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Geophysical and Geotechnical Investigation of Road Pavement Failure in Part of Ibadan Metropolis Southwestern Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Case Study

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ABSTRACT

Road pavement failure observed along a section of Apete-Akufo Major Road in Ibadan metropolis southwestern Nigeria, necessitates the need to ascertain whether the failure results from poor construction practices or poor engineering properties of subgrade materials. Geophysical and geotechnical survey results were compared to investigate the cause of the road pavement failure. Vertical Electrical Sounding (VES) with geotechnical study which include; grain size analysis, Atterberg limits and California Bearing Ratio (CBR) tests, were carried out on disturbed subgrade samples obtained between 0 – 1 m depth from VES Stations 1, 2 and 5, corresponding to unstable, stable and highly unstable sections of the road respectively. The quality of the subgrade was evaluated based on Atterberg limits, layer resistivity and CBR values. Eight (8) VES stations established 100m apart along the road section delineated 5 lithology; topsoil, clayey sand/lateritic clay, weathered bedrock and fresh bedrock with resistivity range of 68-238Ωm, 72-236Ωm, 224-859Ωm and 6720-15351Ωm respectively. Low overburden resistivity characterized failed sections. Sample from VES Station 5 has very low wet or dry bearing capacity responsible for observable failure of the road section. Sample from VES Station 1 presents high dry bearing capacity (70%) but low wet bearing capacity (11%), suggesting poor drainage may be responsible for pavement failure at the section. Sample from VES Stations 2 presents similar wet and dry bearing capacity resulting in stable road pavement.

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The study indicates poor construction practices, lack of proper drainage and poor engineering properties of subgrade materials as the causes of road pavement failure along the observed section of Apete-Akufo Major Road.

Keywords: Atterberg limits; California bearing ratio; vertical electrical sounding; subgrade.

1. INTRODUCTION

The impact of roads on the socioeconomic development and progress of any country cannot be over-emphasized. Like many parts of the world, road transport in Nigeria dictates the distribution of wealth and human resources [1]. Engineering characteristics of foundation soils (subgrade) and highway pavements are of paramount importance towards advancing the socioeconomic condition of any state through proper road network [2]. The occurrence of cracking, rutting, potholes, differential heave, deformation and peeling along a section of a paved road indicate its failure [3]. The reoccurring case of road pavement failure along Apete-Akufo road in Ibadan Metropolis southwestern Nigeria became a cause for concern due its impact on the socioeconomic activities of the area. The road pavement here has repeatedly failure after several rehabilitations with the formation of potholes some of which had advanced to form trenches along the road section (Fig. 1). The road serves as the only link between Ibadan city and one of its major dumpsites ‘Awotan Dump’. Frequent breakdown of waste disposal trucks along this road while laden with refuse cause air pollution. The road also serves as access route for settlers and vegetable farmers from the ‘Akufo’ vegetable farms to the city center.

Several causative factors can be linked to road pavement failures including geomorphological, geological and geotechnical factors, design and construction inadequacies, maintenances and road usage (4,5]. The effect of these factors can be enhanced through climatic alterations by temperature variability and attack of the road base materials by acid rain [6]. Roads are constructed on geological material known as the subgrade unit, as such the prevalence of pavement failures can be attributed to the engineering or geotechnical characteristics of the underlying geology/subgrade materials [7]. Poor geotechnical properties of the subgrade material such as bearing capacity, maximum dry density, liquid limit, plasticity index, optimum moisture content, California bearing ratio and soil compressibility are typically responsible for road failures (Ademilua 2018).

Provided the subgrade material have quality engineering properties, road pavement failure can occur due to construction inadequacies such as lack of proper drainage or poor maintenance and usage practices [8]. The section of the road under is underlain by Quartz-Schist geologic units within the Basement Complex terrain of southwestern Nigeria, thius rock type has been described to exhibit differential weathering [9], hence variability in geological and geotechnical properties of the underlying lithologic unit can be suspected as one of the reasons for the road pavement failure. Aside the geotechnical assessment of subgrade material in understanding soil characteristics responsible for road pavement failure [7,10], geophysical investigations of the significant factors responsible for recurring road pavement failures in parts of southwestern Nigeria has been discussed (Salami et al. 2012) [11].

This study aims to assess the effect of geological and geotechnical factors as possible cause of road pavement failure along a predetermined section of Apete-Akufo road by comparing results from geophysical (VES) and geotechnical (CBR) studies. Taking into account the recurring pavement failure of the Apete-Akufo road, there is a need to assess the integrity of the underlying subgrade material prior to rehabilitation. Road pavement failure is expected where there is relatively low resistivity and low CBR values along the section of the road. The study also offers rapid geophysical measurement as a cheap and non-invasive method for assessing factors responsible for road pavement failure.

1.1 Location and Geology of the Study Area

The study area is located within the Basement Complex of Southwestern Nigeria (Fig. 2), it lies within Latitudes 7^0 27’ 08.0’’N and 7^0 27’ 28.8’’N and Longitudes 3^0 51’ 20.4’’E and 3^0 50’ 58.8’’E of Ibadan metropolis. The road is located about 6 km west from the university of Ibadan main gate.

Fig. 1. a) Failed portion of the Apete-Akufo Road Southwestern Nigeria. (b) Failed portion of the Apete-Akufo road, with hills covered in vegetations showing in the background

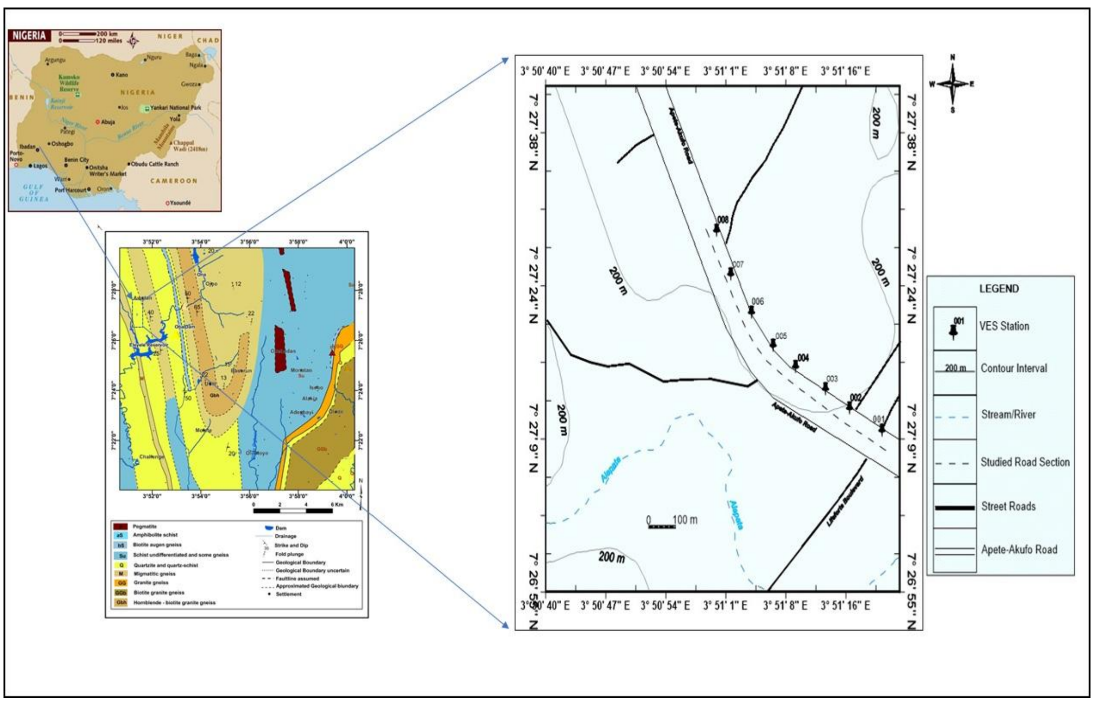

Fig. 2. Geology map of Ibadan showing the Apete-Akufo road section
Source: NGSA [12]

The area is not easily accessible due to the poor road network leading to the study point. Olayinka and Adeyemi [13] described the scenery of this area as being dominated by three major landforms units, namely, the hills, plains, and river valleys (Fig. 1). The hills are the most striking features. Although they constitute less than 20% of the total surface area, two main types can be recognized, namely, quartzite ridges and gneissic inselbergs, of which the former are by the most extensive landform system in the area with an altitude generally ranging from 185 to 222 m above mean sea level. They cover, essentially, the areas between the hill bases and the usually entrenched valley bottoms.

The study area is underlain by quartzite and quartz schist which are part of the basement complex geology of southwestern Nigeria [9]. The lithologic units were observed along the Apete-Akufo road as outcrops striking NW-SE with an average dip of 70^0 East (Fig. 3).

2. METHODOLOGY

Geophysical electrical resistivity measurement via the vertical electrical sounding (VES) was carried out at eight (8) stations (Fig. 2) along the Apete-Akufo road using the conventional Schlumberger array which utilizes four electrodes system which are arranged linearly with different interelectrode spacing, the potential electrode remains partially fixed at the center of the spread, and the current electrode is expanded symmetrically about the Centre of the spread (Fig. 4) [14,15].

The electrical sounding was carried out to determine the thickness of overburden as well as the apparent resistivity of each layer. Electrical drilling was achieved by increasing the separation between the current electrodes so that the current penetration reaches deeper levels. The succession of apparent resistivity reading is taken for increasing electrode spacing AB/2 = 1 – 55 m.

Fig. 3. Quartz-Schist outcrop along Apete-Akufo road section

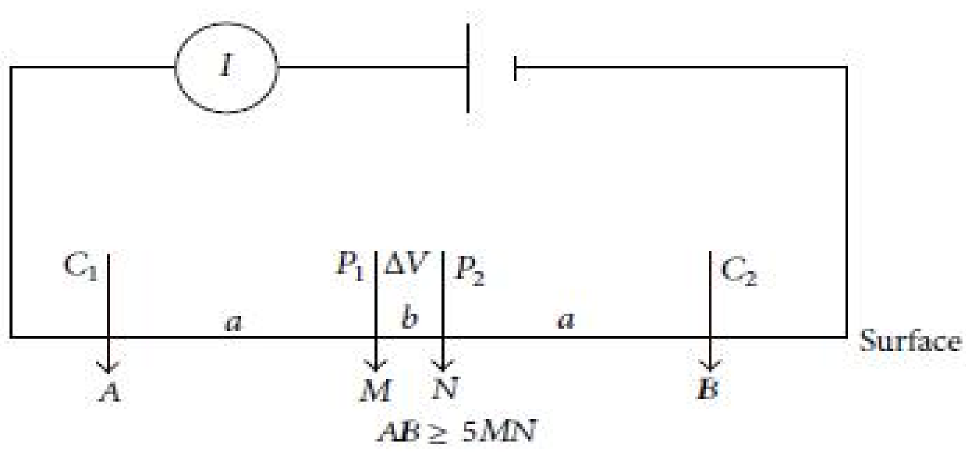

Fig. 4. Schematic view of the Schlumberger electrode array

Geotechnical studies of subgrade samples obtained from 3 stations along the studied road section corresponding to VES stations 1, 2 and 5 (Fairly stable, Stable and unstable/failed sections respectively), include in-situ and laboratory tests of Atterberg Limit, Grain Size and Hydrometer Analysis and California Bearing Ratio. The Atterberg limits tests were carried out in accordance to the ASTM standard test method D 4318 [16]. The tests include, liquid limit (LL), plastic limit (PL) and the estimation of the plasticity index (PI) which is the size of the range of water contents where the soil exhibits plastic properties, and is expressed as the difference between the liquid limit and the plastic limit (PI = LL-PL) [17,18]. The California Bearing Ratio (CBR) test is a simple strength test that compares the bearing capacity of a soil with that of a well graded crushed stone (a high-quality crushed stone material should have a CBR of 100) [19]. The test evaluates the mechanical strength of natural ground or subgrades material beneath road pavement [11]. The CBR test was carried out in accordance with AASHTO [20] specifications. The distribution of different grain sizes affects the engineering properties of soil, as such sieve and hydrometer analysis in accordance with ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils [21] was carried out on the 3 soil samples retrieved along the road section under study.

The coefficient of correlation 'r' of the cross-plots of the geophysical and geotechnical study results obtained from VES stations 1, 2 and 5 was used to determine and quantify the between the resistivity measurements and the various geophysical techniques employed for this study. As the value of 'r' approaches one (1), the stronger the relationship between the two methods compared [15].

3. RESULTS AND DISCUSSION

Initial analyses of results from field observation and geophysical measurement informed the categorization of the studied road pavement section into stable (presence of asphaltic road pavement), unstable (broken or mildly damaged asphaltic pavement), and highly unstable (no pavement with formation of trenches) sections (VES stations 2, 1 and 5 respectively) based on stability or degree of failure of available road pavement (Fig. 5).

Fig. 5. a) Stable (b) Unstable and (c) Highly Unstable sections of the Apete-Akufo road

3.1 Electrical Resistivity Method

The results of the vertical electrical soundings carried out at stations 1-8 (Fig. 2) are summarized as a table of geo-electric parameters (Table 1) and geo electric section (Fig. 6). The geo-electric section presents the variation in weathering of the subsurface lithologic unit along Apete-Akufo road under study with a pictorial view of the differential weathering of the bedrock along the road section. The VES results assist to determine the overall or generalized degree of saturation of the subsurface materials at each station since water saturation indicates occurrence of fractures and voids that could suggest reduced rock stiffness. [22]. VES results show five (5) observable lithologic units in three (3) layered successions along Apete-Akufo road, the first, second and third layers which are topsoil, clayey sand or lateritic clay, and weathered bedrock or fresh bedrock respectively (Fig. 6). The resistivity of the various lithologic units ranges from: 68-238Ωm for Topsoil, 72-236Ωm for clayey sand or lateritic clay, 224-859Ωm for weathered bedrock and 6720-15351Ωm for fresh bedrock. The topsoil is regarded as the subgrade layer directly under the asphalt pavement and it is directly responsible for the stability of the road pavement. The thickness of the topsoil layer ranges from 0.6-1.6 m. The stable section of the road represented by VES station 2 presents topsoil resistivity value of 104 Ωm with thickness of 1.5 m, weathered bedrock resistivity is 236 Ωm with layer thickness of 18.3 m. The fractured bedrock has a resistivity value of 383 Ωm (Fig. 7). The average resistivity of the overburden layers at VES station 2 is 241 Ωm with overburden thickness above 19 m. VES Station 1 represents an unstable section of the road with topsoil resistivity value of 70 Ωm with thickness of 1.6 m, weathered bedrock resistivity is 105 Ωm with layer thickness of 13.3 m. The fractured bedrock has a resistivity value of 368 Ωm (Fig. 7). The overburden thickness at the VES station is in excess of 15 m with an average resistivity of 181 Ωm. The most unstable part of the road section is represented by VES station 5, which presents topsoil and weathered bedrock resistivities of 112 Ωm and 168 Ωm with corresponding thicknesses of 1.2 m and 14.8 m, respectively. The resistivity of the third layer indicated a fresh bedrock zone with resistivity of 6720 Ωm (Fig. 7). The average resistivity of the overburden at VES station 5 is 140 Ωm, with overburden thickness of about 16m.

The stability of road pavement can be inferred from the resistivity of the topsoil and the overburden lithologic units. Increase in moisture and clay content lowers the resistivity values of the overburden (tends to less than 100 Ωm), with the presence of clay and moisture suggestive of weak zones that are capable of undermining the stability of overlying road pavement [23]. It was observed that stability of road pavement along the Apete-Akufo road decreases with lower average overburden resistivity, as the lower resistivity (< 100 – 200 Ωm) is indicative of abundance of clay mineral presence [24].

3.2 Geotechnical Analysis of Subgrade Material

Bulk disturbed samples obtained from 0 – 1 m depth at VES stations corresponding to VES Station 1, 2 and 5 were subjected to Atterberg Limit tests, Grain size analysis and California bearing ratio test (soaked and unsoaked). The results of the Atterberg limit and CBR tests are presented as Table 2. The result of the grain size analysis which comprises of sieve and hydrometer analyses of the sample from VES stations 1,2 and 5 representing unstable, stable and highly unstable sections of Apete-Akufo road respectively are presented on Table 3.

The geotechnical analysis of the subgrade material shows that the results of the Atterberg limit tests fall within the acceptable standards of the Nigerian Federal Ministry of Works and Housing [25] recommended standards for road and bridges. Also, the grain size analysis of the samples conforms with acceptable standards on AASHTO 1982 classification system described by Annan [26]. However, the California Bearing Ratio test result for the highly unstable section falls below acceptable standards for subgrade material as set by the Nigerian Federal Ministry of Works and Housing [25] (Table 4). The soaked CBR value of 4.41% from the failed road section along Apete - Akufo road corresponds to values reported from CBR tests for subgrade materials from other road pavement failure studies by Ekeocha & Egesi, [19] and Emmanuel et al, [6]. Also, Osinowo et al, [27] inferred that the stability of subgrade materials depends on the quantity of fines present in the grains of such material, thus samples from VES station 2 having lowest amounts of fines shows more stability than the others.

Also, CBR results samples from VES Station 1 with soaked and unsoaked CBR of 11.41% and 70.14% respectively, indicate that the subgrade is fairly stable especially when the road is dry and its stability reduces with wetness. Hence the road pavement in this section failed due to poor drainage as observed on site. Samples from VES Station 2 shows that the subgrade is stable when wet or dry with relatively similar soaked and unsoaked CBR values. Samples from the failed section in VES Station 5 has soaked and unsoaked CBR values well below acceptable standards and this can be said to be responsible for the failure of the road section.

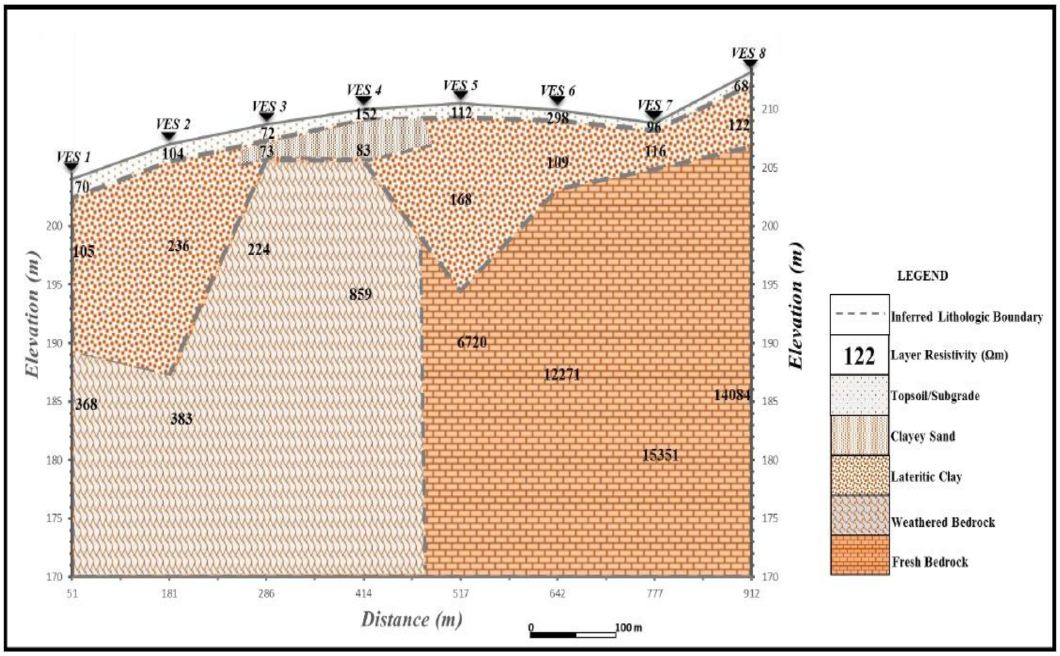

Fig. 6. Geo-Electric Section Along the Studied Section of Apete-Akufo Road

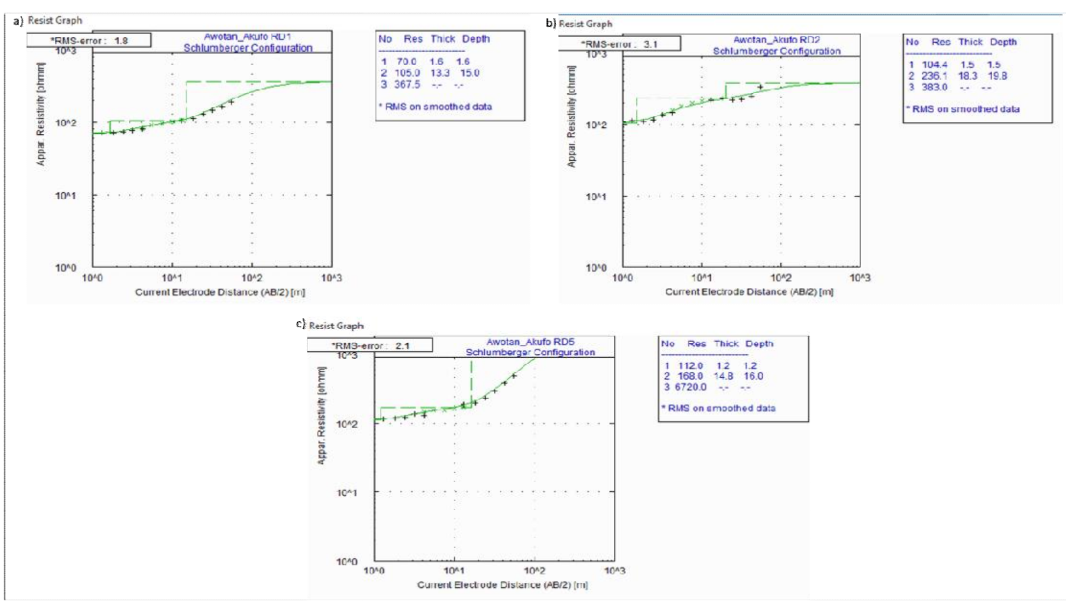

Fig. 7. VES inversion curves for (a) VES Station 1 (b) VES Station 2 and (c) VES Station 5, representing the unstable, stable and highly unstable sections of Apete-Akufo Road

Table 1. Geo-electric parameters from vertical electrical sounding

Station No	Elevation (m)	Coordinates	Layer Resistivity (Ωm)	Thickness (m)	Depth (m)	Probable Lithology	Curve Type	RMS Error%	Road Condition
1	204	*$7^0$27’8.7’’N*	70	1.6	1.6	Top soil	A	1.8	Unstable
			105	13.3	15	Lateritic Clay	_		
		$3^0$51’19.1’’E	367.5			Weathered bedrock	_		
2	207	*$7^0$27’10.8’’N*	104	1.5	1.5	Top Soil	A	3.1	Stable
			236	18.3	19.8	Lateritic Clay	_		
		$3^0$51’15.2’’E	383			Weathered rock	_		
3	208.7	*$7^0$27’12.6’’N*	72	1.4	1.4	Top soil	A	2.1	Highly Unstable
		$3^0$51’12.3’’E	73	1.6	3	Clayey Sand	_		
			224			Weathered rock			
4	210	*$7^0$27’14.7’’N*	152	0.9	0.9	Top soil	H	2.3	Fairly Stable
		$3^0$51’8.7’’E	83	3.5	4.4	Clayey Sand	_		
			859			Weathered rock	_		
5	210.5	*$7^0$27’16.7’’N*	112	1.2	1.2	Top Soil	A	2.1	Highly Unstable
		$3^0$51’6.0’’E	168	14.8	16	Lateritic Clay	_		
			6720			Fresh Bedrock	_		
6	209.9	*$7^0$27’19.8’’N*	298	0.9	0.9	Top Soil	H	2.2	Stable
		$3^0$51’3.4’’E	109	5.8	6.7	Lateritic Clay	_		
			12271			Fresh Bedrock	_		
7	208.8	*$7^0$27’23.4’’N*	96	0.6	0.6	Top Soil	A	5.3	Unstable
		$3^0$50’0.9’’E	116	3.3	4	Lateritic Clay	_		
			15351			Fresh Bedrock	_		
8	213.2	*$7^0$27’27.5’’N*	68	1.1	1.1	Top Soil	A	3.3	Fairly Stable
		$3^0$50’59.2’’E	122	5.3	6.3	Lateritic Clay	_		
			14084			Fresh Bedrock	_		

Table 2. Atterberg limits and CBR tests result for soil samples along Apete-Akufo road

Test Type	VES Station 5 (Highly Unstable Section)	VES Station 1 (Fairly-Stable/Unstable Section)	VES Station 2 (Stable Section)
Liquid Limit (%)	26	32.4	32.5
Plastic Limit (%)	23.1	16	23.
Plasticity Index (%)	2.9	15.5	9.5
Soaked CBR (%)	4.41	11.41	39.08
Unsoaked CBR (%)	3.95	70.14	33.41

Table 3. Result of the grain size analysis carried out after ASTM D 422 - standard test method for particle-size analysis of soils

Soil Type	VES Station 5 (Highly Unstable) (%)	VES Station 1 (Fairly Stable) (%)	VES Station 2 (Stable) (%)
Sieve Analysis			
Medium Gravel	2.8	7.5	3.180
Fine Gravel	26.12	23.02	34.42
Total Gravel Content	28.92	30.52	37.60
Coarse Sand	25.86	16.76	21.84
Medium Sand	38.68	36.62	34.72
Fine Sand	4.40	13.4	5.460
Total Sand Content	68.94	66.78	62.02
Fines	2.08	2.60	0.020

Table 4. Comparison of results with Nigerian specification for road and bridge materials and Aashto 1982 classification system

Sample / ***Subgrade Properties***	VES Station 1 (Fairly-Stable/ Unstable Section)	VES Station 2 (Stable Section)	VES Station 5 (Highly Unstable Section)	Nigerian Specification
Liquid Limit (%)	32.4	32.5	26	≤40
Plastic Limit (%)	16.9	23	23.1	NP
Plasticity Index (%)	15.5	9.5	2.9	<20
Soaked CBR (%)	11.41	39.08	3.95	≥10
Unsoaked CBR (%)	70.14	33.41	4.41	≥30
% Gravel	30.52	37.6	28.92	NP
% Sand	66.78	62.02	68.94	NP
% Fines	2.6	0.02	2.08	≤35
AASHTO classification system	A-3	A-3, A-2-4	A-3, A-2-4	
Remark CBR Based	Fair	Good	Poor	

Table 5. Compared results from geophysical and geotechnical study of Apete-Akufo road

VES Station Number	Average Overburden Resistivity (Ωm)	Fines (%)	Soaked CBR (%)	Unsoaked CBR (%)	Average CBR (%)	Plasticity Index (%)
1	181	2.6	11.41	70.14	40.775	15.5
2	241	0.02	39.08	33.41	36.245	9.5
5	140	2.08	4.41	3.95	4.18	2.9

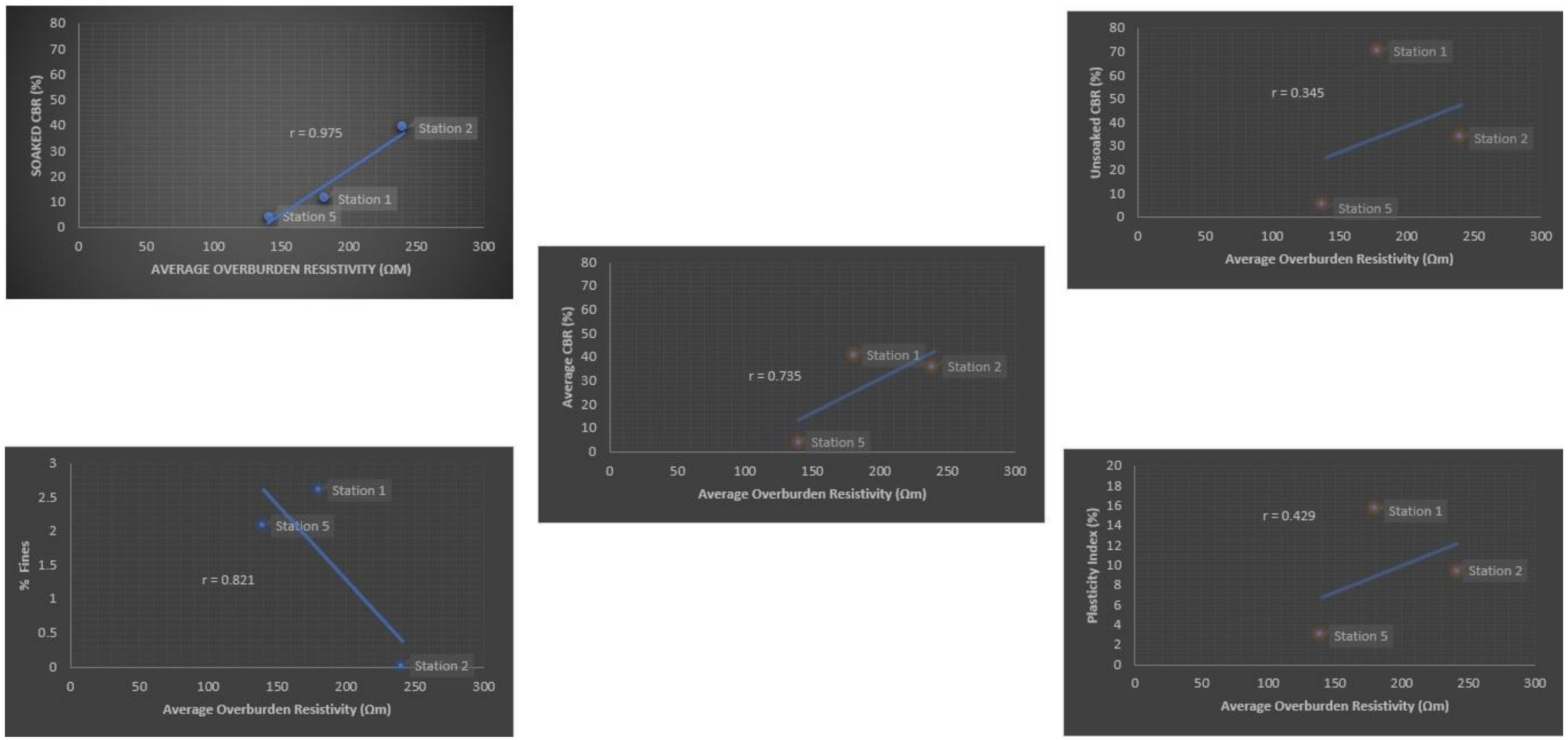

Fig. 8. Coefficient of correlation plots of results from geophysical and geotechnical studies at VES stations 1, 2 and 5 along Apete-Akufo road

From the results obtained from the geophysical and geotechnical study of failed road pavement section along Apete-Akufo road, statistical coefficient of correlation of the relationship between the average overburden resistivity and corresponding geotechnical study results at VES stations 1, 2 and 5 was estimated (Table 5).

The average overburden resistivity shows strong correlation (r = 0.951) with the soaked CBR values obtained from the studied road section, suggesting a linear relationship between subgrade material resistivity and soaked CBR values (Fig. 8). Conversely as described by Osinowo et al [27], there exist an inverse linear relationship (r = 0.8213) between % fine grained particles and observed subgrade material resistivity (Fig. 8). Average CBR values which is an average of both soaked and unsoaked CBR values have a week linear relationship (r = 0.7347) with the average overburden resistivity (Fig.8). The relationship between the overburden resistivity and unsoaked CBR values shows very poor linear correlation (r = 0.3448), the same with plasticity index (r = 0.4286).

4. CONCLUSIONS

The result of the vertical electrical soundings conducted along a failed section of the Apete-Akufo road within Ibadan metropolis southwestern Nigeria indicates that the presence of fine particles in the subgrade material identified from relatively low average overburden resistivity (< 200 Ωm) and sieve size analysis, reduces the stability of overlying road pavement with progressive decrease in stability with increase in fine particle contents observed as the resistivity of the overburden tends to less than 100 Ωm. The effect of overburden thickness or depth to bedrock appears to be negligible as evident from VES station 5 where significant failure of the road pavement was observed with relatively shallow depth to fresh bedrock, reiterating the fact that road pavement failure along the Apete-Akufo road is mostly dependent on the low overburden resistivity resulting from increased fine particle content of the subgrade material. Although, Atterberg limit results from representative samples from the road section under study indicate acceptable conditions for road pavement construction. The presence of fine grain particles in subgrade samples from failed road section and observed CBR values below standard limits were suspected to be responsible factors for road pavement failure along the Apete-Akufo road. Also, poor drainage system as a result of inadequacies in road construction practices enhanced road pavement failure as evident from differences between soaked and unsoaked CBR values from VES station 1 which corresponds to an unstable section of the road. Combined geophysical and geotechnical studies were used as an economical approach in providing comprehensive means of road pavement failure evaluation along Apete-Akufo major road within Ibadan metropolis southwestern Nigeria, with strong linear correlation observed between resistivity and soaked CBR values for the subgrade material. The geotechnical properties, and resistivity help in making reliable inferences about the nature of the subsurface upon which the road pavement is established.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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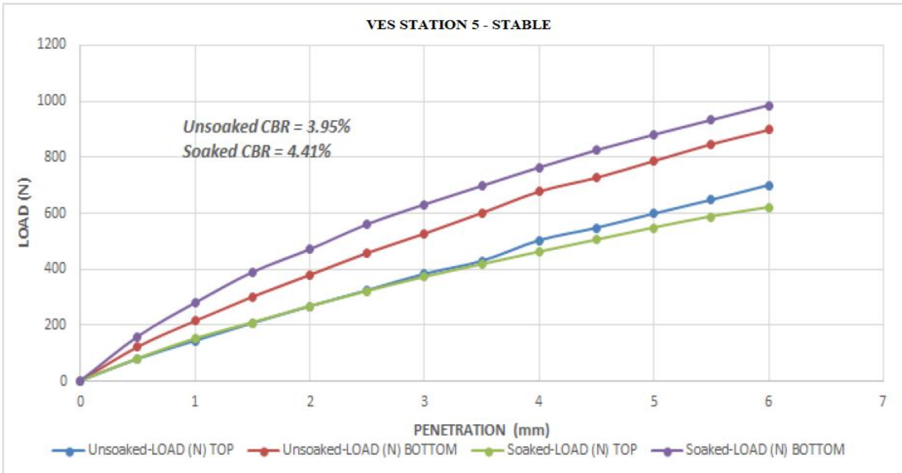
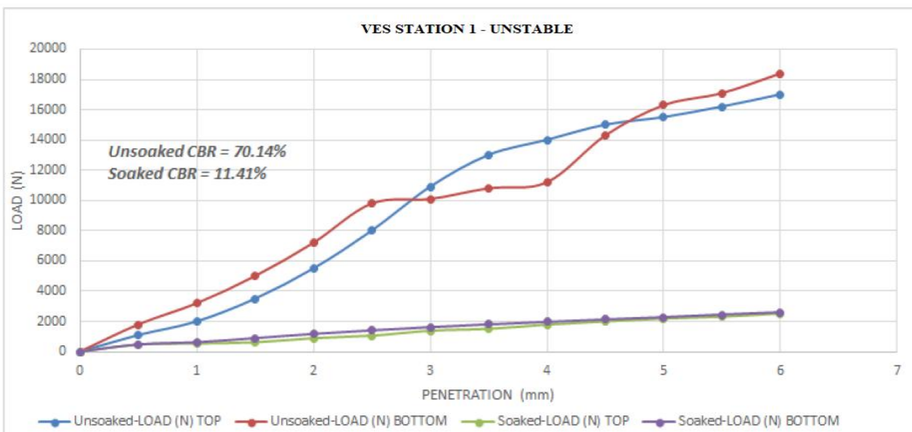
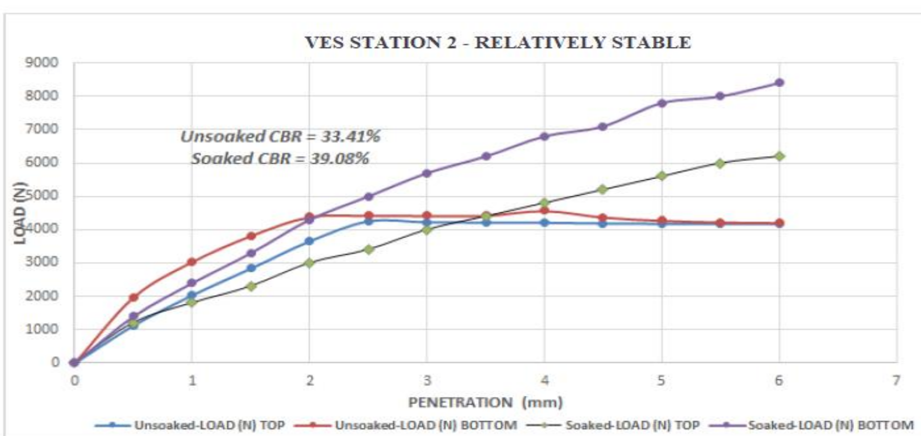
APPENDIX



CBR Result for VES Station 5

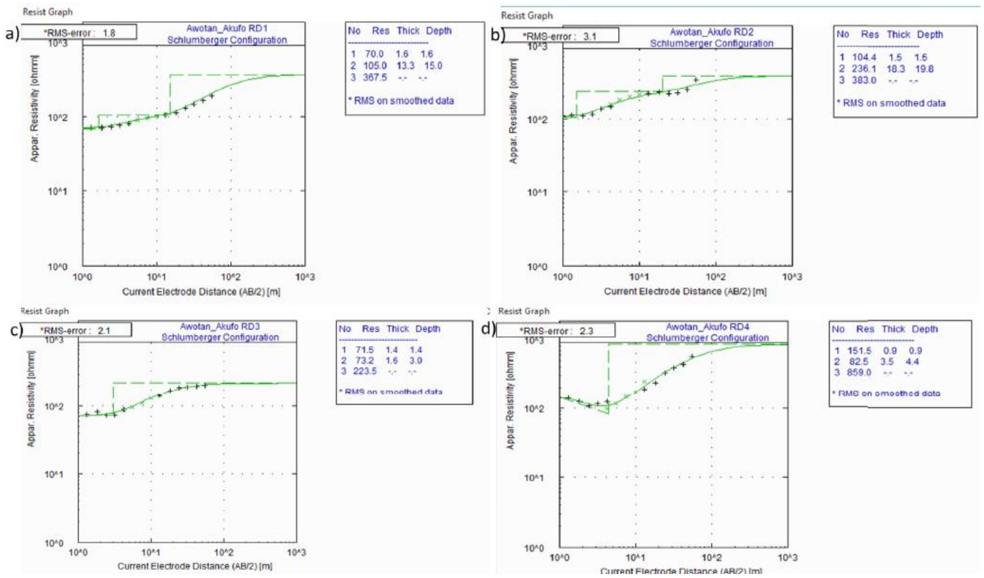


CBR Result for VES Station 1

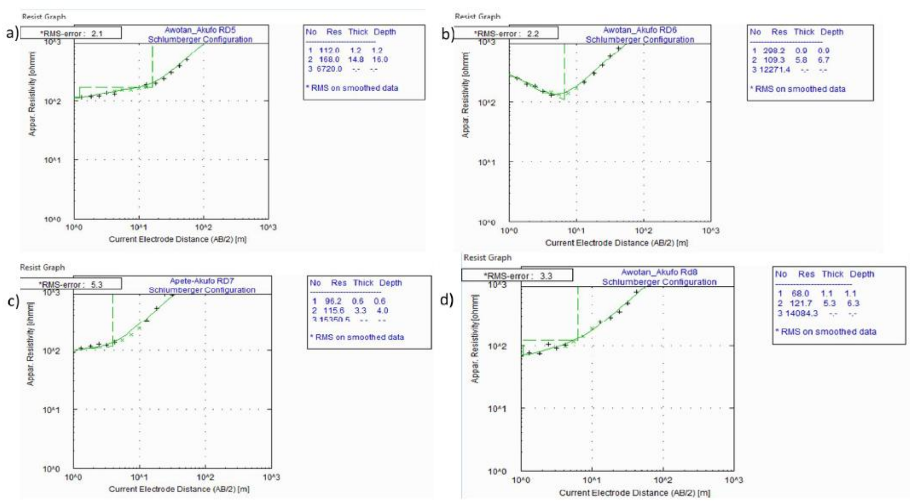


CBR Result for VES Station 2

VES Inversion Curves



Vertical Electrical Sounding Inversion Curves for VES Stations in (a) VES Station 1 (b) VES Station 2 (c) VES Station 3 (d) VES Station 4 Along Apete-Akufo Road



Vertical Electrical Sounding Inversion Curves for VES Stations in (a) VES Station 5 (b) VES Station 6 (c) VES Station 7 (d) VES Station 8 Along Apete-Akufo Road

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