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Impact of geology on the stability of Minna-Bida road, north-central Nigeria

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ABSTRACT.

The rocks and soils underlying Minna-Bida road in central Nigeria were mapped with the view to determine their impact on the stability of the road underlain by them. A total of 4 rock samples were collected from the road and subjected to thin section, XRD and XRF analyses. Groundwater table of wells along the road were observed to determine the seasonal groundwater variation. Twenty-eight (28) water samples were collected from wells along the road and subjected to hydrochemical tests to determine the variations in the ionic concentration and physical properties of the groundwater with the underlying lithologies. A total of 60 soil samples were subjected to grain size distribution test using wet sieving and fifty (50) of the samples were selected and subjected to Atterberg limit tests. Twenty-two (22) and nineteen (19) of those samples were subjected to compaction, permeability and California bearing ratio (CBR). The field mapping, thin section and XRD results revealed that Minna-Bida road is underlain by granites, migmatite, schist and sandstone. The chemical compositions of the rocks indicate that they are mostly acidic rocks/protholith. The physico-chemical tests revealed that the groundwater within the sandstone terrain of the road has the least ionic concentration and physical properties. The grain size distribution test revealed that the soils within the sandstone terrain are mostly sandy soils (SW and SP) while those within the migmatite gneiss and granite terrains are gravely (GW and GP) soils. Permeability of the soils ranges from 4.73×10^{-4} to 9.78×10^{-3} cm/s. The soils occurring within the sandstone terrain has optimum moisture content (OMC) ranging from 9.4 to 18.0%, MDD ranging from 1.74 to 2.2, soaked CBR ranging from 45 to 95%, and unsoaked CBR ranges from 70 to 144%. Within the crystalline rocks, MDD range from 1.73 to 2.08, OMC 12.24 to 19.7%, unsoaked CBR 35.90 to 121.8% and soaked CBR 24.19 to 115%. Permeability of the soils is generally low and does not vary with the different underlying lithologies. Grain size distribution, Atterberg limits, compaction and CBR reveal that soils underlying the sandstone are generally more competent than those underlying the crystalline rocks and can satisfactorily serve as road sub-grade and sub-grade in their natural state. The consistent failure of the Minna-Bida road portion underlain by migmatite gneiss and granite is attributed to the fact that the soils occurring within those terrains have poor geotechnical properties to serve as either sub-grade, sub-base or base material in their natural state.

Keywords: diffractogram, geotechnical, hydrochemistry, lithology, mineralogy, road failure

INTRODUCTION

In spite of frequent efforts by the Niger State government of Nigeria on the maintenance of Minna-Bida road, it has been observed that the road is still not stable. The road condition is particularly worse in parts that are underlain by fractured weathered crystalline rocks, which have resulted to clay minerals. Adequate attention on the understanding of the geology that underlies this road is therefore necessary. This is because the road pavement derives its support to be sound and durable from the subsurface geologic material (Okogbue. 1988). In choosing the route for the highway, one of the important factors considered is the geotechnical properties of the sub-base and subgrade material. When design technique, construction procedure and materials used for road are adequate and the road still experiences failure, the geological, mineralogical, geotechnical, soil, climate and drainage conditions become critical.

In this paper, the geological basis for the failure of the Minna-Bida Road, is analyzed. This road has continued to experience failure since construction. Thus, this research was carried out to determine the possible geologic factors responsible for the road failure.

Several workers have attributed the causes of road instability to factors ranging from mineralogical, geotechnical and soil conditions. Gidigasu (1972) attributed the majority of road pavement failures in the tropics to mineralogical and geotechnical factors. Ajayi (1987) noted that the road failure he studied occurred where the pavement was founded on saprolite rather than the strong lateritic horizons. Adeyemi and Abolurin (2000) noted that the degree of stability of the road he studied increased with the amount of kaolinite present in the subgrade soil and with increase in the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of the sub-grade soils. Ayangade (1992) observed that there was a positive correlation between the strength characteristics of the foundation soils and the stability of the pavement along the Oshogbo – Gbongan road, south western Nigeria.

Okagbue and Ifedigbo (1995) showed that the cut slopes along the Enugu-Onitsha expressway are vulnerable to undermining and over steepening by run-off, due to the generally loose condition of the soil as evidenced by the low bulk density, high void ratio but low permeability and consequent high saturation and strength reduction during the rains. Adeyemi et al (2003) have noted that the soils below the stable section of the Lagos-Ibadan expressway have higher maximum dry density, unsoaked California Bearing Ratio (CBR), uncured unconfined compressive strength than those below the unstable section. They also noted that the soils below the stable portions have a lower proportion of fines and clay sized fraction and a lower optimum moisture content and linear shrinkage than the soils below the unstable section. Jegede and Oguniyi (2004) attributed the incidence of highway pavement failures for Nigerian highways to improperly compacted edges of the pavements to non-provision of drainage facility along the roads, and low California Bearing values among others. Some other works like those of Weinet (1968), Gidigasu (1974), Farquhar (1980), Mesida (1987), Ajayi (1987), Ayangade (1992) and Adeyemi and Abolurin (2000) show that majority of highway failures can be attributed to geological, geotechnical and hygrogeological factors. Clare and Beaven (1962), and Okogbue and Uma (1988) observed that the patterns of pavement performance in West Africa are considerably controlled by geology, topography, soil and drainage conditions. Russam and Croney (1961), Gidigasu (1974) and Okagbue and Uma (1988), noted that depth to water table appears to be the most dominant of the climatic, topographic and drainage factors that affect pavement performance. According to them, when the water table is at the depth of less than 1m, the chances of failure seem to be highly independent of the climate and other environmental conditions.

Geology and Climate of the study area

The study area is located along the Minna-Bida Road. It lies along longitude 06°31'32.4"E to 06°22'53.8"E and latitude 09°35'44.4" N to 09° 05' 38.3"N. The rock types mapped included fine to medium grained biotite granite, granite gneiss, schist and sandstone. The granite has been affected by the Pan African Orogeny with late tectonic emplacement of granites and granodiorites. The end of the orogeny was marked by faulting and fracturing (Abaa, 1983; Gandu *et al.*, 1986; Olayinka, 1992). The granites are thus fractured, jointed and deeply weathered in some places.

The area has an average annual rainfall of about 1,000mm. Rainy season usually starts during the month of April, and reaches the peak by August/ September and ends in October. Low average temperature of 24°C is recorded between the months of July and September while high temperature is usually recorded during the months of February to April, at an average of 35°C. The harmattan wind is experienced between December and January.

METHOD OF INVESTIGATION

Field mapping of the rocks and study of soil profile along the road were done. Groundwater fluctuation that may affect moisture content of subgrade was monitored. Static water levels were measured from hand-dug wells located very close to the road during the peak of the dry (April) and rainy (September) seasons. The depths of the wells (D), dry (A) and wet seasons (B) water depths were measured from which the groundwater fluctuation and percentage of variation (were measured.

Thin section preparation for petrographic analysis was carried out on two rock samples using the Hiiquist Models 1005 and 1010, for cutting and polishing, respectively. XRD was carried out on four rock samples using PW goniometer supply diffractometer with CuKa radiation generation at 40 KV and 30 mA as explained by Velde (1992) and Brindley and Brown (1980).

Wet sieving method was employed for sieve analysis as specified in BS 1377 (British Standards, 1990). Atterberg Limits tests conducted are liquid limit (LL) and plastic limit (PL). The liquid and plastic limits were each determined with about 300 g of soil samples passing 0.425 mm sieve in accordance with BS 1377 (1990). The cone penetrometer method as described by Brain (1983) was used. The constant head permeameter method was employed for the determination of the permeability. Compaction tests were done using the Standard Proctor mould (4.5 kg rammer) while CBR were performed on samples at their maximum dry densities in accordance with the West African Standard, ASTM D1883 and AASHTO T193.

Twenty-eight (28) water samples were analyzed for anions and cations as well as their physical parameters. Colorimetric, Titrimetry and Flame Photometry (Sherwood Flame Photometry) methods were employed using HACH DR/890 Colorimeter, Sherwood Analog Colorimeter Model 252 as described by Abdullahi (2010).

RESULTS AND DISCUSSION

Figure 1 shows that the inter-seasonal water table varies according to the rock types with the granite having the highest followed by the schist and sandstone. This indicates that permeability of the rocks along the road is not the same suggesting that it is being controlled by the geology. The results of the groundwater chemistry show that the cations: Ca^{2+}, Mg^{2+} and Na^{+} have average values of 17.20, 8.28 and 1.83mg/l respectively while the anions: Cl^{-} and SO_4^{2-} have average values of 46.18 and 3.72mg/l respectively. The physical properties: pH ranges from 6 to 9.73; electrical conductivity ranges from 20 to 568µS/cm; TDS ranges from 13.4 to 380.6mg/l and hardness ranges from 11 to 334mg/l. Samples collected from sandstone terrain showed the least ionic concentration while those collected from granites terrain showed the higher ionic concentration than other samples collected from other terrains (see Figure 2). The higher concentration shown by samples collected from granite terrain is attributed to the high fracture density, that characterize the granites (as observed during the mapping) which is leaching pathways of surface water ions. This is also in agreement with the findings of Kovalevsky (2004) and Yousef et al (2009) that the concentration of groundwater ions is controlled by the rate of aquifer recharge, aquifer rock type and leaching process (fracturing)

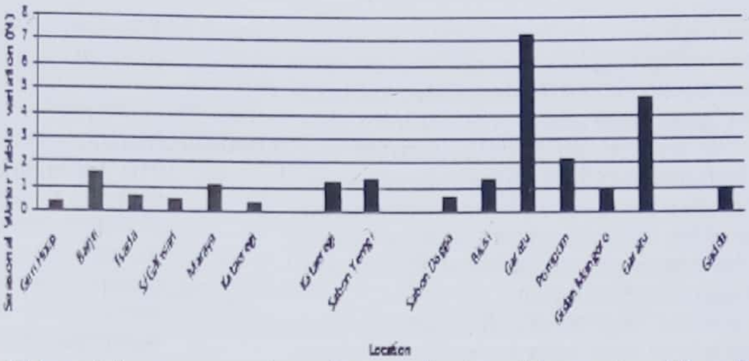


Figure 1. Inter-seasonal water table variation among water wells according to rock types along Minna-Bida Road (from the left, 1st batch = sandstone, 2nd = migmatite, 3rd – granite, 4th = schist).

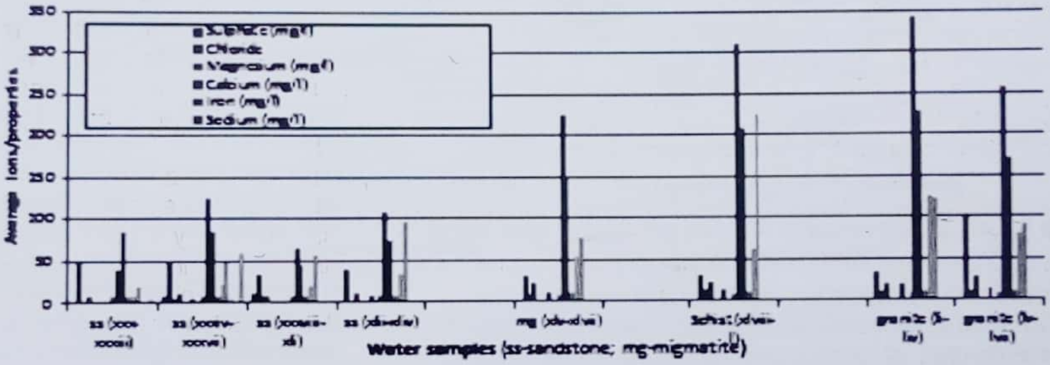


Figure 2. Comparison of physico-chemical parameters of groundwater samples from different rock terrains along Minna-Bida road.

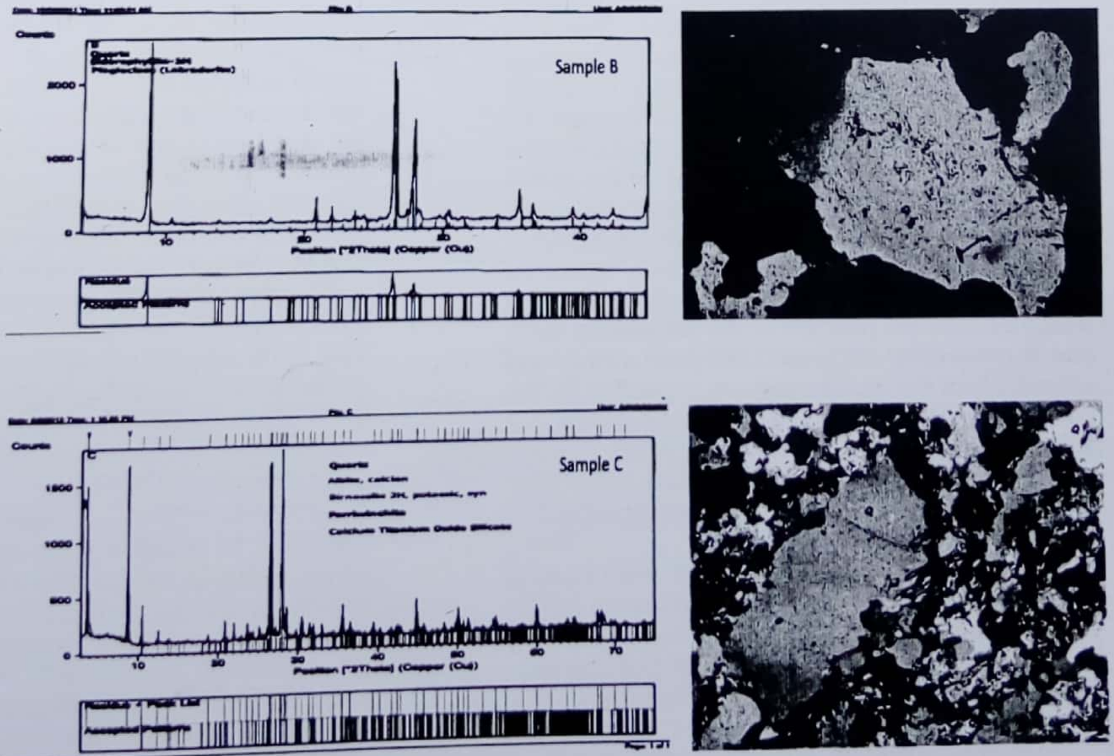


Figure 3: Diffractograms and photomicrographs of the analyzed rocks

Classification of the soil based on Unified Soil Classification System (USCS) shows that the soils underlain by sandstone are composed of sandy soils while the portion underlain by granite and gneiss are composed of gravelly and sandy soils. These indicate that these soils are actually residuals of the underlying lithology of the studied roads. Figure 4 is the grain size distribution superimposed on the geologic map of the area.

Figure 3 shows the X-ray diffraction and photomicrograph of rock samples collected along the road. The analyzed basement rock samples are generally composed of quartz, albite, biotite, muscovite, plagioclase and hornblende that are typical of acidic rocks or acidic protholitic rocks. The low content of quartz and high content of mica minerals in the rocks may render them susceptible to high rate of weathering to soils

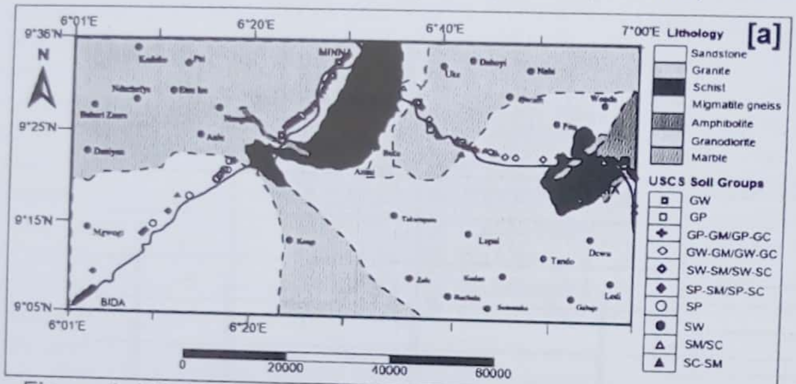


Figure 4. USCS classification and the geology of soils along Minna-Bida Road

Figures 5 to 8 show the results of Optimum moisture content, maximum dry density and California bearing ratio of soil superimposed on the geology along Minna-Bida Road. Figures 5 and 6 reveal that soils occurring in the portion underlain by sedimentary rock (sandstone) showed highest MDD and lowest OMC than those occurring areas underlain by metamorphic and igneous rocks. Areas underlain by sandstone and granite have higher CRB than areas underlain by gneiss, schist as shown in figurer 7 and 8. This is an indication that analyzed soils are residual of the underlying rocks and also that OMC, MDD and CBR (both soaked and unsoaked) of the studied soil are controlled by the parent rocks of the soil. The figures also show that soil that formed from metamorphic rocks (gneiss, schist and amphibolites) generally have lower CBR than those that formed from igneous (igneous) or sedimentary (sandstone) rocks.

The soils studied were compared with Federal Ministry of Works and Housing specification (1970) for different road sections and their suitability determined as shown on Tables 1 to 6. It can be seen from Tables 1 to 3 that all the soil samples collected from the sandstone terrain have CBR that can satisfactorily serve as sub-grade and sub-base material while only one of the samples cannot satisfactorily serve as road base course. Seven of the 10 analyzed samples have liquid limits suitable for a good sub-grade and sub-base while 5 of the samples have liquid limits suitable for a good base course. Also, 9 samples have optimum moisture contents that can satisfactorily serve as sub-grade but only 5 contain the appropriate quantity of fines suitable for road base course. However, few of the samples have plasticity index suitable for good road sub-grade, sub-base and base course. As it is only the plasticity index that some of the samples have shortfall in, this can therefore satisfactorily serve as road sub-grade and sub-base in its natural state. However, some proportion of fine material (clay/silt) and chemical stabilizer should be added to the soil for it to serve as good road base course. Thus, the road portion within the sandstone is expected to be more stable than the portions underlain by migmatite gneiss and granite. This explains why the south-western part of Minna-Bida road, which is underlain by sandstone, is not frequently in deplorable state.

From Tables 4 to 6, it can be seen that all the soil occurring within the granite terrain along Minna-Bida road have CBR that can satisfactorily serve as road sub-grade and sub-base while more than half (63%) have CBR suitable for base course. Only one sample does not have OMC suitable for sub-grade. Three of the samples (out of 11) have liquid limits that can satisfactorily serve as sub-grade and sub-base while only 1 sample has liquid limits that is suitable for road base course. Also, very few of the samples have plasticity index suitable for sub-grade, sub-base and base course. Therefore, the soil occurring within the granite terrain along Minna-Bida road might be fairly good as sub-grade and sub-base in its natural state but will not be stable when used as road base course. A small proportion of stabilizers like lime, wood ash or pyroclastic dust may be added to the soil to improve its liquid limit and plasticity index for it to satisfactorily serve as sub-grade and sub-base. The soil might serve as base course on the addition of higher proportion of such stabilizers and also fine materials (clay or silt).

The soil occurring within the migmatite gneiss/schist may serve better as sub-grade on the addition of stabilizers like lime, marble dust or limestone ash (Okagbue and Yakubu, 1997; Okagbue and Onyeobi, 1999) in correct proportions to improve the CBR, LL and PI of the soil while the addition of the stated stabilizers to soil underlain by the granites will enable the soil to serve better as sub-grade and sub-base. Stabilizing the soils within the migmatite gneiss/schist terrain with the above stated substances to serve as either sub-base or as road base may not be economical. This is because the cost of stabilizing such soil will be more than the cost of replacing the soil.

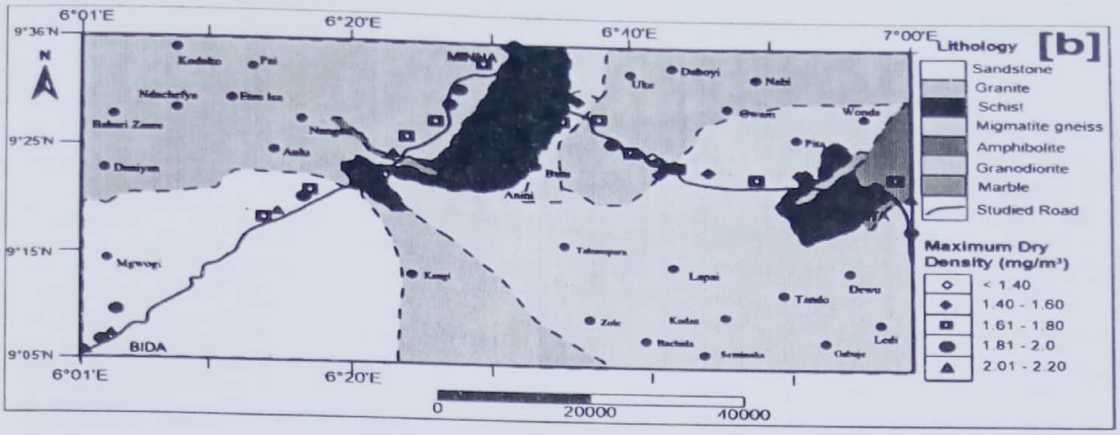


Figure 5. Maximum dry density of soil along Minna-Bida Road.

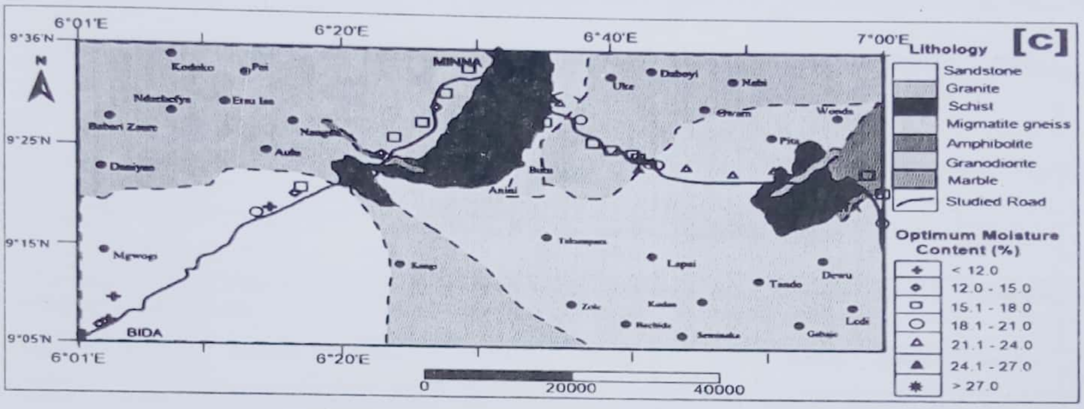


Figure 6. Optimum moisture content of soil along Minna-Bida Road.

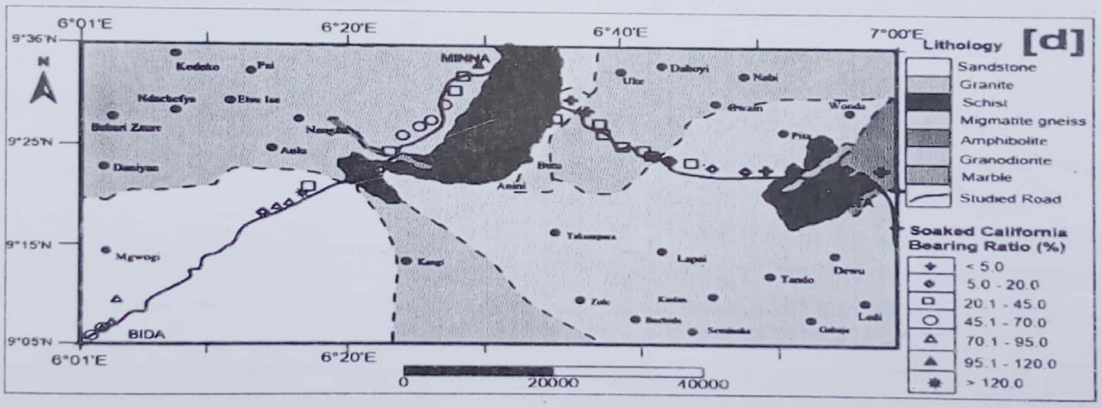
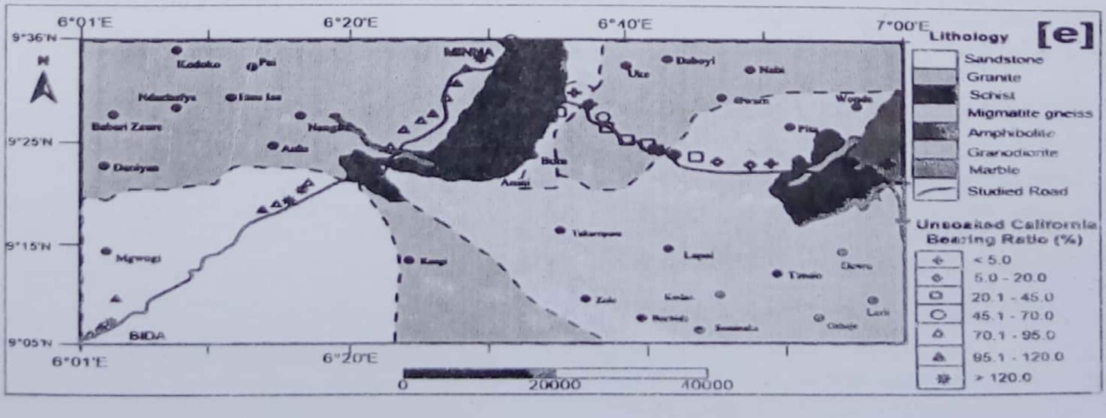


Figure 7. Soaked California bearing ratio of soil along Minna-Bida Road.



Figures 8. Unsoaked California bearing ratio of soil along Minna-Bida Road.

Table 1: Suitability for fill and road sub-grade for soils underlain by sandstone along Minna-Bida road

	47	50	54	58	66	69	76	78	80	84	Suitability percent (scale of 100)
Soil type (USCS)	SP	SP	SP	SP	SP	SP-SM	SM-SC	SP-SM	SP-SM	SP-SM	
% of fines	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100
Liquid limit (%)	Suitable	Suitable	Suitable	Suitable	Marginally suitable	Suitable	Not suitable	Not suitable	Not suitable	Suitable	70
Plasticity index (%)	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	Not suitable	Not suitable	10
Soaked CBR (%)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100
OMC (%)	Suitable	Suitable	Suitable	Marginally Suitable	Not suitable	Suitable	Suitable	Suitable	Suitable	Suitable	90
MDD (mg/m^3)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

Table 2: Suitability sub-base course for soils underlain by sandstone along Minna-Bida road

Property	47	50	54	58	66	69	76	78	80	84	Suitability percent (scale of 100)
Soil type (USCS)	SP	SP	SP	SP	SP	SP-SM	SM-SC	SP-SM	SP-SM	SP-SM	
Liquid limit (%)	Suitable	Suitable	Suitable	Suitable	Marginally suitable	Suitable	Not suitable	Not suitable	Not suitable	Suitable	70
Plasticity index (%)	Suitable	Suitable	Not suitable	Not suitable	Not suitable	Not suitable	Marginally suitable	Suitable	Not suitable	Not suitable	40
*Soaked CBR (%)	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

Table 3: Suitability for base course for soils underlain by sandstone along Minna-Bida road

Property	47	50	54	58	66	69	76	78	80	84	Suitability percent (scale of 100)
Soil type (USCS)	SP	SP	SP	SP	SP	SP-SM	SM-SC	SP-SM	SP-SM	SP-SM	
% of fines	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	Suitable	Suitable	Suitable	Suitable	50
Liquid limit (%)	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Not suitable	Not suitable	Not suitable	Not suitable	50
Plasticity index (%)	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	Not suitable	not suitable	10
Unsoaked CBR (%)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Suitable	90

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

Table 4: Suitability for Fill & road Sub-grade for soils underlain by *Granites and Schist* along Minna-Bida road

Property	Soils underlain by **Granite**									Schist	Migmatite gneiss	Suitability percent (scale of 100.00)
	2	9	12	15	18	22	24	27	31	36	44	
Soil type (USCS)	GW	SP-SM	GW-GC	GP-GM	SC	SP-SM	GP	SW	GW	SM	SP	
% of fines	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100.00
Liquid limit (%)	Not suitable	Suitable	Not suitable	Not suitable	Marginally suitable	Suitable	Not suitable	Not suitable	Marginally suitable	Not suitable	Not suitable	36.36
Plasticity index (%)	Not suitable	Suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	9.09
Soaked CBR (%)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100.00
OMC (%)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	90.91
MDD (mg/m^3)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	100.00

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

Table 5: Suitability for sub-base course for soils underlain by *Granites and Schist* along Minna-Bida road

Property	Soils underlain by **Granite**									Schist	Migmatite gneiss	Suitability percent (scale of 100.00)
	2	9	12	15	18	22	24	27	31	36	44	
Soil type (USCS)	GW	SP-SM	GW-GC	GP-GM	SC	SP-SM	GP	SW	GW	SM	SP	
Liquid limit (%)	Not suitable	Suitable	Not suitable	Not suitable	Marginally suitable	Suitable	Not suitable	Not suitable	Marginally suitable	Not suitable	Not suitable	**36.36**
Plasticity index (%)	Not suitable	Suitable	Not suitable	Suitable	Not suitable	Suitable	Not suitable	Suitable	Not suitable	Not suitable	Suitable	**45.45**
*Soaked CBR (%)	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Suitable	**100.00**

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

Table 6: Suitability for base course for soils underlain by *Granites and Schist* along Minna-Bida road

Property	Soils underlain by **Granite**									Schist	Migmatite gneiss	Suitability percent (scale of 100.00)
	2	9	12	15	18	22	24	27	31	36	44	
Soil type (USCS)	GW	SP-SM	GW-GC	GP-GM	SC	SP-SM	GP	SW	GW	SM	SP	
% of fines	Not suitable	Suitable	Suitable	Suitable	Not suitable	Suitable	Not suitable	Not Suitable	Not suitable	Suitable	Suitable	**54.54**
Liquid limit (%)	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	**9.09**
Plasticity index (%)	Not suitable	Suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	Not suitable	**9.09**
Unsoaked CBR (%)	Not suitable	Suitable	Suitable	Suitable	Suitable	Suitable	Marginally suitable	Marginally suitable	Not suitable	Not suitable	Not suitable	**63.63**

USCS=Unified Soil Classification System; MDD=Maximum Dry Density; OMC=Optimum Moisture Content; *=West African Standard; CBR=California Bearing Ratio; % of fines=% less than 75μm

CONCLUSION AND RECOMMENDATION

The groundwater collected from wells within the fractured granitic terrain along Minna-Bida road has the highest physico-chemical ion concentration followed by the migmatite and sandstone. The inter-seasonal groundwater variation follows the same trend with the physico-chemical properties. Soils occurring within the sandstone environment are more competent than soils occurring within the crystalline rocks implying that soils derived from the studied sandstone are more stable than those derived from the crystalline rocks. The recurrent failure of Minna-Bida road is because the soils occurring within the migmatite gneiss/schist and granite terrain of this road do not have the geotechnical properties that can satisfactorily serve as road sub-grade, sub-base and/or base course in their natural state.

It is therefore recommended that:

1. Soils occurring within the sandstone terrain along Minna-Bida road can satisfactorily serve as sub-grade and sub-base in their natural state but has to be mixed with some proportions of fine (clay/silt) and chemical stabilizer for it to serve as good road base.
2. Soils within the granite terrain along Minna-Bida road are fairly good as sub-grade and sub-base materials in their natural state but can be used as base material on intense stabilization. Soils occurring within the migmatite/schist environment require intense stabilization in order to be used as sub-base and base materials. The soils within the crystalline rocks are better replaced because it is cheaper than stabilizing them.
3. The study of geology and hydrogeology contributes greatly to the solution of problems that are manifested by road pavement.
4. Visual inspection, supported by petrological studies will reveal much information and X-ray diffraction analyses are useful especially when the presence of deleterious minerals particularly clay, is suspected.
5. The findings from this study are of general interest and applicability since the identified problems can occur wherever similar geologic and hydrogeological conditions exist.

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