5	Unstable	47	53	18.2	27.5	11.9	17.7	5	3	40
S11 (Pit 6)	0.4	6	Unstable	45	55	20.5	31	10.2	19.7	9	2	78
S12 (Pit 6)	0.8	6	Unstable	44	56	16	24	11.2	19.9	8	3	63
S13 (Pit 7)	0.5	7	Unstable	36	64	21.2	26.3	9.72	19.7	6	4	33
S14 (Pit 7)	0.6	7	Unstable	40	60	23.8	23.8	11.07	17.8	5	4	20
S15 (Pit 8)	0.3	8	Unstable	36	64	18.6	38.5	18.1	17.8	6	4	33
S16 (pit 8)	0.4	8	Unstable	36	64	17.4	46	18.3	16.7	8	4	50
S17 (Pit 9)	0.6	9	Unstable	45	55	17.5	40	14.5	16.7	6	3	50
S18 (Pit 9)	0.8	9	Unstable	42	58	18.4	30	14.5	17.8	7	4	43
S19(Pit 10)	0.1	10	Stable	71	29	8.1	23.2	10.4	18.5	15	7	43
S20 (Pit 10)	0.5	10	Stable	80	20	7.3	25.5	11.1	20.0	17	8	53
S21 (Pit 11)	0.5	10	Stable	77	21	0.4	25	13.2	26.4	16	10	38

Generally, the 2D resistivity structures along the unstable segment are underlain by the same parent rock (Mica-schist) and are subjected to similar environmental conditions of weathering thus producing similar lithologic characteristics and sequences that are geotechnically weak as foundation soils for highway pavement causing highway failure. This failure is further exacerbated by several heavy-duty trucks which ply the section day and night due to proximity to two major ceramic industries in the state and the lack of a drainage system.

2D Resistivity Structure along Stable Section

Fig.4 shows a 2D resistivity structure along Traverse 11 along the stable section. It shows a remarkable structure different from 2D structures of the unstable section. Very clearly, the subgrade soils have a higher resistivity range (150 - 1000 Ohms-m). This range is interpreted as silty or clayey-sand. The higher resistivity range points to subgrade soils of lower moisture content and more compacted layers. These are believed to have enhanced the stability of the pavement above it. The result also makes geological sense. Granites are essentially made up of quartz, feldspar, and micas (biotite and muscovite). In the weathering of the granitic rock, quartz is more resistant to weathering forms sand. The feldspar and micas weather to clay, thus producing a mixture of clay and sands. Upon compaction of this soil, it tends to form a denser and stiffer soil compared to the weathered product of the Biotite Mica-schist which underlies the unstable pavement that is dominated by clay. The subgrade soil layer is further underlain by a higher resistivity unit inferred as the fresh and competent basement rock with resistivity > 1000 Ohms-m occurring at a relatively shallow depth of 3.2 – 5.1 m. This is predicted to contribute to the overall pavement stability. Geotechnical investigation shows that the grain size distribution (Table 2) of the subgrade soils (‘S19 - ‘S 21’) obtained along Traverse 10 of the stable section are characterized by lower amounts of fines (20 – 29%), a higher percentage of sand (71 -80%), lower Liquid limit (23.2 – 25.5) and lower Plasticity Index (0.4 – 8.1) when compared to the subgrades of the unstable section. These soil samples fall under the A-2-4 soil classification. This group is characterized by silty-sandy soils with excellent – good subgrade ratings [23]. The compaction test revealed that the OMC and MDD range from 10.4 – 13.2% and 18.5 – 26.4 kN/m^3. This range of values satisfies the minimum requirement for subgrade soils [24]. The unsoaked and soaked CBR ranged from 15 – 17% and 7 – 10% respectively. While the unsoaked CBR values satisfy the minimum requirement, the soaked CBR falls just below the requirement ≥10% of [24]. The soaked CBR showed that there will be a 38 – 53% reduction in the subgrade strength due to the ingress of water. The drainage systems incorporated into the design of the highway by the contractors already had taken care of the possible effect of water on the subgrade soil. The generally suitable geotechnical properties of the subgrade soil, as well as the design, could be responsible for the stability of this section.

V. CONCLUSION

The study has shown that the combination of electrical resistivity imaging and geotechnical investigation is reliable in studying the nature of the subsurface lithology and sequence as well as their competency. Furthermore, the study revealed that the unstable section of the highway is characterized by low resistivity clayey subgrade soils. Geotechnical investigation showed that most samples have plasticity index and compaction characteristics that meet minimum requirements. However, the high amounts of fines, low amount of sand, low soaked and unsoaked CBR fell short of the standard specification. The study has successfully elucidated a major geological/geotechnical factor responsible for the incessant failure of the highway. It is recommended that the subgrade soils of the unstable section be stabilized chemically and or have higher mechanical energy of compaction. Also, a drainage system should be provided. The 2D structures can aid in planning a suitable geotechnical sampling program for further studies.

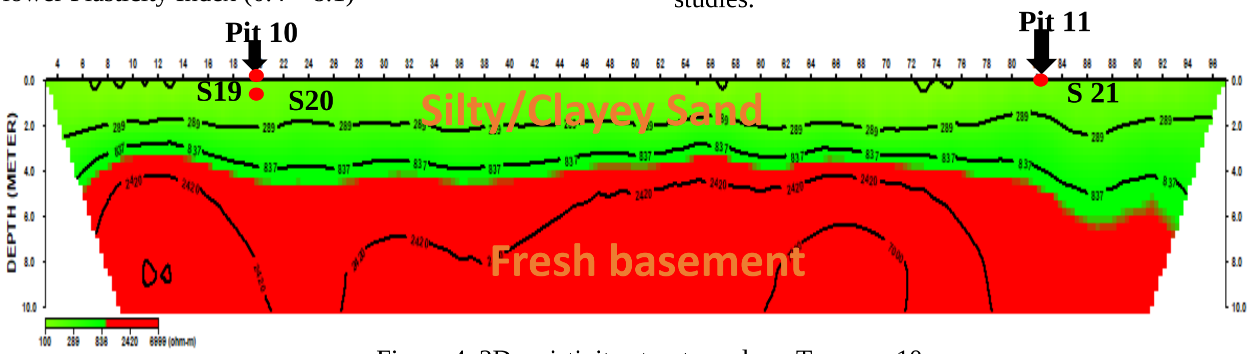

Figure 4. 2D resistivity structure along Traverse 10

Compliance With Ethical Standards
The authors declare that they have no conflict of interest.

REFERENCES

[1] Khandker, A., Angnostou, J. and Deo, P. (2013). Geotechnical Challenges in Highway Engineering in Twenty First Century: Lessons

[2] Osuolale, O. M., Oseni, A. A. and Sanni, I. A. (2012). Investigation of Highway Pavement Failure along Ibadan - Iseyin Road, Oyo State, Nigeria. *International Journal of Engineering Research and Technology* 1(8) 1-6

[3] Olorunfemi, M.O and Meshida, E.A. (1987). Engineering Geophysics and Its Application in Engineering Site Investigation (Case study of Ile-Ife area). *The Nigeria Engineer* 22(2) 57-66.

[4] Jegede, G. (2004). Highway pavement failure induced by poor geotechnical properties along a section of Okitipupa-Igbokoda highway, southwestern Nigeria. *Ife Journal of Science*, 6(1) 41-44.

[5] Arumala, J.O. and Akpokodje, E.G. (1987). Soil properties and pavement performance in the Niger Delta. *Q. J. Engr. Geol*. 20, 287-296.

[6] Ogundipe, O.M. (2008). Road pavement failure caused by poor soil properties along Aramoko-Ilesa highway, Nigeria. *Journal of engineering and applied sciences*. 3(3) 239-241

[7] Okigbo, N. (2012). Causes of Highway Failures in Nigeria. *International Journal of Engineering Science and Technology*, 4(11) 4695-4703

[8] Adegoke-Anthony, W.C and Agada, O.A. (1980). Geotechnical characteristics of some residual soils and their implications on road design in Nigeria. *Technical Lecture*. Lagos, Nigeria. 1 – 16.

[9] Meshida, E.A. (1981). Laterites on the highways – understanding soil behaviour. *West African Technical Review*. 112 – 118

[10] Ajayi, L.A. (1987). Thought on road failures in Nigeria. *The Nigerian Engineer*. 22 (1) 10 – 17.

[11] Adeyemi, G.O. (1995). The influence of parent rock factor on some engineering index properties of three residual laterised soils in southwestern Nigeria. *Bull. Assoc. Eng. Geol*. Paris 52, 3-8.

[12] Adebisi N.O., Ariyo, S.O and Sotikare, P.B. (2016). Electrical resistivity and geotechnical assessment of subgrade soils in southwestern part of Nigeria. *Journal of African Earth Sciences* 119, 256-263.

[13] Omorogieva, O.M and Okiti, I. (2022). Geotechnical Appraisal and Geological Influence on Road Failure: A New Perspective in Geotechnical Engineering. *International Journal of Earth Sciences Knowledge and Applications*. 4(1) 124-132

[14] Umar, M.U. Ejepu, J.S; Aweda, A.K; Ozoji, T.M; Adamu L.M; Abdulkad, S.A and Umoru , C.I. (2020). A multi-dimensional approach to revealing causes of pavement failures: a case study of Mina Suleja highway, North-central Nigeria. American Journal of water science and Engineering 6(3) 81-88

[15] Osinowo, O.O., Akanji, A.O and Akinmosin A. (2011). Integrated geophysical and geotechnical investigation of the failed portion of a road in basement complex Terrain, Southwest Nigeria. *RMZ – Materials and Geo-environment*, 58 (2) 143–162.

[16] Okpoli, C.C and Bamidele, A.A. (2016). Geotechnical Investigation and 2-D Electrical Resistivity Survey of a Pavement Failure in Ogbagi Road, Southwestern Nigeria. *International Basic and Applied Research Journal* 2(7) 47-58.

[17] Kamtchueng, B. T., Onana, V. L., Fantong, W. Y., Ueda, A., Ntouala, F. D., Wongolo, M. H.D., Ndongo, G. B., Ngo'o Ze, A., Kamgang, V.K.B and Ondoa, J. M (2015). Geotechnical, chemical and mineralogical evaluation of lateritic soils in humid tropical area (Mfou, Central-Cameroon): Implications for road construction. International Journal of Geo-Engineering 1 -21. DOI 10.1186/s40703-014-0001-0

[18] Izumotani, S., Takeuchi, M., Murayama H, and Okazaki K. (2020). Estimating rock properties using seismic refraction survey data: a case study in an abandoned road tunnel. *Exploration Geophysics.* https://doi.org/10.1080/08123985.2020.1828856.

[19] Islam, I., Ahmed, W., Rashid, U.M., Orakzai, A.U and Ditta, A. (2020). Geophysical and geotechnical characterization of shallow subsurface soil: a case study of University of Peshawar and surrounding areas. *Arab J Geosci.* 13:949. https://doi.org/10.1007/s12517-020-05947-x

[20] Ganiyu, S.A., Oladunjoye M.A., Olobadola M,O. Arizebeokhai A.P and Badmus B.S (2021). Investigation of incessant road failure in parts of Abeokuta, southwestern Nigeria using integrated geodetic methods and soil analysis. *Environmental Earth sciences* http://doi//10.1007/s/2665-021094464

[21] Onimisi, M., Obaje, N. G. and Daniel A. (2013). Geochemical and petrogenetic

characteristics of the marble deposit in Itobe area, Kogi state, Central Nigeria. *Advances in Applied Science Research*, 4(5):44-57

[22] Loke, M. H. (1999). Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D surveys. 1-67

[23] AASHTO (2006). Standard Specification for transportation materials and methods of sampling & testing, 14^{th} Ed., Washington, D.C

[24] Federal Ministry of Works (2013). Highway Manual Part 1: Design. Volume III: Pavements and Materials Design. 1-165