GLOBAL JOURNAL OF GEOLOGICAL SCIENCES VOL. 3, NO. 1, 2005: 17-24
ISSN 1596-6798

INFLUENCE OF GEOLOGY ON PAVEMENT PERFORMANCE: A CASE STUDY OF SHAGAMU-BENIN CITY ROAD, SOUTHWESTERN NIGERIA

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(Received 25 July 2003; Revision accepted 8 September, 2004)

ABSTRACT

The Shagamu-Benin city Road, a major link highway to the commercial capital of Nigeria in southwestern Nigeria is oriented approximately east-west and traverse geologic formations with extremely variable engineering properties. Field and laboratory investigations which involved geologic mapping, auger boring, sampling and laboratory testing were carried out to determine the stratigraphy and geotechnical properties of the sub-grade and their relationship to the pavement condition.

Field observation indicated that the road may have been based on a single design concept, without due consideration to the influence of geology on the performance of the pavement. The laboratory testing indicated in-situ dry density ranging from 1717 kg/m^3 to 2085 kg/m^3 in the lateritized zone in Edo state, and from 1678kg/m^3 to 1970kg/m^3 in the micaceous sections of Ondo state. The soaked CBR values for sub-grade materials of the Ondo section are accordingly low (3% to 6%), while the CBR values for the Edo state section which is reasonably drained is modestly high (2% to 16%). The low CBR values exhibited by the Ondo state section indicated that the sub-grade had a weak bearing strength and was susceptible to erosion on exposure to precipitation or surface runoff, thereby encouraging and exacerbating rutting and deformation of pavement.

KEYWORDS: Geology, Road failure and Performance.

INTRODUCTION

Pavement failures are common features of Nigerian roads. In spite of its wide distribution, the reasons for their occurrence seem not to be well understood. Some earlier workers notably, Ruddock (1966), Akoto and Singh (1981); Alao (1982); and Youdeowei and Teme (1993) described the properties of soils underlying road pavements without linking variations in such properties with pavement performance. Reasons for poor performance range from under-design to the use of inferior materials as road aggregates. An assessment of pavement failures on the east-west road linking Portharcourt to Warri indicates that they are largely caused by a combination of inappropriate and defective design, and poor maintenance (Abam et al, 2000).

Irrespective of the cause, a major consequence of pavement failures in Nigeria is the high road traffic accident rate (Omange 1997), which is frequently associated with heavy human casualties. The pervasiveness of poor pavement condition in Nigeria and the virtual absence of documentation on peculiarities of Nigerian roads and identification of lines of research towards improved pavement performance may suggest insensitivity of institutions responsible for policy, planning and management of highways in Nigeria. This underscores the need to identify the most important properties of road making materials, and hence the most fruitful lines of research.

Roads of various categories in the country have shown signs of distress in the form of cracking, rutting, deformation and peeling off. These signs of distress are developed and are visible within a short period after commissioning, usually, well within the design life of the road. Abam e t al, (2000) attributed many of these road failures, particularly, in the Niger delta to the use of foreign standards, particularly the British (BS) and American Standard (ASTM) that have no regard for local environmental and ecological peculiarities.

The Shagamu – Benin city road is one of Nigerias most strategic road, in the sense that it carries the largest traffic every year (Fadaka 1995). This highway is also a part of the Trans-African road net-work linking Nigeria to the Cameroun. Although pavement failure on the road is rampant, there is no recorded precedence of any road failure being thoroughly investigated by planners to establish the cause(s) of failure. Such a study would consider a variety of factors, such as asphaltic characteristics and the materials, and should provide a basis for cost reconstruction if necessary. The present study investigates the relationship between pavement condition and the underlying geology, with the intent to establish the influence of geology on pavement performance.

Geology and Topography

The Shagamu-Benin city Road is in the southwestern part of Nigeria. The geology of the area (Jones and Hockey, 1964) embraces the Precambrian Basement Complex rocks and Cretaceous sedimentary Formation of southwestern Nigeria (Figure 1). The Formations underlying the road alignment (from the Benin city end) consist of sands and clay; clay sand shale with lignite, false bedded sandstones, coal and shale,

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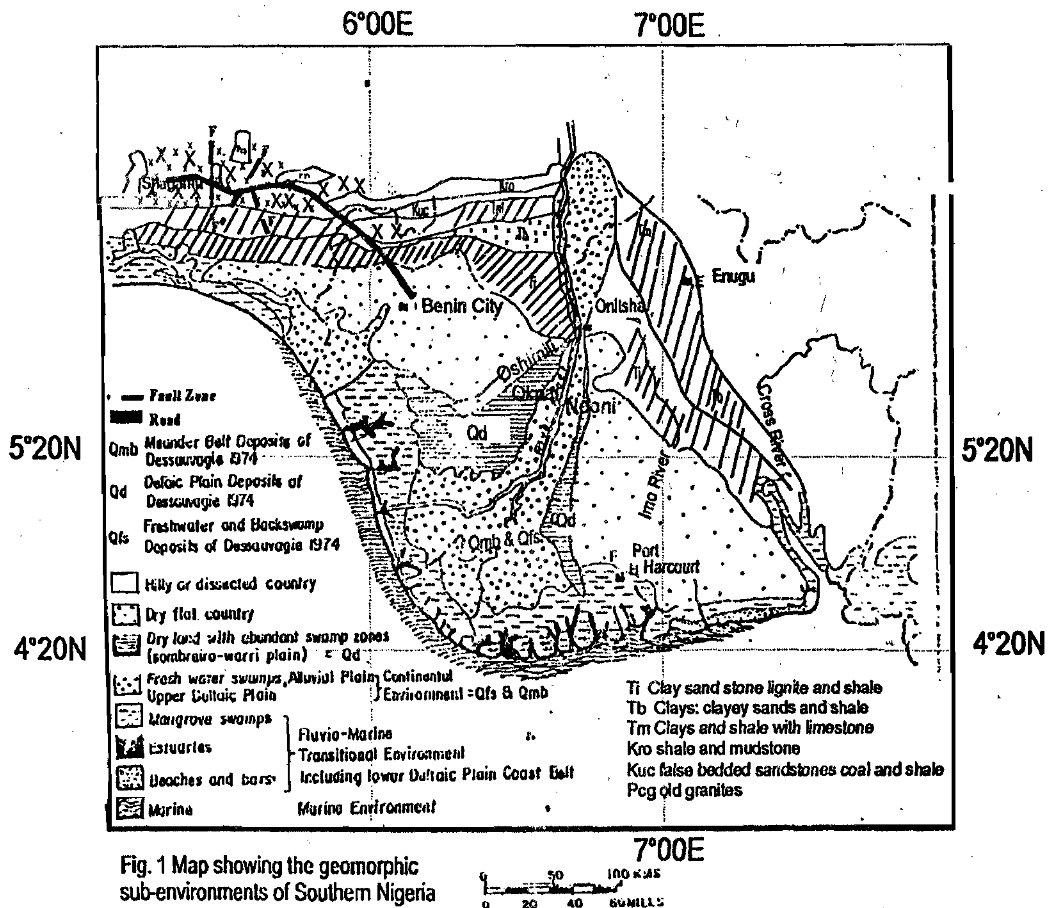


Fig. 1 Map showing the geomorphic sub-environments of Southern Nigeria and adjacent areas (Short and Stauble 1967)

undifferentiated gneiss migmatite, sands, clays and calcareous peat. The road alignment runs across about three fractures that are more or less orientated perpendicular to the road. The area of occurrence of these fractures are dominated by the undifferentiated gneiss migmatites.

The superficial soils comprise red ferrosols on loose sandy sediments. These are highly weathered ferralithic soils that have low exchange capacity, acidity and dominated by oxides of iron, alluminium and kaolinite. The road traverses an area that is largely covered by secondary forests. Relatively small sections of the road run through seasonal swamps and semi-evergreen forests.

Shagamu-Benin city Road traverses areas of moderate relief. Essentially the topography comprised largely low lands with an elevation generally between 200metres and 400metres above sea level. The road cuts across Ogun, Ondo and Edo States of southwest Nigeria. The climate of the study area is dominated characteristically by high rainfall (2100mm/annum) and humidity (88%), particularly from June to October. Over 75% of the annual rainfall usually occurs in four months between June and October.

METHOD OF INVESTIGATION

The investigation comprised both field and laboratory studies. During the field survey, the local geology was studied and disturbed soil samples were collected from auger holes to different depths, mainly at cut sections along the road. Soil samples were described from visual inspection while the geometry of the cut slopes were noted. The nature of failure in the cut sections was also noted. The weathered zone that are exposed in cut sections were mapped. In-situ moisture content of the soils at different depths was measured using Thomas Ashwort speedy meter tester.

The soils were tested in the field and laboratory in order to classify them and determine their engineering properties in accordance with the American Standards for Testing and Materials ASTM and Unified Soil Classification System (USCS). In-situ density and moisture content test were conducted in the field, while the laboratory tests carried out include: grain size analysis, consistency limits (liquid and plastic limits), compaction test, and California Bearing Ratio test on the sub-grade. The tests were conducted in accordance with the ASTM standards D43[illegible] (1994), D422 (1990) and D1557 (1991). The compaction test was conducted on soil samples compacted in three layers in a CBR mould each 25mm thick and applying 56 number of blows of 4.5kg rammer falling freely through a height of 450mm in accordance with ASTM D1557 (1991). The CBR test was carried out with a mould of capacity 945 x 10^{-6} m^3 at optimum moisture content and a 4-day soaking period which simulates the prolonged inundation and submergence experienced during the wet season between June and October. The

Table 1. Typical sections with the geologic formation and age and geometry of slope of cuts along the Shagamu-Benin city Road

S/No	Town	Slope Height (m)	Age of geologic formation	Slope Angle (deg.)	Condition of Pavement
1	Shagamu	2	Cretaceous (kb) Abeokuta Formation consisting of sands and clay	50-55	Fairly stable with minor cracks
2	Ijebuode	15-18	Cretaceous (kb) Abeokuta Formation consisting of sands and clay	55-60	Critical failure on cut section
3	Ajabandele	15	Precambrian-Upper Cambrian (Pcb), Basement complex	50-55	Base failure on both sides
4	Ore	7-12	Cretaceous (Ruc), false bedded sandstone and upper coal measures	60-65	Base failure 200m of the cut section
5	Onishere	6-8	Cretaceous (Ruc), false bedded sandstone and upper coal measures	45-50	Critical failure with potholes and peeling off of wearing course
6	Ofosu	1-3	Tertiary (Tm), Clay and shale	50-55	Critical pavement failure
7	Iguobo	2	Tertiary (Ti), Ogwashi-Asaba Formation consisting of lignite, clays and sandstone	45-50	Long stretch (300m) of failure with spider cracks, deep potholes and rutting
8	Oluku	15	Quaternary (Qp), Benin Formation consisting of sands and clays	55	Fairly stable with minor longitudinal cracks
9	Benin	2-15	Quaternary (Qp), Benin Formation consisting of sands and clays	45-50	Stable pavement with minor longitudinal cracks.

compaction and CBR tests were only conducted on the sub-grade soils which are derived mainly from weathered rocks and sediments and which carry a significant part of the traffic load.

RESULTS

Field Observation

The field investigations revealed that the Shagamu-Benin city Road traverses six major geologic formations, namely; Basement complex, Ajali Sandstone and Nsukka Formation. The others include Abeokuta Formation, Imo shale, Ogwashi-Asaba Formation and Benin Formation. The road passes through a rolling terrain, necessitating heavy cutting and embankment in some sections. The slope angles of the cuts vary within a narrow range of 45 and 60 degrees, in contrast to the slope heights which vary over a wider margin (1-18m) as shown in Table 1. The embankments typified by figure 2 are mostly steep with angles generally between 55° and 65°. Due to a combination of steep slope and relatively weak soil sub-grade, the embankments have developed cracks that have progressed to shear failures affecting the asphaltic surface of the road. A schematic representation of the structural relationship of the geologic formations along the road alignment is shown in figure 3. Quartz veins and striations are exposed in road cuts along the undifferentiated gneisses in the Shagamu section of the road (Fig. 4). The age of the formations and the major road sections where these occur are outlined in Table 1.

The Ondo State section is characterised mainly by poor pavement condition that are dominated by critical and

Fig. 2 Showing the high embankment

Fig. 4 Exposed Road cut showing quartz vein and striations.

Fig. 5 Evidence of poor pavement condition

base failure types. Scenes of poor pavement condition are depicted in figure 5. Field observations indicate that pavement failures are common in the deep cuts where the road is constructed on a sub-grade consisting of friable and heterogenous materials within the mottled and pallied zone of the weathering profile (Fig. 6). At these horizons, the soils which comprise mostly of decomposed rocks are susceptible to fragmentation under stress. This tendency is typified by the Ajebadele-Ore section in the Ondo State segment of the road, where the deep cut inevitably exposed decomposed weathered rock formation in the basement complex areas. Although the soil formation at this section of the road had experienced some weathering, it had maintained its close resemblance with the basement complex. At the present stage of weathering, the superficial soils are largely reddish lateritic and clayey soil derived from the decomposition of the gneiss and mica schist rocks comprising the basement complex (Table 2). The exposed cut slope surfaces showed leaching of the siliceous material leaving the more durable ferric and quartzite element of the lateritic residuals soils.

Laboratory Results

The soils classify mostly as sandy silt, clayey silty sand and clayey soils (MH, SC and CH) respectively based on the Unified Soil Classification System (USCS) and A-2 to A-7 in the AASHTO classification system (Table 3). A representation of the plasticity characteristics of the soils in the Casangrande plasticity chart (fig. 7) show that they mostly fall above the A-line, indicating that they consists predominantly of inorganic materials. The degree of scatter on the plasticity chart reflects the degree of variability of the soils, particularly in clay types and percentage content of fines. The proportion of clay sized particle ranges from 15% to 77%. The percentage clay tends to be higher in the sub-grade materials that experienced widespread and severe pavement failure especially in the Ondo State section of the road.

The test results of modified Proctor compaction tests are summarized for eight samples in table 4. Maximum dry densities are relatively low for the sub-grade soils, compared to the sub-base materials, which were transported.

The in-situ dry density ranged from 1717 kg/m^3 to 2085 kg/m^3 in the lateritized zone in Edo state, and from 1678kg/m^3 1970kg/m^3 in the micaceous sections of Ondo state. The soaked CBR values which are shown in table 5 for sub-grade materials of the Ondo section are

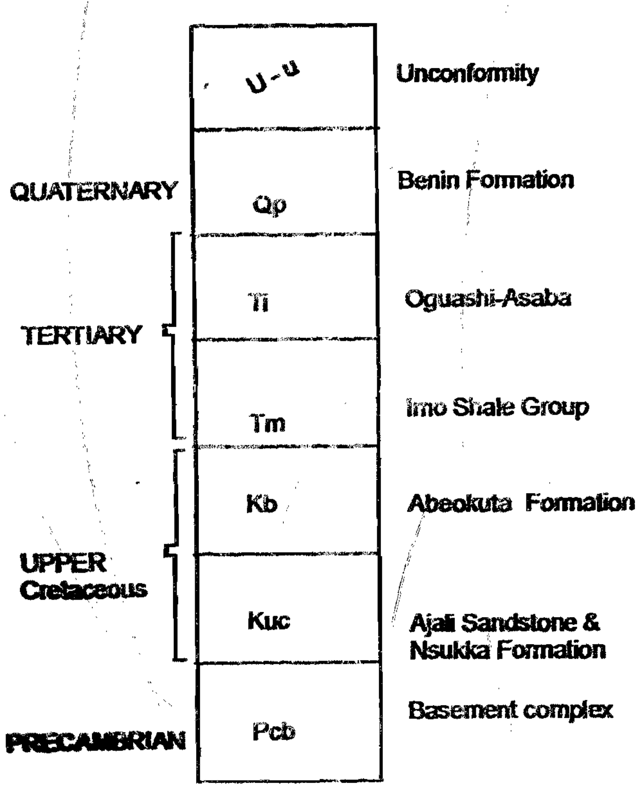
Table 2. Typical lithologic log of the test pit at cut sections of the road

S/No.	Location	Depth (cm)	Visual Soil Description
1	Shagamu	0-230	Loose reddish clayey soil
2	Kajola	0 –50	Reddish gravelly lateritic soil
		50-90	Gravelly sandy soil
3	Ajabandele	0-63	Grayish silty soil
		63-95	Brownish silty soil
4	Onishere	0 – 65	Brownish silty soil
		65-85	Grayish fine silty soil
		85-150	Coarse sand
5		0-90	Reddish clayey silt
	Asejire (Ore)	90-213	Yellow reddish clayey silt
6	Onishere	0-30	Reddish clayey soil
		30-140	Yellowish Brownish clay
		140-210	Brownish yellowish clay
7	Owena	0-30	Reddish Clayey soil
		30-50	Reddish brownish clay soil
		50-90	Light brownish clay soil
		90-150	Gravelly sandy clayey soil
		150-210	Clayey gravelly sand

accordingly low (3% to 6%), while the CBR values for the Edo state section which is reasonably drained is modestly high (2% to 16%). The low CBR values exhibited by the Ondo state section indicate that the bearing strength of the sub-grade soils is weak. As a result, such sub-grade soils become susceptible to erosion on exposure to precipitation or surface runoff, thereby encouraging and exacerbating rutting and deformation of pavement.

DISCUSSION

The over 250km stretch Shagamu-Benin city Road presents diverse effects of geology on pavement performance. At Onishere, the road is constructed on a 8m deep cut section into the partly decomposed micaceous schist with ponding at the toe of the slope. At both sides of the road, there were critical base failures of the pavement. Similarly, there were failures at several sections of the road, especially at cut sections within Ajebandele Ofosu section. Apart from the creation of kinematically feasible soil masses at these points, the soil layers displayed high susceptibility to erosion, thus creating unstable soil masses, which collapsed by sliding under adverse moisture conditions.



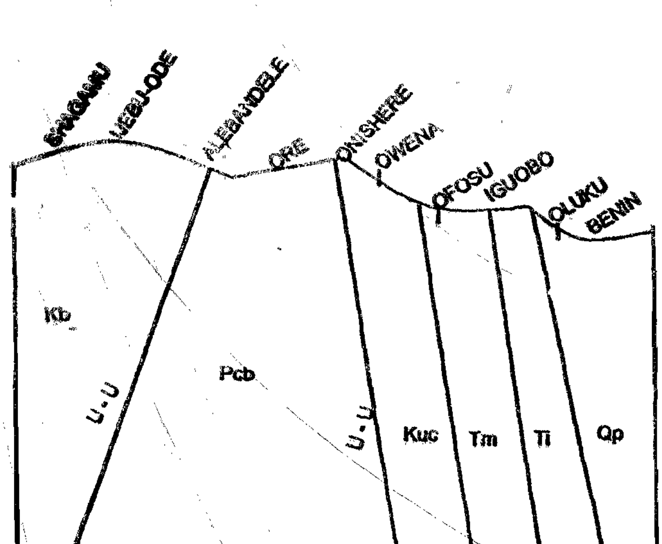


Fig. 3 Schematic cross section of Shagamu - Benin City Road

The in-situ moisture contents in both Ondo and Edo states increased with depth. This is because, the infiltrating water percolates down until it intercepts the unweathered basement rock or the water table. As the consequent upward saturation progresses, ground water may seep out at the toe of the slope, causing toe erosion and creating weak interfaces that easily constitute slip surfaces. This process results in a tendency for failures to occur in sections where the basement complex rocks outcrop on road cuts such as in the Ajebandele-Ore section. In places where the lateritized zone is thin, it is found that weathering intensity is decreased with depth. Road failures are preponderant in sections, which traversed the friable, heterogenous materials of the mottled and pallied zones. This is because any existing structural bonding is destroyed by heavy rainfall, causing side slumps and erosion. The loss of bonding in the micaceous material of this group is accompanied by a considerable loss of strength and the formation of slurry as evidenced in the Ajabandele-Ore section.

The relatively low maximum dry density and high moisture content of the soil are ascribed to the structure and texture of the micaceous geologic material. The flaky structure of the micaceous minerals produce a highly porous but impermeable matrix even when compacted (Sowers and Sowers 1970). Water can ingress freely into such pores, resulting in higher moisture content as observed in the Ondo state section of the road. However, due to the poor permeability of these soils, the water is retained within the soil matrix, resulting in generally weaker strength and lower bearing capacity.

The Ondo State sub-grade soils have higher and wider range of moisture content than Edo State sub-grade soils. This is due to the higher water table influence of micaceous materials in Ondo State. The moisture content in both sections is mostly wet of optimum, particularly in the Edo section, which was already much better compacted. In spite of this, the liquidity indices of the soils showed the sub-grade soils in the Ondo section as in very poor condition. This is an indication that the compaction of the sub-grade in the mica schist terrain of the Ajabandele-Ore section in Ondo State did not attain its expected maximum dry density, during the construction period. A comparison of the in-situ density measurement with the maximum dry density obtained from the laboratory compaction tests indicate that the relative compaction in the Ondo State section varied

Table 3: Typical engineering properties of the soil

S/No	Location	Depth (cm)	Particle sizes 2mm	63µ	2µ	LL (%)	PI (%)	USCS	AASHTO
1	Shagamu	0-230	95.8	51.5	11.5	53.2	38.3	CH	A-7-6
2	Ijebu Ode	0.50	55.0	38.0	12.5	55.0	27.4	GC	A-7-6
		50-110	71.9	33.4		28.4	28.4	SW	A-2-6
3	Ajebandele-Ore	0-63	98.9	30.8	4.0	30.2	21	SW	A-2-4
		63-95	97.9	33.4	11.0	44.2	18.4	SC	A-2-7
4	Onishere	0-65	90.8	60.6	12.0	68.5	14.0	MH	A-7-5
5	Ofosu	0-86	96.4	77.0	7.5	43.7	21.5	CL	A-7-6
		86-88	98.4	75.6	29.0	64.0	48.7	CH	A-7-6
		88-148	83.5	34.1	7.0	58.6	33.6	SC	A-2-7
6	Iguobo	0-90	94.3	76.8	34.0	75.5	33.9	MH	A-7-5
		90-213	96.3	72.4	8.0	89.4	32.3	MH	A-7-5
7	Oluku	0-30	99.0	35.3	20.0	33.0	17.2	SC	A-7-6
		30-140	94.0	81.3	24.0	72.2	42.7	CH	A-7-6
		140-210	95.6	82.1	22.0	82.0	55.1	CH	A-7-6
8	Benin	0-30	82.3	21.6	7.5	12.0	28.8	SC	A-2-7
		30-144	94.1	18.4	7.0	43.6	29.9	SC	A-2-7
		144-190	99.0	60.8	20.0	69.7	40.3	CH	A-7-6
		190-220	98.4	19.2	6.0	42.0	28.7	SC	A-2-7

between 84% and 97%, in contrast to the Edo State section which varied between 98% and 100%. A remarkable difference was however observed in some cases. The road sections constructed on the Benin Formation showed reasonably good performance. The coastal plain sands which are reddish to brownish yellow silty often clayey sand are ill-sorted deposits that are common within the Edo section. This section of the road did not show any signs of distress because the soils are well drained and have developed a matrix of ferric and kaolinite bonding of the sand grains that improves the load bearing characteristics.

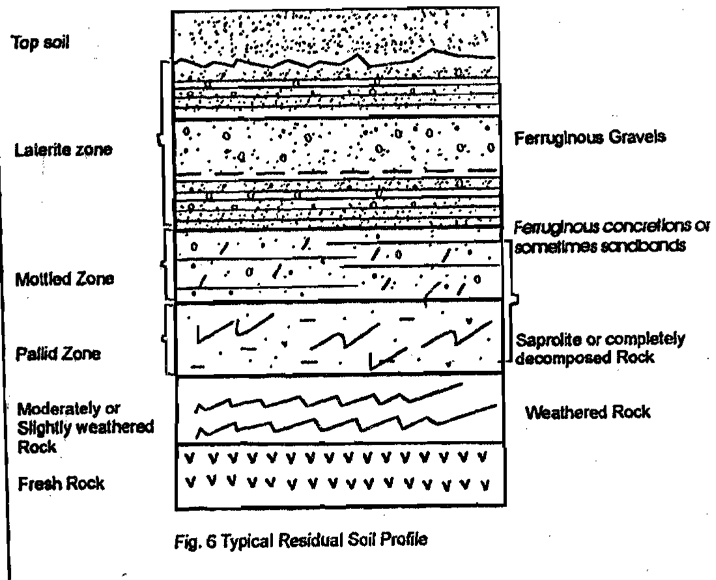


Fig. 6 Typical Residual Soil Profile

The role played by moisture content and soil drainage highlight the importance of the control of moisture content of the road structure itself, which may affect the choice of materials for various layers of the structure; and the sub-surface drainage, which may affect the moisture content of the sub-grade and hence its strength and stiffness. A study of the effect of deep drains (Russan 1967) indicated that they could be economic for roads on silty clay sub-grade.

The consideration of the high rainfall that characterize the Niger delta for example promptly reduces any design based on the BS or ASTM for locations within the Niger Delta region to both inadequate and inappropriate. This is because, the heavy rainfall which is concentrated within five months of the year creates conditions which result in prolonged inundation and submergence, for periods that far exceed those governing the prescribed BS and ASTM Standard tests. Under such circumstances, even the application of quality assurance and quality control (QA/QC) plans are not likely to produce much improved performance.

The design of the Shagamu – Benin city road had been based on a general engineering understanding of the properties of road making materials and the structural function of the pavement without due regard to the

Table 4 Range of Maximum dry density and Optimum Moisture content

Section	Laboratory Results		In-situ Measurement			Remarks
	Maximum Dry Density $x10^3$ (kg/m^3)	Optimum Moisture Content (%)	In-situ Dry density $x10^3$ (kg/m^3)	In-situ subgrade Moisture content (%)	In-situ Moisture Content in test pit (%)	
Ondo	1.72-1.99	8.5-18.5	1.678-1.97	17.0-38.2	13.7-44.8	High water table
Edo	1.68-2.3	9.0-17.5	1.715-2.09	20.4-24.0	12.8-33.8	Low water table

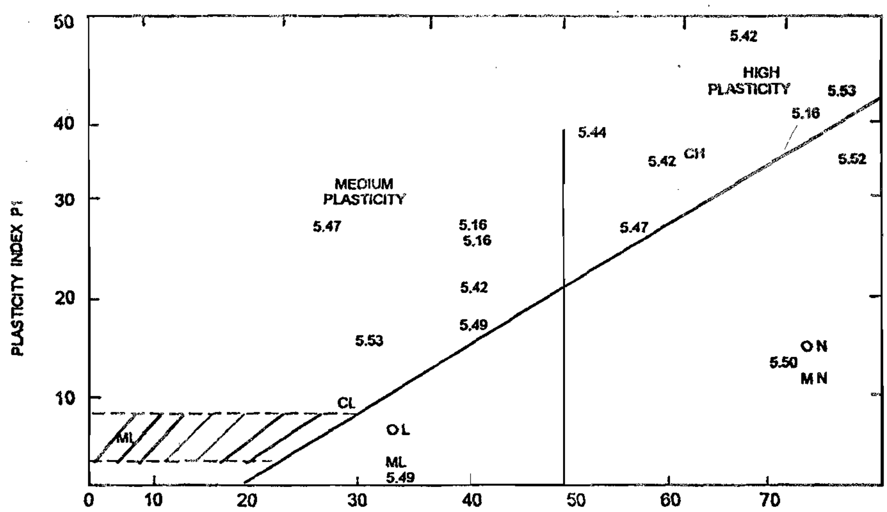


Fig. 7 Distribution of Plasticity characteristics of the soils

Table 5: Mean maximum dry density, optimum moisture content and CBR for sub-grade and sub-base materials

Mean values			
Road Section	Max. Dry Density $x10^3$ (kg/m^3)	Optimum moisture content (%)	CBR (%)
Edo section			
Sub-base	1.97	12.92	
Sub-grade	1.90	11.75	2-16
Ondo section			
Sub-base	1.96	13.7	
Sub-grade	1.83	15.5	3-6

peculiar environmental conditions of the area. An improved pavement design could for example require a specification of environmental conditions, particularly temperature and rainfall. According to Burt (1969) high temperatures have an adverse effect on the structural properties of bituminous materials. The ranges of temperature and the consequent changes in dimensions induce thermal stresses in concrete pavements.

CONCLUSION

Based on this study, it is concluded that the geology and the weathering history of the area exert great influence on not only the engineering properties, such as maximum dry density and optimum moisture content, but also on the performance of the road. The sub-grade soils, comprising residual lateritic soils derived from sandstones, weathered basement complex rocks and shales, often with micasceous minerals and clays, exhibited different geotechnical behaviour under similar conditions. Pavement failures were mostly encountered in deep cut sections comprising decomposed micaceous schists, due to weaker chemical bonding, poor drainage and the appreciably poor load bearing characteristics.

Analysis of the engineering properties of weathered profiles along the route indicates that the lower zones are less suitable for the sub-grade of road pavements on account of their high water content, liquid limit, plasticity index, amount of fines and low CBR. When a sub-grade is placed in the upper horizon of the soil strata, the large volume of sub-surface flow that will percolate will move away from the roadway, leaving only small quantity of water to drain downwards at the verge of the road. In contrast, roads constructed on the lower horizon of the weathered zone, adjoining hard impermeable rock surfaces become natural receptacles for seepage that assist in leaching some fines on its path, resulting in destruction of the soil fabric, structural collapse, higher compressibility, rutting of the pavement surface and eventual failure.

Road pavements constructed on sub-grades derived from different geologic formations are subject to variable reactions. This is exemplified by the poor pavement quality in the micaceous rocks in contrast to relatively better pavement condition in the Abeokuta Formation or the Benin Formation at the Edo state section of the road. For effective design, adequate knowledge of the characteristics and behaviour of the soils is necessary. Further more, due consideration should be given to the interactions and sections of the soils under the influence of the peculiar environmental condition. These effects would assist in reducing the occurrence of road failures and improve pavement performance, particularly at this time of harsh economic realities. Based on this study, it is recommended that the sub-grade of roads in the study area should be confined to the lateritized horizon along the cuts, to ensure improved pavement performance.

Foreign standards particularly the BS and ASTM should not be used for pavement design and material selection without prior review to incorporate peculiar local conditions.

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