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RELATIONSHIP BETWEEN ROAD PAVEMENT FAILURES, ENGINEERING INDICES AND UNDERLYING GEOLOGY IN A TROPICAL ENVIRONMENT

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ABSTRACT

This article presents the results of a study carried out to relate the frequency of pavement failures, the engineering indices of the subgrade materials and the underlying geology. The results show a high variability in the indices such as the liquid limit, LL, the plasticity index, PI, the maximum dry density, MDD, the optimum moisture content, OMC, compressibility and the California Bearing Ratio, CBR, between the different geologic units. Engineering indices having significant correlation with CBR (the major criteria for assessing the quality of subgrade materials), are used to develop a scheme for evaluating the materials at different failure points along the Calabar-Itu Highway in Nigeria. The evaluation shows that locations exhibiting high failure rates are underlain by shaly or marly subgrade whereas locations characterised by low failure rates are underlain by weathered basement or sandy unit as subgrade. It is recommended that maintenance and provision of drainage facilities will go a long way to reducing the rate of failure.

KEYWORDS: Engineering indices, Failure, Road pavement, Subgrade, Nigeria

INTRODUCTION

The Government of Nigeria has over the last three decades, embarked on the construction of roads and highways to improve the socio-economic connections between towns and cities. However, the realisation of this objective is being threatened by the failures of these pavements, with some of the pavements turning to 'death traps'. For instance the Nigerian Association of Road Transport Onwers (NARTO), is presently contemplating taking the Federal Government to court for the poor state/condition of the nation's highway, attributing it to the main cause of road accidents (Nigerian Vanguard, July 6 2002).

The roads and highways in Nigeria, including the study area, were designed to meet certain objectives as outlined by Peattice (1978). These include carrying traffic safely, conveniently and economically over the design life of the pavement by protecting the subgrade from the effects of traffic and climate and ensuring that no materials used in the pavement suffer any unacceptable deterioration. These roads however, have not satisfied these objectives. The observed failures which range from mild to severe (Plates 1 to 3), may be due to lack of maintenance, greater haulage loads than designed for and the underlying geology of the highways.

This study focused on the underlying geology of the highway. It used engineering indices of the subgrades at observed failure points to evaluate the quality of the subgrades and underlying geologic materials.

Studies by others have shown that the failure of pavements is variously linked to the inadequate provision of drainage facilities (Adegoke-Anthony & Agada 1982; Akpan (2002); excessive haulage loads, rutting, pitting, asphalt bleeding, insufficient compaction, insufficient pavement thickness and the shearing of flexible pavements (Adeniji 1984; Anowai 1986); volume changes due to seasonal water table variations (Van Der Merwe, 1980); and expansive subgrades (Van Der Merwe & Ahronovitz 1973; Richards 1979; Bullman 1980; Ola ,1983; Akpokodje 1986; Gourley & Newell1993; Gourley et al 1993; Uduji et al 1994). One of the major factors responsible for pavement failure in the tropical climates is the application of temperate region specifications in tropical regions (Gidigasu 1980). The work of Tanner (1963) on the performance of roads in 30 countries in tropical regions indicates that the frequency of failure increases with pavement age. In Nigeria, some studies have been carried out on the influence of geology on pavement failures. These studies are, however, restricted to mono-lithologic units such as the crystalline basement (Adeniji 1984; Anowai 1986; Teme et al 1987), and shale and clay (Ola ,1983; Akpokodje 1986; Uduji et al 1994). The work of Gidigasu (1983) and Madedor (1983), however, gave a general outline for the design of pavements, taking into consideration the environmental, soil and geologic characteristics of the terrain.

STUDY SITE

The study site is located in a humid tropical climate. The area experiences two major seasons, the wet and the dry. Meteorological data for the period 1990-2000 show that the temperature varies between 21.3 and 34.3° C and 21.1 and 35.2° C for the wet and dry seasons, respectively. The amount of rainfall varies between 0 and 286.3 mm and 5.4 and 796.6 mm for the dry and wet seasons, respectively.

The area comprises numerous lithologic sequences ranging in age from Precambrian to Tertiary. The major geologic formations include the Precambrian Oban massif (gneiss, schist, granite, pegmatite etc), the Aptian-Albian Awi Sandstone (sandstone, siltstone), the Albian Mfamosing Limestone (various types of limestone), the Late Albian-Turonian Ekenkpon Shale (organic shale, calcerous mudstone), Coniancian New Netim Marl (marl with minor calcerous siltstone beds), the Late Campanian-Maastrichtian Nkporo Shale (carbonaceous shale with mudstone and gypsum beds), and the Tertiary Coastal Plain Sands (gravel, sand, silt, clay), as shown on Fig. 1 and in Table 1 (Ekwueme et al 1995).

SAMPLING, ANALYSIS AND DESIGNATIONS

The samples of subgrades were collected from pavement failure points using a hand auger to a depth of 1 m, within different geologic units (Fig. 1, Table 1). The samples were analysed to determine their engineering parameters for

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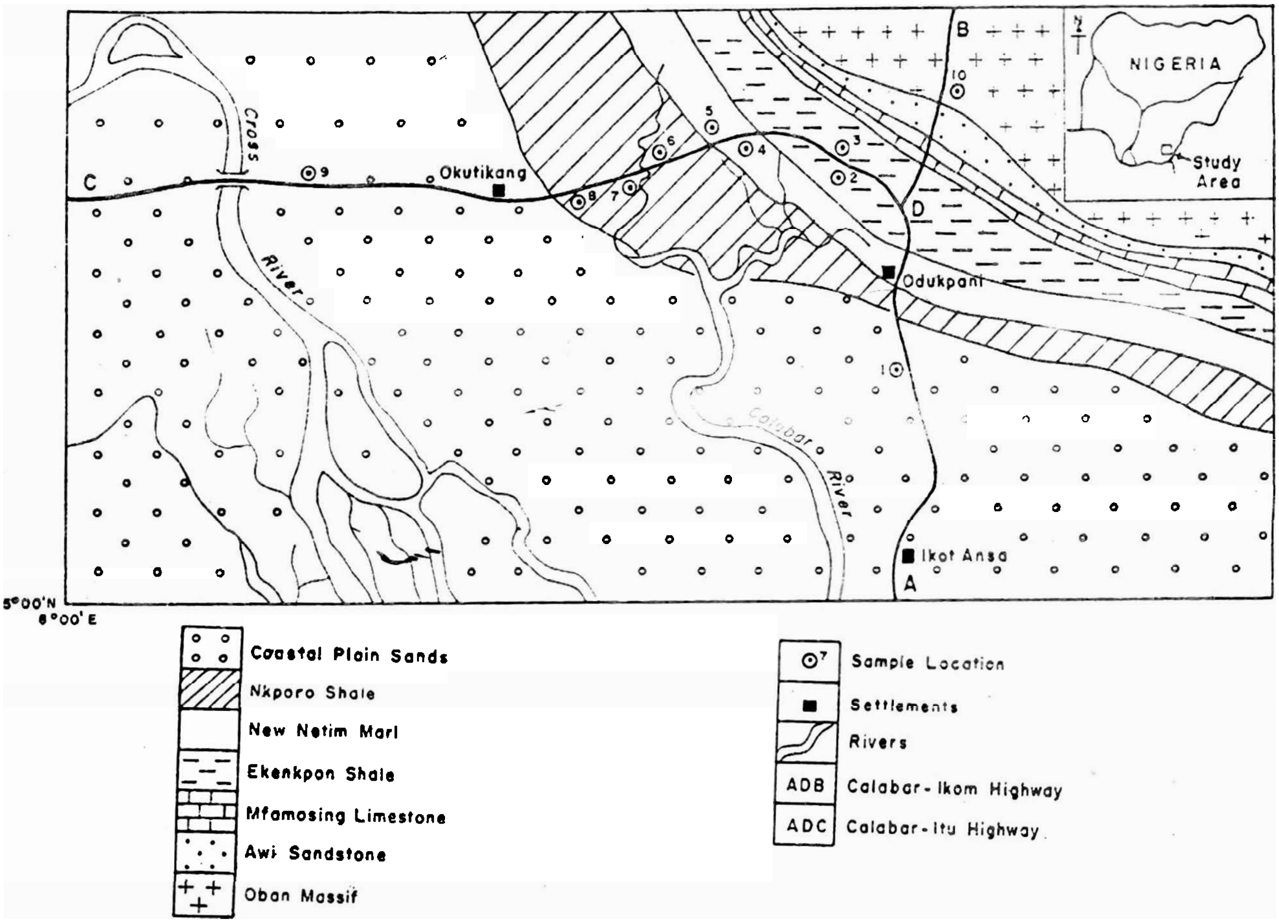

Figure 1 Outline geology of study area including sample locations

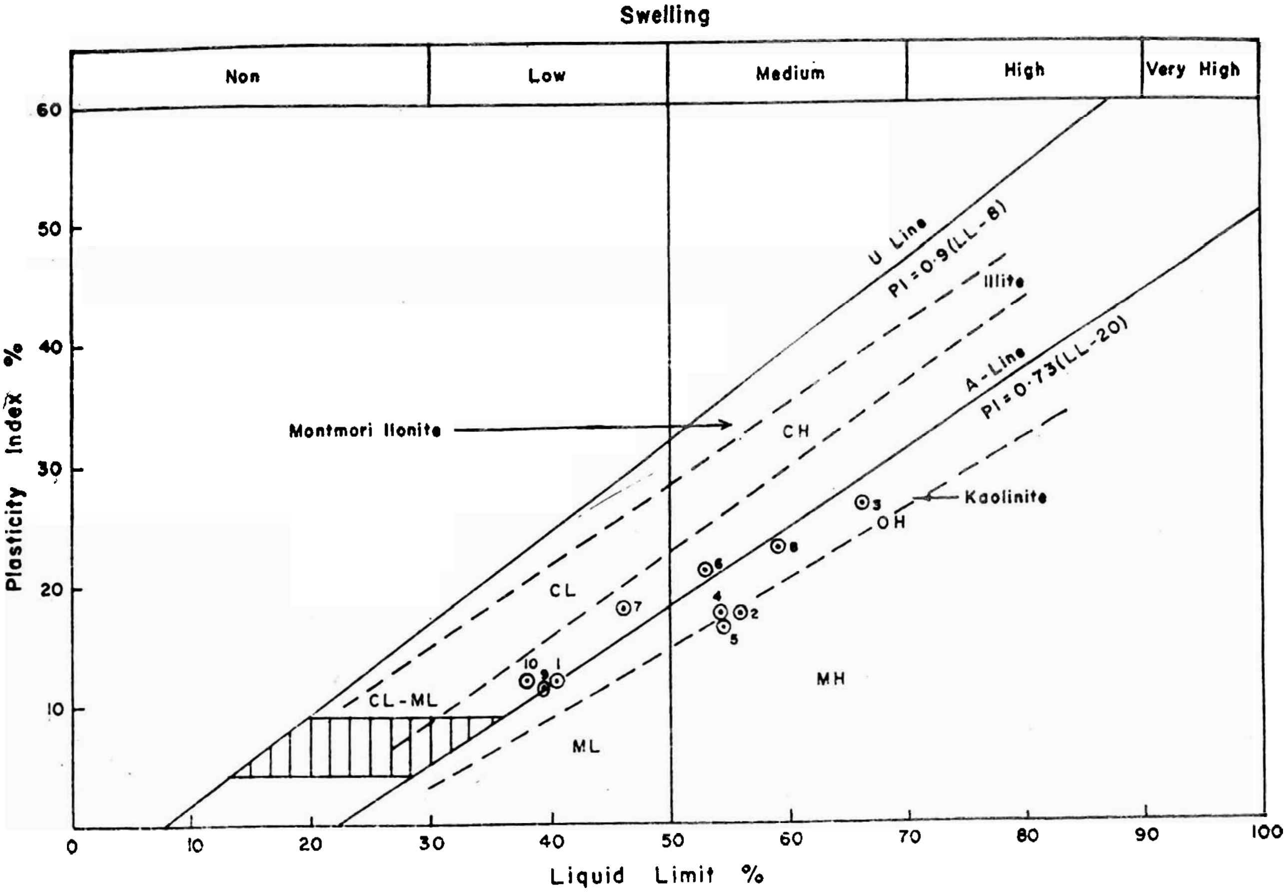

Figure 2 Plot of plasticity index and liquid limit values on plasticity chart

the purposes of classification and evaluation. The parameters included grain size, density, natural moisture content, Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC) and California Bearing Ratio (CBR), based on International standards (AASHTO 1978; BS 1990).

Samples were collected from the following geologic formations that make up the Calabar Flank: Coastal Plain Sands (samples 1 and 9); Ekenkpon Shale (samples 2 and 3); New Netim Marl (samples 4 and 5); Nkporo Shale (samples 6, 7 and 8) and Oban massif (sample 10). Samples were not collected from the Awi Sandstone and Mfamosing Limestone Formations, since the study locations did not pass through these units and no failure points were observed on them. Locations 1 and 10 were used as controls because no failure occurred in them. In all cases the number of sampling points was determined by the frequency of failure points.

PAVEMENT FAILURE PATTERN AND FREQUENCY

Four major types of pavement failures were identified using the scheme of Teme et al (1987). These included:

(i) Distress evidenced by the loss of asphalt (locations 6,7,8 and 9), Plate 1

Table 1 Sample location, lithology and designations

Age	Formation*	Lithologic descriptions	Sample Location	Failure frequency
Tertiary-Recent	Coastal Plain Sands	Gravel, sand, silt, clay	1, 9	none, 3
Late Campanian to Maastrichtian	Nkporo Shale	Dark carbonaceous shales with mudstone and gypsum beds	6, 7, 8	18,23,17
Coniacian	New Netim Marl	Grey fossiliferous marl	4, 5	10, 8
Late Albian to Turonian	Ekenkpon Shale	Dark friable, fissile shale with intercalations of marls, calcerous mudstone and oyster beds	2, 3	16, 11
Late Albian	Mfamosing Limestone	Fossiliferous limestone	no sample	
Aptian to Early Albian	Awi Sandstone	Conglomerates, sandstone, siltstone, mudstone, shale	no sample	
Precambrian	Oban massif	Gneiss, schist, granites, diorites, granodiorites, pegmatites	10	none

* After Ekwueme (1995), Fig 1 locations 1 to 9 Calabar-Itu highway location 10 Calabar-Ikom highway(control)

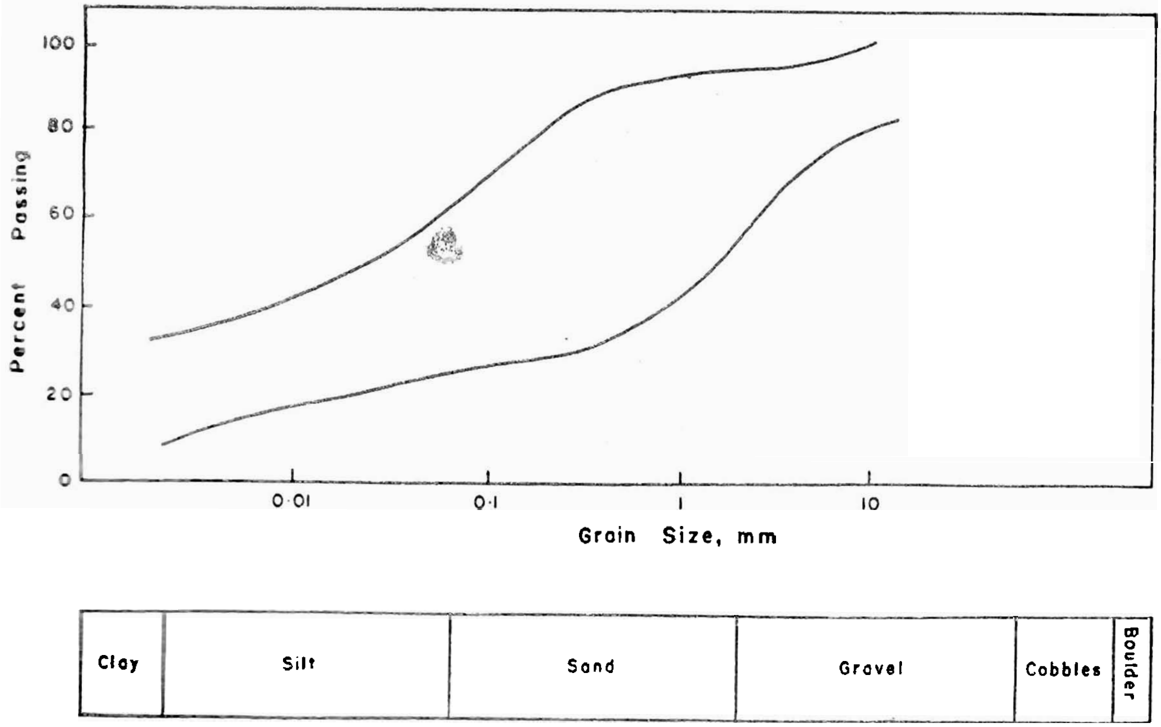

Figure 3 Range of grainsize curve

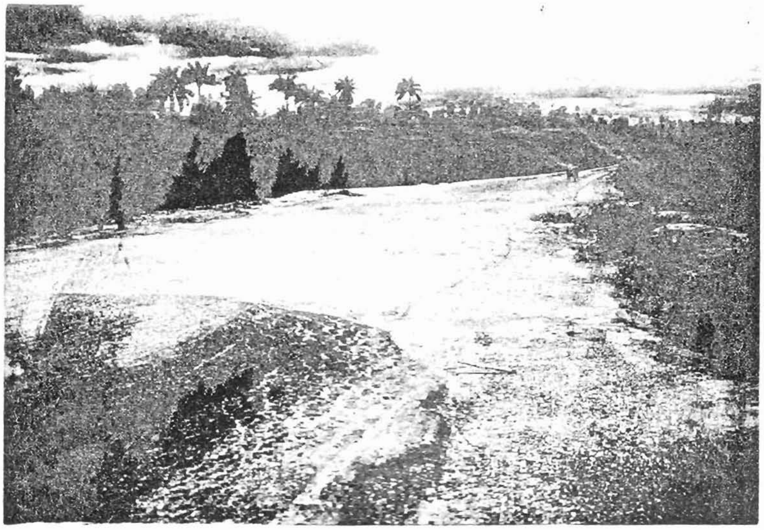

Plate 1 An example of complete removal of asphalt at location 9

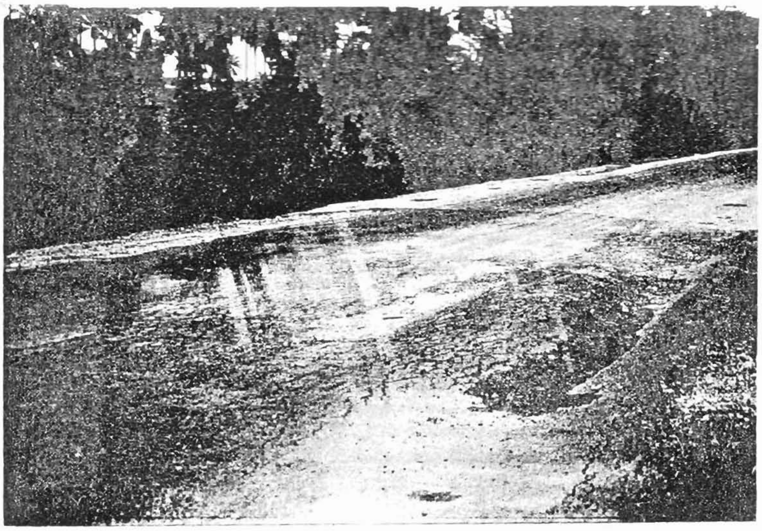

Plate 2 Wavy surface at location 4

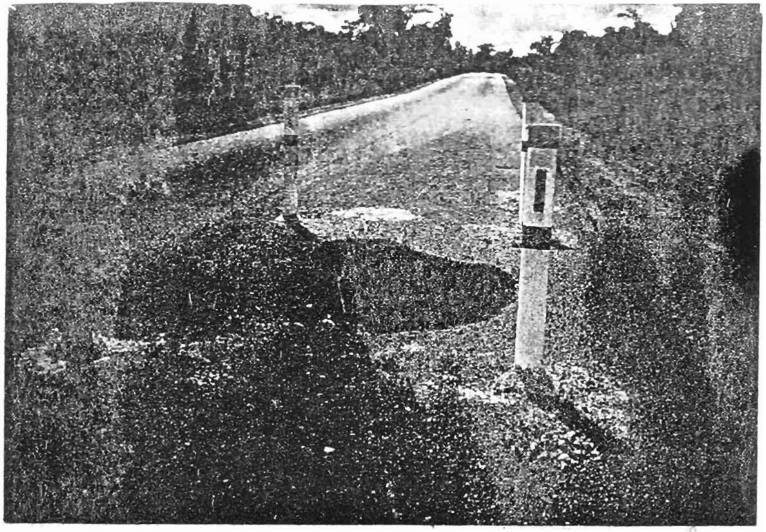

Plate 3 A pothole near at location 7 extending to the subgrade

(ii) Wavy or heaving surface (locations2,3,4,5,6,7,8 and 9), Plate 2

(iii) Pitting or minor dents, longitudinal cracks running parallel to the centre line of the highway (locations 4,5 and 9) and

(iv) Shear or massive failures or potholes extending through the pavement into the subgrade (locations 2,3,4,5,6 and 8), Plate 3

The frequency of failure, based on the average number of failure points per km show that the highest number of failure ıre within the Ekenkpon and Nkporo Shales followed by w Netim Marl and Coastal Plain Sands (location 9) 1). No failures were observed at locations 1 (Coastal ands) and 10 (weathered basement). At location 9, the nvolved a complete and continous loss of the asphalt) 1.5 km (Plate 1).

ΞERING INDICES

JRE CONTENT AND CONSISTENCY LIMITS

The natural moisture content (w_n) varied between a m of 10% at location 1 and a maximum of 29% at ı 6. These values reflect a variation from one lithologic another. The highest range of values 20-29 % erise the Ekenkpon and Nkporo Shale subgrade ls. The w_n for the other subgrade materials include: t 21-22 %, the Coastal Plain Sand at 10-11% and 16% ;ambrian basement (Table 2). The relatively high w_n for ement subgrade materials in comparison to the sandy le is due to the clayey nature of the weathered nt subgrade.. The density of the sandy subgrade ls was in the range 2.63-2.74 Mg m^{-1} and was the The density range of between 2.60 and 2.65 Mg m^{-1}, tained for the shaly and basement subgrades. The ıbgrade materials had the lowest values from 2.54 to ı m^{-1}.

The liquid limit (LL), plasticity index (PI) and ȷe limit (SL) ranged from 53 to 66%, 17 to 27% and 5.8 % respectively, for the shaly subgrade materials. ndices were in the range from 54 to 55%, 12 to 17% and 6.85 to 7.95% respectively, for the marly subgrades. Sandy subgrades showed ranges from 20 to 41%, 10 to 11% and 2.7 to 2.9%, respectively. The corresponding values for basement subgrades are 38%, 12% and 5.07% respectively. Qualitatively, these materials are described as having moderate (sandy, marly and basement subgrades) through moderate to high (shaly subgrades) plasticity (Table 3). A plot of LL and PI on the plasticity chart (Fig. 2), places the materials within the low (locations 1, 7, 9 and 10) to medium (locations 2,3,4,5,6 and 8) swelling potential ranges. The low swelling potential of sample 7 may be due to the sandy nature.

Based on the consistency indices, the materials are very stiff, (Tables 2, 3). The clay activity (A) values show the shaly subgrade materials as mostly active, while the materials underlain by marly, sandy and weathered basement subgrades are inactive to normal clay types (Tables 2 and 3).

GRAIN SIZE AND CLASSIFICATION

The grain size analyses indicate a predominance of clayey (20-40 %) and silty (30-56 %) components in the shales and sands (22-73 %) in the other materials (Table 2). The materials are well graded (Fig. 3).

Under the Unified Soil Classification System (USCS), the materials are classified variously as CL (low plasticity clay, sandy) for the sandy and basement subgrades; MH (high plasticity sandy silt with some gravel), and CH (high plasticity sandy clay with some gravel) and CL for shaly subgrades. On the basis of the American Association of State Highway and Transportation Official (AASHTO), the sandy and basement subgrades materials are in the groups A-2-7(0-2) and A-2-

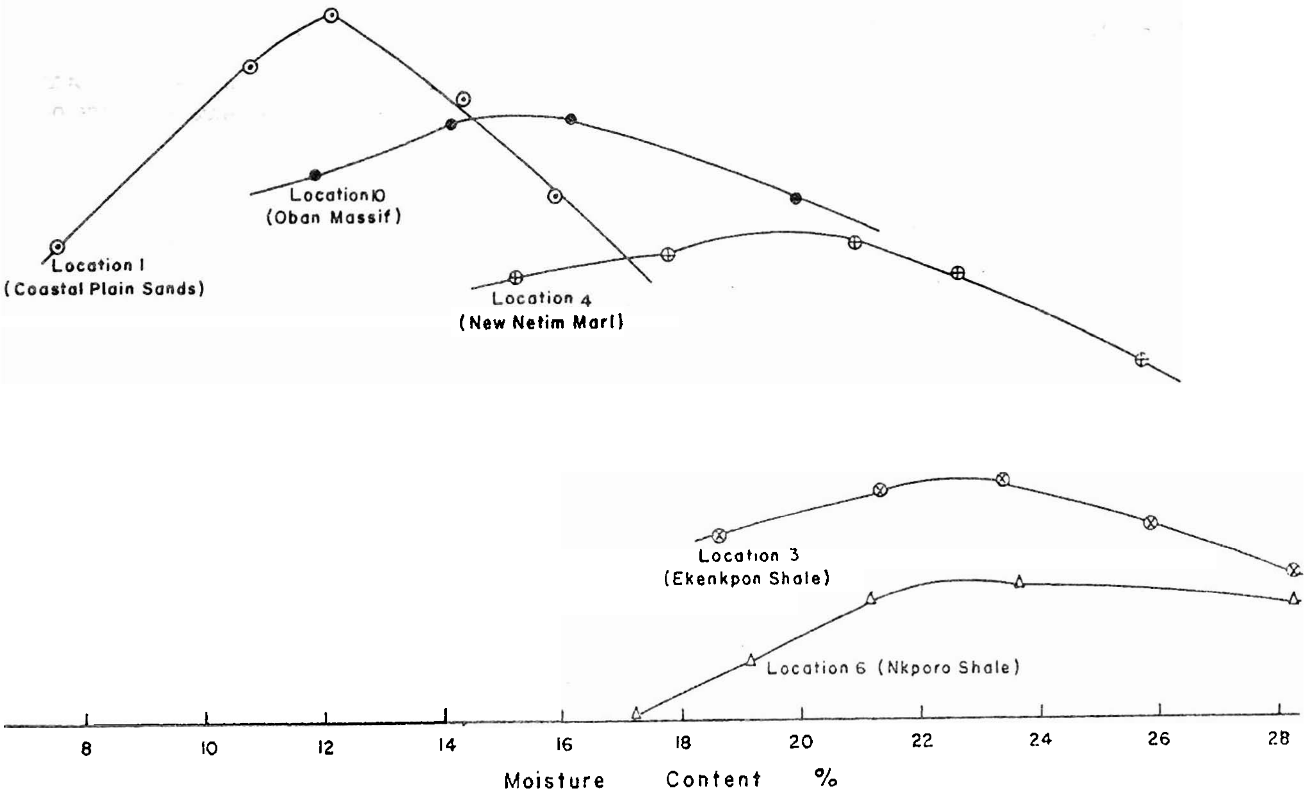

Figure 4 Compaction characteristics

Table 2 Engineering indices

Location	Density ($\mathrm{Mg\ m^{-3}}$)	Natural water content (%)	Liquid limit (%)	Plasticity index (%)	Linear shrinkage (%)	Consistency index	Activity	% Clay	% Silt	% Sand	% Grav
1	2.75	10	41	11	2.9	2.81	0.79	12	13	73	2
9	2.65	11	40	10	2.7	2.79	0.62	18	29	38	15
2	2.6	21	56	17	5.8	2.06	0.55	36	40	22	2
3	2.65	20	66	27	9.42	1.7	1.17	24	56	17	3
4	2.54	22	54	17	7.97	1.88	0.77	20	34	33	13
5	2.56	21	55	12	6.85	2.83	0.73	18	32	40	10
6	2.6	29	53	21	5.8	1.14	6.61	24	30	32	14
7	2.6	24	59	23	6.5	1.52	11.35	24	34	38	4
8	2.61	23	46	18	5.8	1.28	6.5	40	24	26	10
10	2.63	16	38	12	5.07	1.83	0.92	12	28	48	12

Table 3 Qualitative character of the soil

Location	Plasticity[a]	Consistency[a]	Activity[b]	Swelling[b]	Compressibility[a]	Consolidation[c]
1	moderate	very stiff	normal	low	high	oc
9	moderate	very stiff	normal	low	high	oc
2	moderate	very stiff	inactive	moderate	very high	hc
3	high	very stiff	normal	moderate	very high	hc
4	moderate	very stiff	normal	moderate	very high	hc
5	moderate	very stiff	inactive	moderate	very high	hc
6	high	very stiff	active	moderate	very high	oc
7	high	very stiff	active	moderate	very high	oc
8	high	very stiff	active	moderate	high	oc
10	moderate	very stiff	normal	low	very high	nc

nc normally consolidated, oc overconsolidated, hc high level consolidation

[a]Bell (1992), [b]Skempton (1944, 1953), [c]Means & Parcher (1963)

6(10) respectively. The marly subgrades are in group A-7-5(6-7), while the shaly subgrades are in groups A-7-5(7-11) and A-7-6(8), Table 4. This indicates that the sandy and basement materials are fair to good subgrades and shaly and marly materials are poor to very poor subgrades.

CONSOLIDATION CHARACTERISTICS

The consolidation characteristics are based on liquidity index (I_L) defined as w_n–PL/PI where w_n is the natural water content, PL is the plastic limit and PI is the plasticity index; and the compressibility using the relation $C_c=0.009(LL-10)$, where C_c is the compression index and LL the liquid limit (Mean & Parcher 1963; Bell 1992). The I_L values show that the marly and shaly subgrades (samples 2 and 3) are highly overconsolidated clays while the sandy subgrades and shaly subgrades (6,7 & 8) are overconsolidated. The basement subgrade materials are normally consolidated.

The C_c values indicate the shaly, marly and basement subgrades to be of very high compressibility. Sandy subgrade and shaly subgrade (sample 8) are of high compressibility, Tables 3 and 5.

COMPACTION CHARACTERISTICS

The compaction characteristics of the materials were evaluated for the different lithologic units using the Standard Proctor test (Table 5, Fig. 4). The mean maximum dry density (MDD) for the sandy subgrades ranged between 1.97 and 1.98 Mg/m^3 with corresponding optimum moisture content (OMC) values of 11.8-12.0%. The basement subgrade showed MDD (1.91 Mg/m^3) and higher OMC (15.5%). A further decrease in MDD (1.80 to 1.82 Mg/m^3) and increase in OMC (20.4 to 20.9%) characterised the marly subgrades. The lowest MDD (1.53 to 1.80) Mg/m^3) and the highest OMC (18.3 to 24.9%) characterised the shaly subgrades.

According to Gidigasu (1983), Gidigasu et al (1987) and Saha & Chattopadhyay (1988), the compaction characteristics of a soil are controlled by the index parameters. In this study, the MDD showed significant negative correlation with w_n, , LL, PI and the amount of clay and significant positive correlation with the amount of sand. The reverse is, however, the case for OMC (Table 6). The MDD decreased as w_n, LL, PI and %clay increased and increased as the amount of sand increased. The opposite is the case for OMC.

CALIFORNIA BEARING RATIO

The mean values of California Bearing Ratio (CBR) for both soaked and unsoaked samples ranged from 5.5% for sample 3 (shaly subgrade) to 20.5% for sample 10 (basement subgrade), Table 5. Significant correlation existed between CBR and the amount of sand with a correlation coefficient of 0.626 at $p=0.05$ (Table 6). The soaking of these samples showed a reduction in the CBR values with the highest reduction of 90% for shaly subgrades and the lowest reduction of 6% for sandy subgrades.

DISCUSSION AND CONCLUSION

No pavement failures were observed at locations 1 and 10 used as control. Location 9 (sandy subgrade) is an old river bed that was filled and compacted with lateritic materials incorporating drainage. These fill materials have been washed away by flood and the drainage has collapsed. Thus the failure

Table 4 Sample classification

Location	USCS		AASHTO	Geologic description
1	CL	Lean clay with sand	A-2-7(0)	Silty sand
9	CL	Sandy lean clay with gravel	A-2-7(2)	Silty sand
2	MH	Sandy elastic silt with gravel	A-7-6(5)	Silty clay
3	MH	Sandy elastic silt	A-7-5(8)	Clayey silt
4	MH	Sandy elastic silt with gravel	A-7-5(7)	Clayey silt
5	MH	Sandy elastic silt with gravel	A-7-5(6)	Clayey silt
6	CH	Sandy fat clay with gravel	A-7-5(7)	Clayey silty sand
7	MH	Sandy elastic silt with gravel	A-7-5(11)	Sandy silt
8	CL	Sandy lean clay with gravel	A-7-5(7)	Silty clay
10	CL	Sandy lean clay with gravel	A-2-6(10)	Gravelly sand

USCS Unified Soil Classification system
AASHTO American Association of State Highway and Transportation Official

Table 5 Consolidation,Compaction and CBR charateristics

Location	Consolidation		Compaction				CBR		
			Unsoaked		Soaked		Unsoaked	Soaked	% reduction
	Liquidity index I_L (%)	Compressibilty C_c	MDD ($Mg\ m^{-3}$)	OMC (%)	MDD ($Mg\ m^{-3}$)	OMC (%)	(%)	(%)	
1	-1.82	0.23	1.99	12 1	1.95	11.5	18	17	6
9	-1.9	0 27	2.01	12 3	1.95	11.7	20	18	11
2	-1 06	0 41	1.56	24 8	1.61	25	10	2	80
3	-0.7	0.5	1.6	23 1	1.69	22.8	10	1	90
4	-0 29	0.4	1.8	20 4	1.8	19.5	18	6	67
5	-0.3	0.41	1.82	20 9	1.79	20.1	17	5	71
6	-0.14	0.4	1.53	24 4	1.59	24	13	5	62
7	-0.52	0.44	1.66	18 9	1.66	19.5	12	3	75
8	-0 28	0.32	1.71	18 7	1.73	17.9	12	3	75
10	-0 33	0.25	1.91	15 5	1.91	15.2	22	19	14

MDD maximum dry density OMC optimum dry density CBR California bearing ratio

Table 6 Spearman correlation between MDD, OMC, CBR and some index parameters

Parameter	Units	MDD		OMC		CBR	
		r	p	r	p	r	p
W_n	%	**-0.859**	0.001	**0.559**	0.093	**-0.512**	0.130
LL	%	**-0.589**	0.073	**0.721**	0.019	**-0.742**	0.014
PI	%	**-0.768**	0.009	**0.604**	0.065	**-0.847**	0.002
LS	%	-0.418	0.229	**0.620**	0.056	**-0.498**	0.143
Clay	%	**-0.767**	0.009	**0.618**	0.057	**-0.577**	0.081
Silt	%	-0.364	0.301	0.360	0.307	**-0.498**	0.143
Sand	%	**0.547**	0.102	-0.442	0.200	**0.626**	0.053
Gravel	%	-0.148	0.683	0.082	0.897	0.047	0.897
MDD	(Mg m^{-3})			-0.772	0.009	**0.695**	0.026
OMC	%	**-0.772**	0.009			**-0.529**	0.116
C_c		**-0.602**	0.065	**0.750**	0.012	**-0.780**	0.008

r correlation coefficient and p probability

Table 7 Rating used for evaluation

Parameter	Units	Low L 1	Medium M 2	High H 3	Very high VH 4
CBR	%	< 10.0	10.0-15.0	15.0-30.0	> 30.0
LL	%	> 70.0	50.0-70.0	30.0-50.0	< 30.0
PI	%	> 17.0	15.0-17.0	12.0-15.0	< 12.0
MDD	(Mg m^{-3})	< 1.80	1.80-1.85	1.85-1.90	> 1.90
C_c		> 0.35	0.30-0.35	0.25-0.30	< 0.25

at this point was not attributed to the underlying geology. The other locations (shaly and marly subgrades) are marked by massive failures primarily due to heaving and swelling accompanied by the breakdown of installed drainage which then allow storm water to seep into the foundation. This together with excessive haulage loads has resulted in failure of the pavements at locations 2, 3, 4, 5, 6, 7 and 8.

In order to quantify the relationship between the frequency of pavement failure, index parameters and the underlying geology, a semi-quantitative scheme was used. For this evaluation, only the parameters that showed significant correlation with CBR were used. These parameters are: liquid limit (LL), plasticity index (PI), maximum dry density (MDD) and compression index (C_C) (Table 6). The values of these parameters were divided into class ranges with qualitative ratings of low (L), medium (M), high (H) and very high (VH). The ratings were then assigned points with VH having the highest of 4 and L the lowest value of 1 (Table 7). Each sampled location was then evaluated using the index parameters and the total points (TP) summed from the points

Table 8 Evaluation of the materials different failure points

Location	Underlying geologic materials	CBR	LL	PI	MDD	Cc	Total point	Failure frequency
1	Coastal Plain	H (3)	H (3)	VH (4)	VH (4)	H (3)	20	none
9	Sands	H (3)	H (3)	VH (4)	VH (4)	H (3)	20	3
2	Ekenkpon	L (1)	M (2)	M (2)	L (1)	L (1)	8	16
3	Shale	L (1)	M (2)	L (1)	M (2)	L (1)	[illegible]	11
4	New Netim	M (2)	M (2)	H (3)	M (2)	L (1)	12	10
5	Marl	M (2)	M (2)	VH (4)	M (2)	L (1)	13	8
6	Nkporo Shale	L (1)	M (2)	L (1)	L (1)	L (1)	7	18
7		L (1)	M (2)	L (1)	L (1)	L (1)	7	23
8		L (1)	M (2)	M (2)	L (1)	L (1)	8	17
10	Basement	H(3)	H (3)	H (3)	VH (4)	H (3)	19	none

L low, M medium, H high, VH very high Number in brackets represent the rating (see Table 7)

Table 9 Description of materials at each location

Total point range	Description	Location	Mean failure frequency
> 20.0	Very good		
15.0-20.0	Good	1,9,10	1
10.0-15.0	Moderate	4, 5	9
< 10.0	Poor	2,3,6,7,8	17

for CBR, LL, PI, MDD and C_c The TP was used to describe the material at each site (Table 8). From Table 9, sandy and basement subgrades showed good quality with low failure frequency. The marly subgrades were of moderate quality with a comparatively higher failure frequency. The highest frequency of failure was recorded for the shaly subgrades which are of poor quality.

In conclusion, the index parameters which varied greatly with the different lithologic units show that the sandy and basement subgrades are of good quality while the marly and shaly subgrades are of poor quality. The failure frequency was also found to vary greatly with lithology.

It is recommended that, maintenance, repair and adequate drainage facilities be provided especially for areas underlain by the marl and clays.

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