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Geophysical and Geotechnical Investigations of Failed Sections of Road Pavements in Parts of Northcentral Nigeria

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Abstract: *Due to the incessant failure of roads in Nigeria, geophysical and geotechnical studies were conducted along Crusher-Felele Road and Natako-Felele Road in Lokoja, Northcentral Nigeria to unravel the lithology, deformational features, underlying geology, and ultimately the causes of such failures. The geophysical methods involved electrical resistivity, while the geotechnical methods include Grain size analysis, Liquid limit (LL), Plastic limit (PL), Plasticity index (PI), Linear shrinkage (LS), Compaction, and California bearing ratio (CBR) tests respectively. From the 3geoelectric parameters retrieved by interpreting the VES soundings quantitatively, 3 to 4 geoelectric layers exist (topsoil/unweathered layered, weathered layer, partially weathered layer, and fresh basement layer) accordingly. The second layer possesses a low resistivity range (1.2-88.7 Ωm), revealing weak and saturated zones capable of jeopardizing the integrity and stability of the road pavement. The grain size analysis results show that the percentage of soils passing sieves No. 10, 40, and 200 falls within the range of 55-98.3%, 21-50.6%, and 2.0-8.2% respectively. The range of the result for the LL (21.1-38.6%,), PL (6-23.1%), PI (0.0-17.1%), LS (5.0-9.3%), Optimum moisture content (11-17%), Maximum dry density (1835-1980 kg/m^3), unsoaked CBR (27-62%) and soaked CBR (15-35%) reveals the properties of the soils. Based on AASHTO classification, the soils are grouped as A-2-4, A-1-b, and A-2-6 representing silty sand, or silty gravelly, and clayey sand respectively. The soils are fairly good as pavement subgrade but poor as sub-base materials.*

Keywords: *Sub-surface soils; Road pavement; VES; Subgrade; Geoelectric layers.*

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1. 0 Introduction

Roads are a very critical national infrastructure that speaks volumes of the extent of development of a country (Adiat *et al.*, 2017; Ighodaro, 2009). Road networks connect rural and urban areas and provide accessibility for human movement and goods and services from one locality to the other (Aderemi and Adeola, 2021).

Failure of roads in Nigeria is one menace that has plagued the transportation industry, with some of the roads failing shortly after completion and commissioning. Numerous causes have been adduced for such failures, which include natural and man-made causes. The role of man in road failure is in the area of the display of incompetence by experts, cost-saving approach, amount of compaction efforts applied to the subgrade and base course materials, poor asphalt composition, use of poor construction materials, poor drainage system, and inadequate pre-construction site investigations among other reasons (Momoh *et al.,* 2008). Natural causes of road failure include the underlying geology, deformational imprints (fractures, faults, joints, shear zones, etc.), underlying buried stream channels, presence of clay within the subsurface, and the mineralogy and swelling potentials of such clays (Adiat *et al.,* 2017; Momoh *et al.,* 2008; Osinowo *et al.,* 2011). Whether or not road failures are of natural or man-made causes, it has resulted in the loss of several man-hours, with commuters having to spend several hours on such bad portions of the road (Ede, 2010; Egboka *et al.*, 2019), which makes stabilization of filling materials imperative (Cabalar and Mustafa, 2015; Cabalar *et al.,* 2016; Dhar and Hussain, 2018).

Geotechnical investigations for index and strength properties (Aigbadon *et al.,* 2021) have been a long-used traditional way of determining the characteristics of subgrade pavement for road design and construction and knowing the causes of road failures (Cabalar and Mustafa, 2015; Oyelami and Alimi, 2015). In recent times both geophysical and geotechnical investigations have been utilized by researchers to adequately study the subsurface soil properties, underlying geology, and stress-strain characteristics (Jekayinfa and Osinowo, 2021; Kowalczyk *et al.,* 2016; Maślakowski *et al.,* 2014; Osinowo *et al.,* 2011; Olayanju *et al.* 2017), to suggest tangible actions required to minimize cases of road failures. A geophysical investigation is very robust and complementary to geotechnical techniques in that it can replicate a semblance of near true properties of the soil (such properties as lateral variation in lithology, occurrences of fractures and weathered lithologies, groundwater occurrences, etc.), which will improve the information about the subsurface (Kowalczyk *et al.,* 2016, 2017; Momoh *et al.,* 2008; Osinowo and Falufosi, 2018). According to Osinowo and Falufosi (2018) the added advantage of using geophysical techniques is that it is inexpensive and fast to deploy, and it provides solutions to understanding complex subsurface structures and deformational records.

Therefore, this research aims to investigate the underlying geology of the pavement subgrade and the subsurface soil properties of the concerned roads in the study area. This was achieved by jointly deploying geophysical and geotechnical techniques with the following objectives:

i. To determine the geotechnical properties of the road pavement subgrade and its significance to the failed portions

ii. To establish the occurrences of fractures, weathered lithologies, and groundwater.

2.0 Materials and Methods

2.1. Location and physiography of study area

The study area Lokoja is situated within latitude $7^0 46' 00''$ to $7^0 51' 30''$ and longitude $6^0 40' 00''$ to $6^0 45' 00''$ in North Central Nigeria (Fig. 1). It has an elevation ranging from 45-125 m with an undulating terrain of high and lowland, and it is dissected by the Niger and Benue Rivers respectively (Ozulu *et al.* 2021).

Lokoja town, which has similar physiography to other parts of North Central Nigeria, experiences two climatic seasons: the rainy season, which is short, starts from May through September, with most rains in August and September and a long dry season that starts from October through April every year. According to Iwena (2012), the area has maximum temperatures of 34 $^{0}{}_{C}$ and minimum temperatures of 17 $^{0}{}_{C.}$ However, according to Adefisan and Egiku (2018) temperature can be higher than 40 ^{0}C during March and April at mid-day.

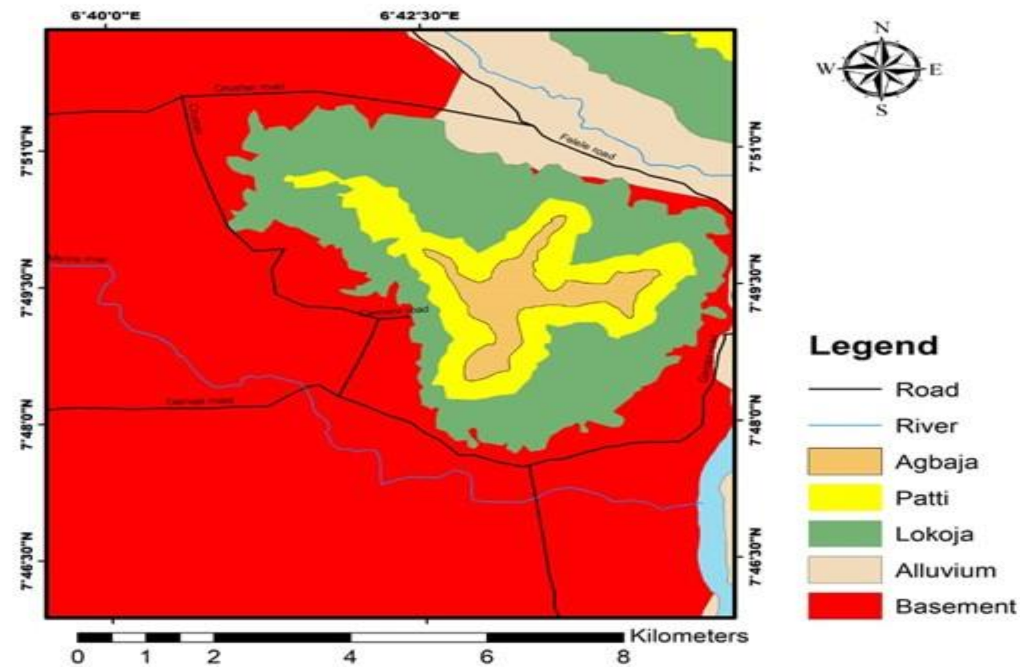


Fig. 1 Location/Geologic map of the study area. Modified after Musa & Schoeneich, (2011)

2.2. Geology of the area

The study area is a largely Basement complex terrain characterized by three major rock types: Migmatite, Gneiss, and Granitic rocks, and the Natako-Felele portion of the town has sedimentary outcrops (Fig. 1). The granitic rocks are made of Aplite, medium-grained, and Porphyritic granites based on the texture and mineralogy of the crystals. Migmatites are a complex mix of light and dark crystals reminiscence of metamorphosed granitic rocks and metamorphic rocks respectively. The Gneiss is of three types: Biotite Gneiss, Augen Gneiss, and Banded Gneiss (Ozulu *et al.*, 2021).

The northern flank of the Lokoja- Abuja expressway, specifically around the Natako-Felele section, has exposures of Formations belonging to the Bida Basin. Obaje *et al.* (2011) are of the view that the Bida basin is a typically gentle depression and that its origin can be traced to the mountain-building activities that influenced the Southeastern Nigeria and the Benue Valley during the Santonian age. The Basin is divided into Northern and Southern portions based on the lateral lithofacies characteristics (Obaje *et al.*, 2011). The Lokoja axis of the Basin is assigned to be the Southern part of the Basin which is made of three Formations: Lokoja Formation, Patti Formation, and Agbaja ironstone respectively (Nwajide, 2013). The most distinct exposures of the Lokoja Formation are at Agbaja which consists from bottom to top of the poorly sorted conglomerate to cross-bedded sandstone underlain by Basement Complex. The Patti Formation is made up of moderately – well-sorted sandstones, which overlie the Lokoja Formation and its facies attribute shows that it is of tidal-shore face depositional facies (Ojo and Akande, 2020).

2.3. Geophysical survey

The geophysical investigation involved the conduct of 10 vertical electrical soundings (5 soundings carried out on the Natako-Felele section of Abuja highway and 5 conducted on Crusher-Felele Road, both in Lokoja town), using the Schlumberger electrode configurations, with current electrode spacing (AB/2) not exceeding a maximum of 50 m (Fig. 2). The distance between one sounding and an adjacent one was kept between 50-100 m (Fajana, 2020). The potential electrode was fixed for some time while the current electrode was varied between 0.5-50 m and the potential electrode moved after a few soundings were taken. A DDR 3 sensor Terameter was used to carry out the field measurements of ground resistance to current flow, and the readings were computed to obtain the apparent resistivity of the subsurface. As discussed in Koefoed (1979) and Keller and Frischnecht (1966) AB/2 against apparent resistivity was plotted on a bi-log paper, and the resulting curves matched with master curves. The curves were then iterated using WINRESIST software to minimize errors and generate the different layers penetrated during the soundings, while Surfer 8 software was used to draw the geoelectric sections.

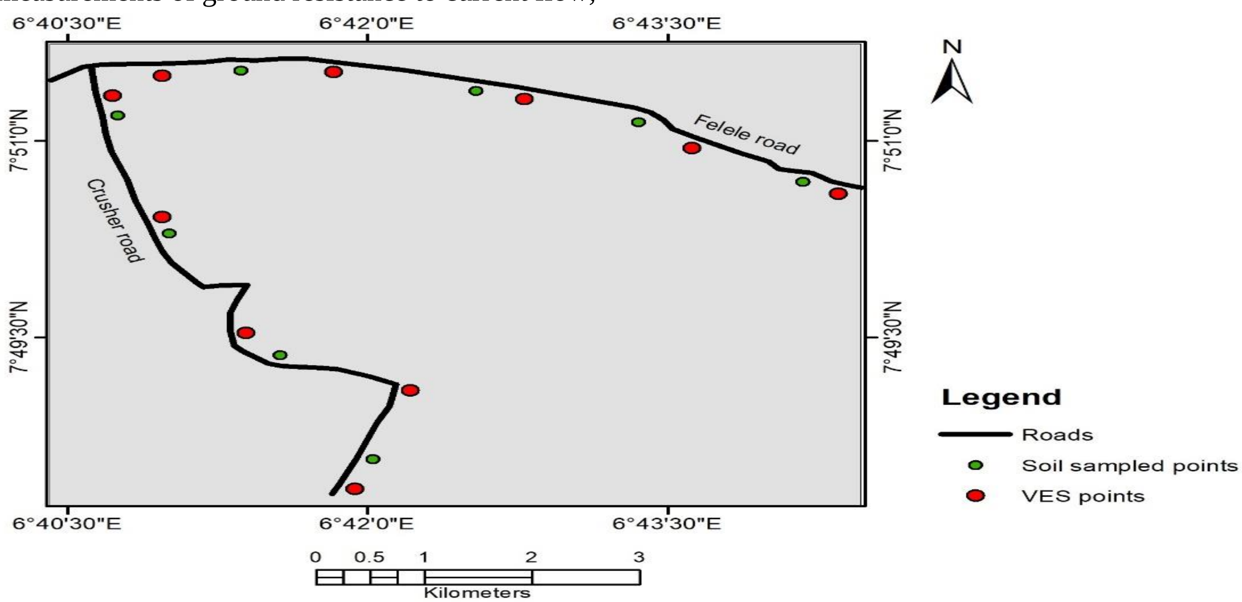


Fig. 2 Field sampling map showing Vertical electrical sounding points and soil sampling points.

A total of eight soil samples (4 samples collected from the Natako-Felele section of the Abuja highway and four samples collected from Crusher-Felele Road) were collected using a digger and a hand auger for geotechnical tests. The digger was first used to open up holes 3 meters away from failed portions of the road pavement coinciding with the vertical electrical sounding points (VES), and a hand auger was then used to retrieve soil samples from a depth of 0.8-1.0 m. The soil samples were carefully packaged in black polythene bags and taken to the laboratory for geotechnical analysis.

2.4. Laboratory analysis of soil samples

Grain size analysis was done to identify the particle size distribution that makes up the soil samples collected. This was done by pouring oven-dried soil samples on top of a well-arranged set of American sieves and then vibrating for ten minutes using an electric sieve shaker. The samples retained on each sieve were weighed and the percentage passing each sieve was calculated.

The procedure employed for the determination of the liquid limit was the ASTM method, which involved sieving an appreciable quantity of air-dried soil samples through ASTM sieve #40 (0.425 mm). About one hundred (100 g) grams of the dry soil was taken and distilled water was added and mixed thoroughly to enhance the formation of a uniform and homogenous paste. Some portions of the paste were put in the cup of the liquid limit device (Casagrande apparatus), smoothened off to a maximum depth of 1cm, and the grooving tool was used to make a groove along the symmetrical axis of the cup such that the groove was held perpendicular to the cup at the point of contact. For the plastic limit determination, a portion of the soil sample was moulded into a ball and rolled with a hand on a glass plate to form a thread until it crumbled when the diameter was 3 mm. The crumbled soils were put into a can and the moisture content was determined accordingly. The linear shrinkage was carried out by measuring about 150 g of the soil was made into a paste in line with its liquid limit and the paste was put in a mould. The soil length was then measured before drying and then measured after oven drying and the linear shrinkage was calculated from the value of the initial length and the length after oven drying is completed. To obtain the plasticity index (PI), the plastic limit value was subtracted from the liquid limit values in all samples tested ($PI = LL - PL$). The details of the Atterberg limit tests are reported in the American Society for Testing and Materials (ASTM D4318).

A Compaction test was done in the laboratory to determine the relationship between moisture content and dry density of the samples. The samples for compaction were prepared, put in a mould, and compacted in layers by applying standard efforts following the procedures explained in (ASTM, D698).

The CBR tests were adopted by the American Association of State Highway and Transportation Officials (AASHTO, 1993) as a means of determining the integrity of subgrade materials for road pavement design. The sample for CBR determination was compacted to the required optimum moisture content (OMC) and maximum dry density (MDD) using 2.5 kg of the hammer falling freely at a height of 300 mm for compaction in 5 equal layers at 61 blows/layer in a compaction mould having a volume of 2350 cm^3. The test was then done by penetrating the sample at a rate of 1 mm per minute. At intervals of penetration of 0.25 mm to a total penetration not greater than 7.5 mm, the readings of the force were taken. The samples for soaked CBR analysis were soaked for four days to allow the samples to be completely saturated and assume a worst-case scenario, and then compacted in line with (ASTM, D1883) described in (Cabalar *et al.*, 2016; Mendoza and Caicedo, 2017).

3.0 Results and Discussions

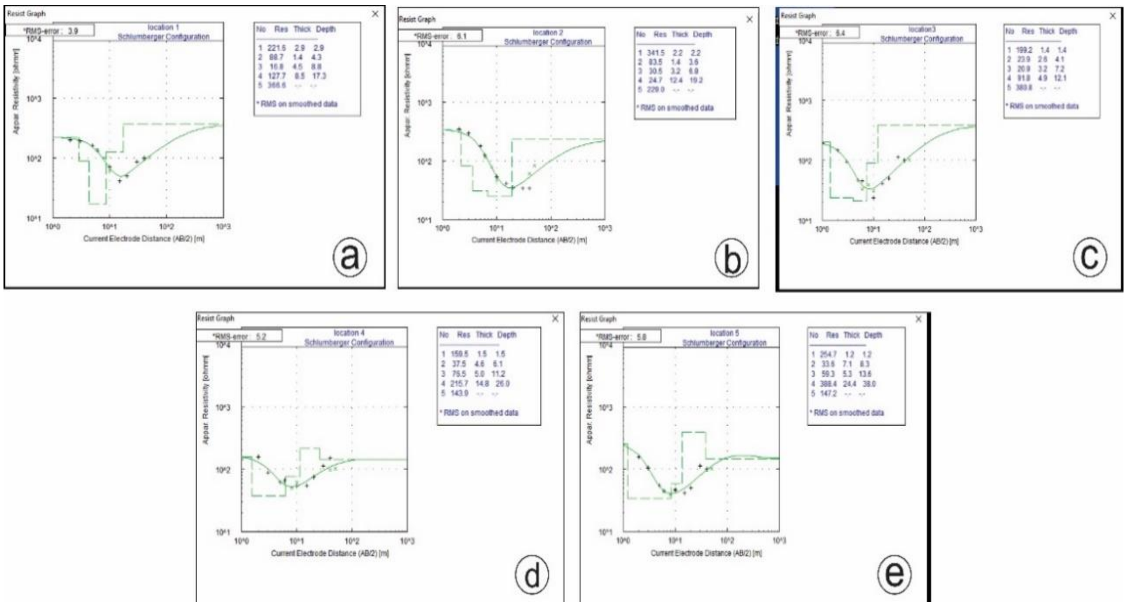
3.1. Geophysical investigation results

A summary of the preliminary geophysical results interpreted from the 10 VES points is displayed in Table 1. Two curve types characterize the Crusher-Felele Road (VES1-5) area, and they are Q and H-type curves (Fig. 3).

Table 1 Interpreted VES Results

	Layer Thickness (m)				**Layer Resistivity (Ωm)**				
VES Points	**h_1**	**h_2**	**h_3**	**h_4**	**ρ_1**	**ρ_2**	**ρ_3**	**ρ_4**	**ρ_5**
1	2.9	1.4	4.5	8.5	221.6	88.7	16.8	127.7	366.6
2	2.2	1.4	3.2	12.4	341.5	83.5	30.5	24.7	229.0
3	1.4	2.6	3.2	4.9	199.2	23.9	20.9	91.8	380.8
4	1.5	4.6	5.0	14.8	159.5	37.5	76.5	215.7	143.9
5	1.2	8.3	13.6	38.0	254.7	33.6	59.3	388.4	147.2
6	4.9	10.3			73.6	62.5	376.3	∞	∞
7	2.9	8.6			56.6	13.1	494.4	∞	∞
8	1.7	9.3			113.9	10.4	28.8	∞	∞
9	0.7	1.5			136.0	4.7	1196.9	∞	∞
10	2.6	4.7			48.6	1.2	102.0	∞	∞

The VES 1-5 sounding points revealed a four-layer bedrock consisting of QH (Fig. 3a, c, and d) and QQ curve type (Fig. 3b). These curve types, therefore, reveal the lithology and geology that underlies the study areas. The existence of Q and H-type in the area implies two possibilities. The first possibility is that the study area (VES 1-5) is characterized by the presence of fresh /unweathered basement rocks at shallow depths ranging from 1.2 m-2.9 m (Fig. 3a-c). The second layer in the Crusher-Felele Road (VES1-5) is made up of a weathered and saturated layer, which invariably weakens the road and exposes it to failure because the weathered saturated area is shallow (<9 m).



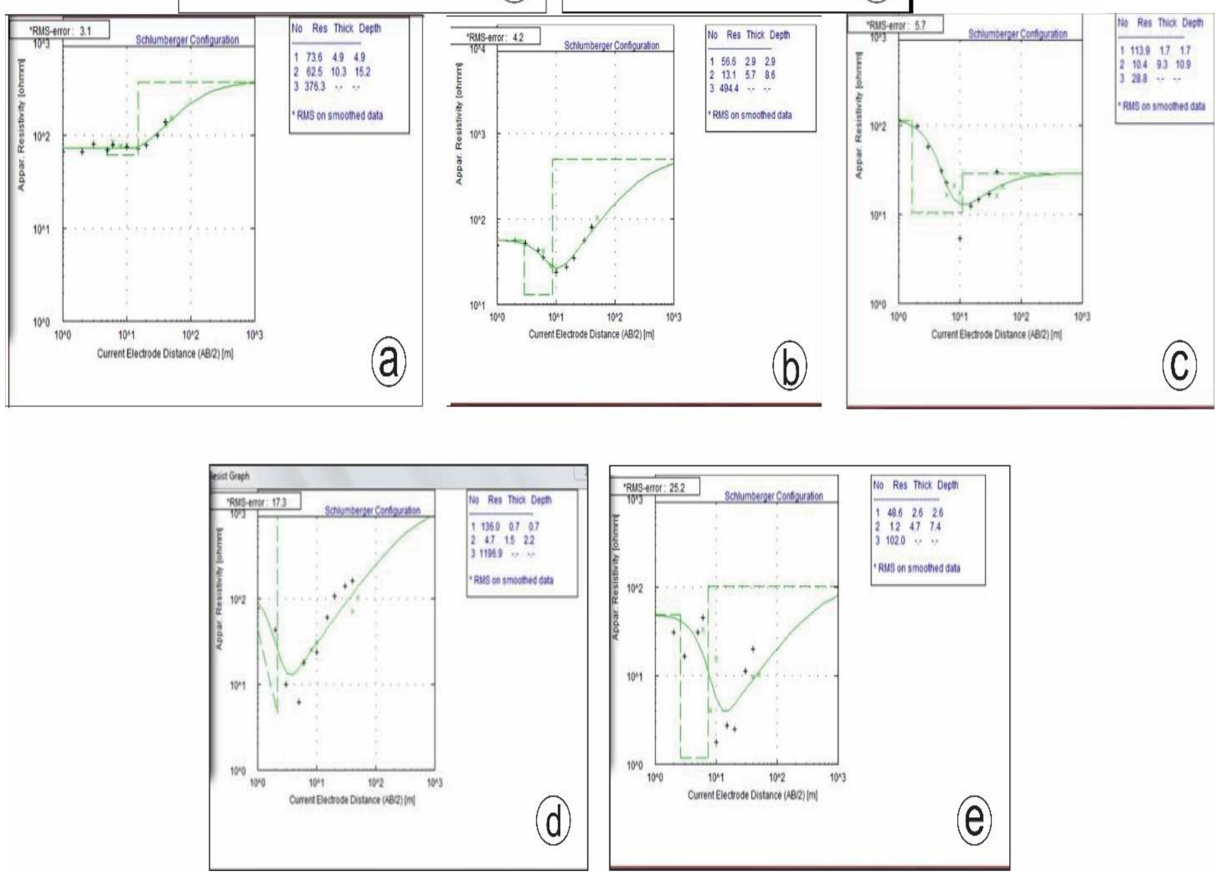


Fig. 4: Interpreted VES curves for (a) VES 6 (b) VES 7 (c) VES 8 (d) VES 9 (e) VES 10

The Natako-Felele road, on the other hand, comprises the H-type curve (Fig. 4). For VES 6-10, the area consists of clayey/silty sand with resistivity values that range between 48.6 to 136 Ωm within the topsoil at shallow depth (0.7-4.9 m) and a maximum thickness of 4.9 m. In the first layer, only VES 8 and 9 surpassed 100 Ωm, indicating that the geology of the overburden has materials largely weathered from Feldspars found in adjoining basement rocks in the study area.

The second layer (VES 6-10) has a resistivity range of 1.2-62 Ωm, which is typical of the saturated clayey soil layer. These low resistivity values that characterize the second layer are indicative of fragile zones that may subvert the integrity and stability of the road. This explains the reason for the persistent failure of the investigated portions of the roads.

Fig. 5a &b is the geoelectric section showing the changes in resistivities and thicknesses of the underlying strata for Crusher-Felele road (Fig. 5a) and Natako-Felele road (Fig. 5b), respectively. This provides vital details of the subsurface succession of the strata penetrated during the VES survey of the failed portions of the study area. Three prominent layers, namely, topsoil, weathered layers, and fresh Basement, respectively, are revealed by the geoelectric section.

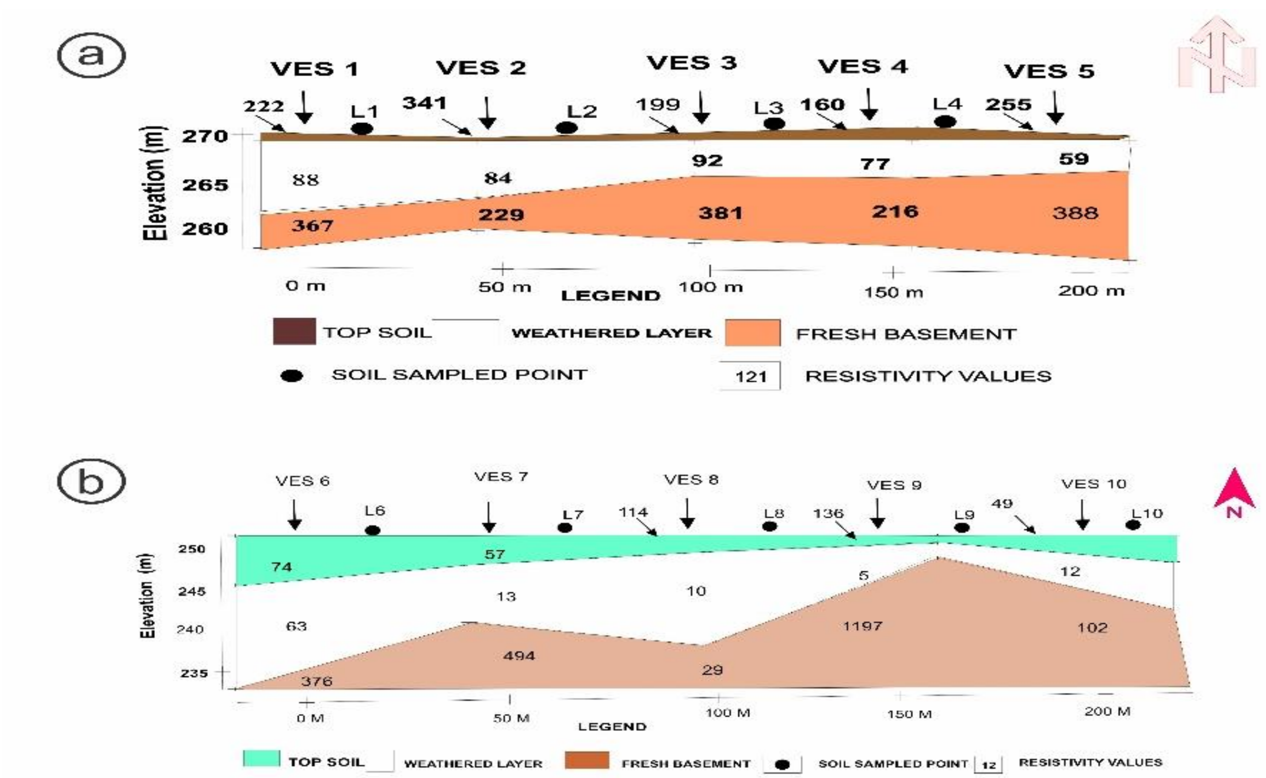


Fig. 5: Geoelectric cross-section underneath the road traverses along the North-South direction

3.2. Geotechnical investigation results

The particle size distribution (PSD) curves (Fig. 6) shows that Fig. 6a PSD curves representing samples from the Crusher-Felele roads (L1-L4) are well graded, having all the grain sizes making up the sample. The percentage of soils passing. sieves No. 10, 40, and 200 fall within the range of 55-97.3%, 21-50.6%, and 2.0-6.3% (Table 2) respectively. The engineering index properties and soil characteristics for the Crusher-Felele Road (Table 2) reveal that the natural moisture content ranges from 3.7 to 20.3%. The liquid limit, plastic limit, linear shrinkage, and plasticity index ranges from 21.1-33.2%, 19.4-22.2%, 5.0-7.9%, and 0.0-11.05% respectively.

The samples from Natako-Felele road (L5-L8) reveal that the curves (Fig. 6b) are spaced from each one, suggestive of slight differences in the grain compositions of the samples from that area. The percentage of soils passing sieves No. 10, 40, and 200 falls within the range of 85.3-94.8%, 38.2-50.6%, and 5.4-8.2% (Table 2) respectively.

The engineering geotechnical properties in the Natako-Felele road indicate that the natural moisture content ranges from 10.4 to 21.1% respectively. For the Natako-Felele road, the liquid limit ranges from 32.2-38.6%, the plastic limit of 21.1-23.1%, linear shrinkage of 7.1-9.3%, and plasticity index of 9.8-17.1% respectively.

Table 2: Index properties and classification of soils

Variables	L1	L2	L3	L4	L5	L6	L7	L8
Moisture Content, %	7.6	12.2	20.3	3.7	21.1	18.2	15.6	10.4
Liquid Limit, Wp %	28.3	33.2	28.2	22.1	38.6	32.2	33.4	38.2
Plastic Limit $W_{P\,\%}$	19.4	22.2	21.2	NP	23.4	22.4	23.1	21.1
Linear Shrinkage, $LS_{\%}$	12.0	10.1	11.5	11.5	9.1	10.6	10.6	10.1
Plasticity Index, PI %	8.9	11.1	7.0	0.0	15.2	9.8	10.3	17.1
% Passing No.10 sieve	97.3	98.3	78.4	55.0	87.4	94.8	85.5	85.3
% Passing No.40 sieve	23.6	50.6	30.3	21.0	44.5	48.8	40.8	38.2
% Passing No.200 sieve	4.0	5.3	6.3	2.0	6.0	7.0	5.4	8.2
AASHTO Classification	A-2-4	A-2-4	A-2-4	A-1-b	A-2-6	A-2-4	A-2-4	A-2-6
USCS Classification	SCL	SCL	SCL	GCL	SCL	SCL	SCL	SCL

**** SCL- Clayey or Silty Sand; GCL-Clayey or Silty Gravel; NP – Not Plastic.**

The Nigerian Ministry of Works and Housing (FMWH, 1997), recommends that soils having ≥35% passing (finer) than sieve No. 200 are clays and not suitable as subgrade and sub-base materials for road pavements. For the current study, the samples meet the specifications and they are largely sand with some fines.

The natural moisture content of the samples from Crusher-Felele Road all slightly falls within the specified limit. The slightly higher moisture content recorded in Natako-Felele road is because the samples here are sands with more fines and invariably possess higher water retention capacity. As reported in Aghamelu *et al.* (2011), liquid limit and plasticity index of >35% and >12% respectively, are reflective of silty soils. A liquid limit of ≤50% and plasticity index of ≤30% and plastic limit of ≤30% are recommended for subgrade pavement, while a plasticity index of ≤12% is recommended for sub-base. It is also recommended that linear shrinkage should be <8% for subgrade pavement materials (FMWH, 1997; Tsado *et al.*, 2018). According to Olayanju *et al.* (2017), soils with linear shrinkage of <8% are non-swelling and inactive clays and are good as pavement subgrade. For this current study, most of the samples are within the safe threshold except sample L5 (9.3%) and samples L2 and L8 (both 7.9% each), which are on the upper limit of the specified standard value. Subgrade at L5 can be a major source of road pavement weaknesses and failures.

According to AASHTO (AASHTO 1993) classifications (Table 2), samples L1, L2, L3, L6, and L7 are all classified as A-2-4 which has <35% passes sieve No. 200, and as such are called SCL (sandy clay of low plasticity) according to unified soil classification (USCS). Samples L4 is classified as A-1-b, which is referred to as GCL (gravelly clay of low plasticity) according to USCS classification. Samples L5 and L8 are classified as A-2-6 and based on USCS it is referred to as SCL (Clayey or Silty sand). The GCL and SCL samples are fairly good as pavement subgrade.

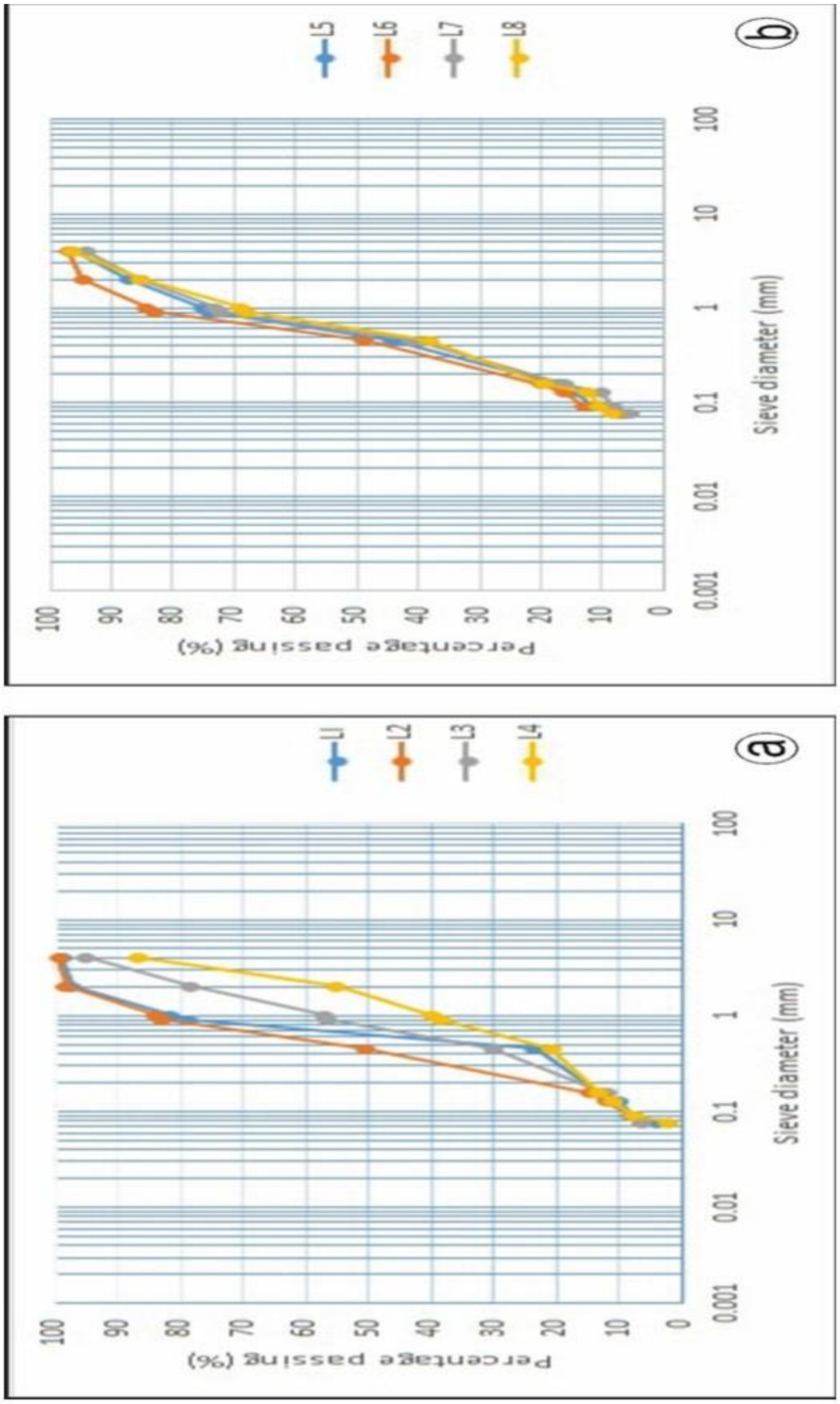


Fig. 6 Particle size distribution curves for (a) samples L1-L4 (b) sample L5-L8

The compaction and CBR test results are displayed in Table 3. The optimum moisture content (OMC) has a minimum value of 11.1% and a maximum value of 17.0%, while the minimum and maximum values for maximum dry density (MDD) are 1835 kg/m^3 and 1980 kg/m^3 respectively. From the results in Table 3, the OMC and MDD all meet the specified values of ≤18% for OMC and ≥1700 kg/m^3 for MDD (FMWH 1997) for pavement subgrade as reported in Oyelami and Alimi (2015) and Tsado *et al.,* (2018).

The CBR values range from 27-62% for unsoaked samples and 15-35% for soaked samples (Table 3), respectively. A CBR value of ≥30% and ≥15% for unsoaked and soaked samples respectively, are required for pavement subgrades, while it is additionally required that a CBR of ≥ 30% after soaking samples for at least 24 hours is required for pavement sub-base materials (FMWH 1997). Of all the samples, only sample L8 did not meet the recommended standard having an unsoaked CBR of <30% and soaked CBR of ≤15% respectively. Such low values undermine the compaction ability of the soil and it carrying capacity as pavement subgrades and sub-base respectively.

4. 0 Conclusion

Integrated geophysical and geotechnical methods were deployed to investigate the possible causes of failures of some sections of two roads in Lokoja, Northcentral Nigeria. The results from the geophysical soundings reveal that the stable bedrock is shallow and thin, generally <5 m as shown by the processed and interpreted results. The second layers are weathered and saturated and located even as low as 2.2 m. The Natako-Felele road revealed a sandy clay layer with an appreciable quantity of fines (clayey/silty sand) at the topsoil/overburden. The second layer here is made up of saturated clay. The overburden and geology of the subsurface as shown by the VES curves, indicate that the geotechnical results corroborate the geophysical results. The overburden and geology, especially in the Natako-Felele road, which shows low resistivity overburden made up of sandy clay (which is a product of weathering of feldspars from adjoining basement rocks in the area), thin overburden, and a shallow second layer consisting of fractured saturated layers are possible causes of failures of the road pavement here. Additionally, these clays, with low permeability, absorb water and retain it, thereby weakening the road pavement subgrade. The geology of the Crusher-Felele Road, on the other hand, consists of a more stable bedrock and a fractured and saturated second and third layer respectively. Because of this, the failure of the portions in Crusher-Felele Road is rather due to the shallow saturated second layer and construction materials since the pavement subgrade/bedrock is made up of fairly stable geology.

The AASHTO classification grouped the soil samples as A-2-4, A-1-b, and A-2-6, respectively. This, therefore, implies under the USCS classification that they are Clayey or Silty Clay (SCL) and Clayey or Silty Gravel (GCL). The properties of the soils sampled and the underlying lithology and geology show that the soils are fairly good for pavement subgrade. However, it is not suitable for use as sub-base materials for road pavement construction. It is recommended that before construction, the weak zones should be excavated and replaced with suitable soils.

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Declarations

The authors declare that they have no conflict of interest.

Data availability

All data used in this study will be readily available to the public.

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data Public.

Competing interests

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6.0 Author's Contributions

All the authors contributed greatly to the completion of the manuscript. EOA, KOM, FAA, JBA, and MS undertake fieldwork and data acquisition. SI drew the diagrams, EOA compiled the manuscripts and all authors reviewed the manuscript before it was sent out for publication.