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Full Length Research Paper

Geotechnical and environmental problems related to shales in the Abakaliki area, Southeastern Nigeria

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Six (6) samples of shale and five (5) water samples from hand-dug wells and boreholes, from different locations within the Abakaliki shale formation, have been assessed to evaluate the impact of the shale formation to the geotechnical and hydrogeo-environmental problems prevalent in the Abakaliki area (Southeastern Nigeria). Results indicated that the shale samples have Atterberg limits that might be considered moderate to high; while Liquid Limit (LL) ranged from 49 – 54, the Plasticity Index (PI) ranged from 34 – 38. These relatively high LL and PI suggested presence of expansive clays, some swelling of the shale on moisture influx and high compressibility. Natural moisture content (with mean value of 20%) was also significantly high. Hydrochemical analyses, on the other hand, revealed that the water samples had comparatively high content of ions and dissolved particles; Ca^{2+} ranged from 8.0 – 134.0 mg/l, Mg^{2+} ranged from 0.2 – 3.3 mg/l, HCO^{-}_{3} ranged from 21.8 – 1176.1 mg/l and total dissolved solids ranged 56.9 – 1415.0 mg/l. Dissolution of soluble minerals (predominantly calcite and other rock salts) contained in the shale might likely be responsible for the release of these particles. Geotechnical behaviours of the shale and hydrogeochemical characteristics of water samples from the shale formation, thus, provided insights into the probable causes of seasonal waterlogging, consistent poor groundwater quantity and quality, structural and foundation problems that are prevalent in the Abakaliki area.

Key words: Abakaliki shale, dissolution, environmental problems, geotechnical analysis, groundwater quality, structural failure.

INTRODUCTION

Shale is the commonest type of sedimentary rock, covering a vast area of the earth's surface. It exhibits a wide spectrum of geotechnical behaviour and has often been a cause for concern on environmental and geotechnical issues. Thus shale, most often, is regarded as problem materials. These problems (both environmental and geotechnical) possessed by shales in shaley terrains of the world are, in most cases, being influenced by mineralogy, especially the predominant clay mineral type(s) (Okagbue, 1989; Obiora and Umeji, 2004) as well as the climate and physiography of the area under consideration (Ezeribe, 1994).

An example of a shaley terrain in Southeastern Nigeria (Figure 1) is the Abakaliki Metropolis; underlain by the Albian Asu River Shale (predominantly shales and localized occurrences of sandstone, siltstone and limestone intercalations). Details on the geology of the Asu River shale are presented in previous works by Reyment (1965), Murat (1972), Nwachukwu (1972), Ofoegbu and Amajor (1987) and Benkhelil et al. (1989).

Owing to the abundance of the shale and high cost of haulage of the other alternative and often more suitable construction materials, the Abakaliki shale is being utilized both as subgrade that is (*in-situ*) and as aggregates in most construction projects. A survey of the roads and some structural projects in the area (Ezeribe, 1994; Okogbue and Aghamelu, 2010a) has however, revealed that these projects suffer incessant failures. Previous studies (e.g., Underwood, 1967; Sowers and Sowers, 1970) note low permeability, perhaps, low hydraulic conductivity and low specific yield (Todd, 1980) as some of the attributes of shaley formations (that is, aquicludes).

In this work, an attempt has been made to employ

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relevant laboratory tests to assess some of the geotechnical problems and environmental hazards prevalent in the Abakaliki area. The assessment mainly intended to highlight whether the shale formation contributes to the incessant structural failures of some engineering projects (most of which the Abakaliki shale serve both as subgrade and aggregates), shortage and poor quality of groundwater, and other environmental problems consistently experienced in the area.

Geology

The first marine transgression of the Benue trough is generally believed to have started in the mid-Albian period with the deposition of the Asu River Group. Figure 2 shows the distribution of the Asu River Group and other lithologic units in the lower (or southern) Benue trough, Southeastern Nigeria. The Asu River group sediments are predominantly shales, commonly referred to as the 'Abakaliki shale formation' in and around the Abakaliki metropolis (about 452 sq.km), and localized occurrences of sandstone, siltstone and limestone intercalations (Ofoegbu and Amajor, 1987).

Emplaced in these Asu River group sediments are intermediates to basic intrusive, extrusives and Pyroclastics (Murat, 1972; Nwachukwu, 1972; Ofoegbu and Amajor, 1987; Tijani et al., 1996). The group has average thickness of about 2000 m and rests unconformably on the Precambrian Basement (Benkhelil et al., 1989). The Abakaliki shale formation, which has an average thickness of about 500 m, is dominantly shale, dark grey in colour, blocky, and non-micaceous in most locations. It is calcareous (calcite-cemented) and deeply weathered to brownish clay in the greater part of the formation (Okogbue and Aghamelu, 2010b).

Physiography and climate

The relief of the area is generally undulating and no location exceeds 400 m above-sea-level. A major relief structure is hills formed by the pyroclastic bodies. No trend has been established by previous research (Ofoegbu and Amajor, 1987) of these conical shaped hills and other residual hills that spread sporadically within the area. The predominant shale has favoured the low erodability of the lithology, resulting in absence or near absence of deep cut valleys and erosion channels. The major river that drains the area is the Ebonyi River and its tributaries; Udene and Iyiokwu Rivers. Both tributaries are perennial and usually overflow their banks at the peak of the rains. Stunted trees and pockets of derelict woodland exist where the lithology has undergone high degree of laterization. Elsewhere, typical characteristics of the tropical rain forest are displayed; multitude of evergreen trees, climbing plants, parasitic plants that live on the other plants, and creepers.

Two main seasons exist in the Abakaliki area, the dry season which lasts from November to March and the rainy season which begins in April and ends in October with a short period of reduced rains in August commonly referred to as "August break". Temperature in the dry season ranges from 20 to 38°C, and results in high evapotranspiration, while during the rainy season temperature ranges from 16 to 28°C, with generally lower evapotranspiration. The average monthly rainfall ranges from 31 mm in January to 270 mm in July, with the dry season experiencing much reduced volume of rainfall unlike the rainy season, which has high volume of rainfall. Average annual rainfall varies from 1,500 to 1,650 mm. These climatic conditions are responsible for the development of thick lateritic soils in the area.

Major economic activities

The major economic activity within the Abakaliki area is subsistence agriculture. Statistics show that more than 60% of the population is engaged in it. One of the main cash crops grown is rice. This has necessitated setting up of rice milling industries in the Abakaliki area. The available land for agriculture is fertile and supports rice and cassava cultivation. The main industries in the area, apart from rice milling industry, are quarrying and rock crushing. Lead-zinc mining occurs around Enyigba and Ameka; in the outskirts of Abakaliki metropolis. The traffic comprising mainly of heavy-duty vehicles, resulting from the transportation of agricultural produce and other economic activities, mount pressure on the existing road and highway networks in the area.

MATERIALS AND METHODS

Sampling

A total of six (6) shale samples were taken from some shale outcrops within the Abakaliki area; two (2) each from Ntezi Abba, Iyiokwu River and Juju Hill (Figure 1) for sample locations. For all the shale samples collected sampling depths ranged from 0.5 to 2.0 m. The shale sampling strictly followed standard procedure for soil sampling specified in British Standard Institution (BSI) 1377 (1990). The *in-situ* samples of the Abakaliki shale produced effervescence on contact with dilute hydrochloric (HCl) acid. The effervescence buttressed calcareous nature of the shale formation. All sampling was done in the dry season, between December and February, 2008.

Five (5) water samples (3 from hand dug wells and 2 from bore-holes) were collected from Mgbabo and Ogharaugo areas within the study area. Depth of hand-dug wells sampled ranged 6 to 8 m. Depths of sampled boreholes were not ascertained, however, general borehole depths in the Abakaliki area range between 12 and 55 m. Sterilized 1 L plastic containers were used for conveying the water samples to the laboratory for the analyses of some parameters that could not be carried out in the field. Conservative measures specified by Appelo and Postma (1993) were taken to prevent changes in the chemical composition of the sample before analysis; 100 ml of water sample for Ca^{2+}, Mg^{2+} and Na^{+} was acidified to pH >2 using 0.7 ml of 65% HNO_3, while water sample

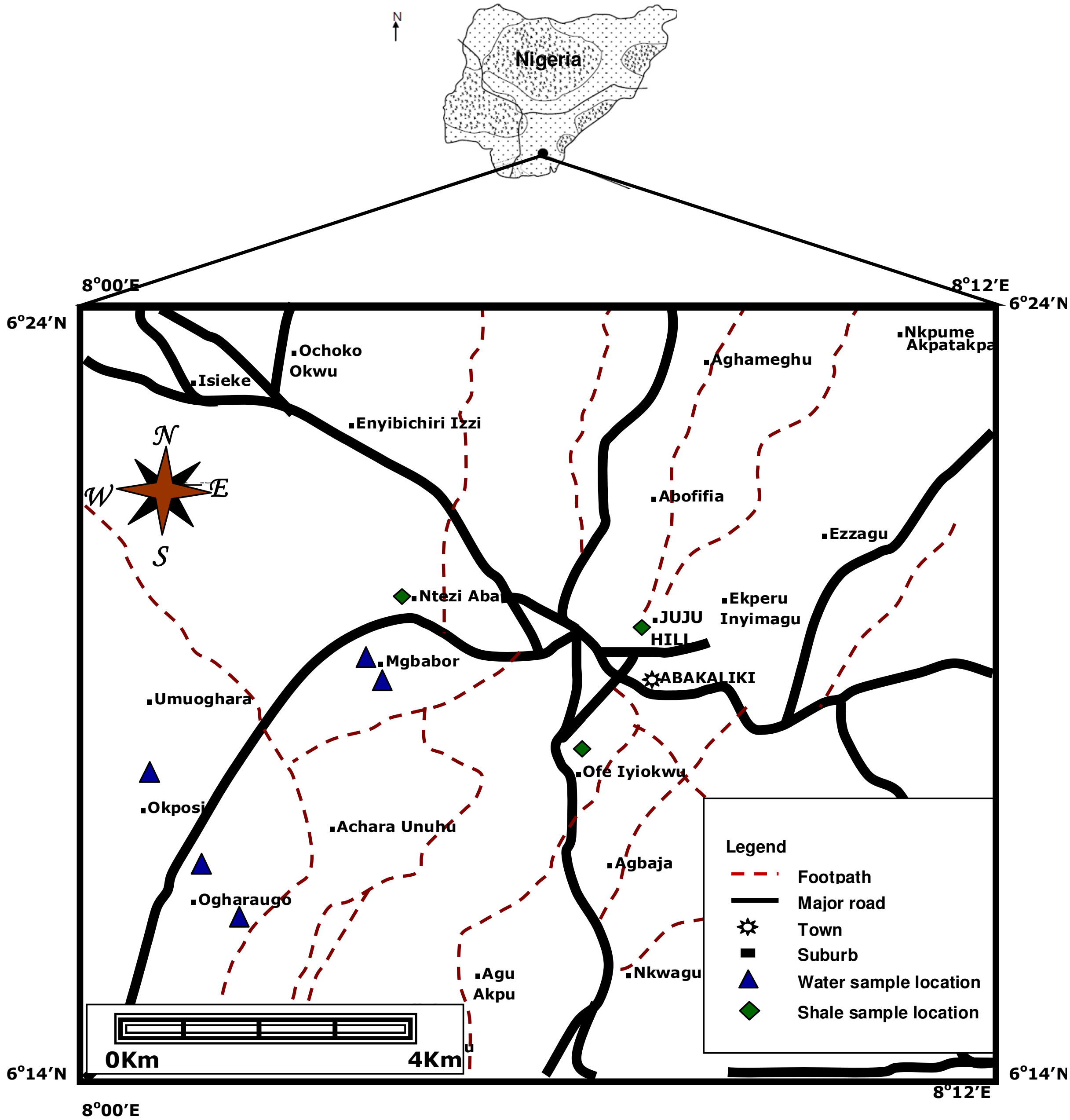

Figure 1. Map of Abakaliki area showing access routes and sampled areas (Enlarged from map of Nigeria).

for NO^-_3 was stored cool at 4°C.

Laboratory analyses

Geotechnical

The tests carried out on the shale samples included Atterberg limits (liquid and plastic limits), specific gravity, natural moisture content, compaction, California Bearing Ratio (CBR) and shear strength. The sample preparations and laboratory testing for these geotechnical parameters followed standard methods of testing soil for civil engineering purposes. The liquid limit and plastic limit tests were carried out on air-dried samples that passed 0.425 mm (BSI No. 36) sieve; both tests then followed standard procedures specified by BSI 1377 (1990). Crushed shale samples that passed through 0.076 mm (BSI No. 200) sieve and oven-dried at 105°C for 24 h were utilized for the specific gravity tests. The tests were also carried out with the aid of a 100.15 ml pycnometer bottle and distilled water with specific gravity of 0.99654 (distilled water temperature was 27°C), in accordance with testing method described by Lambe (1951). Laboratory procedure of this test attempted determination of the specific gravity of the shale excluding air and water contents.

Natural moisture contents determination followed simple method outlined by Akyrod (1957). The laboratory compaction tests were limited to particles of shale that passed through 19.05 mm BSI sieve and followed procedure specified by BSI 1377 (1990). CBR

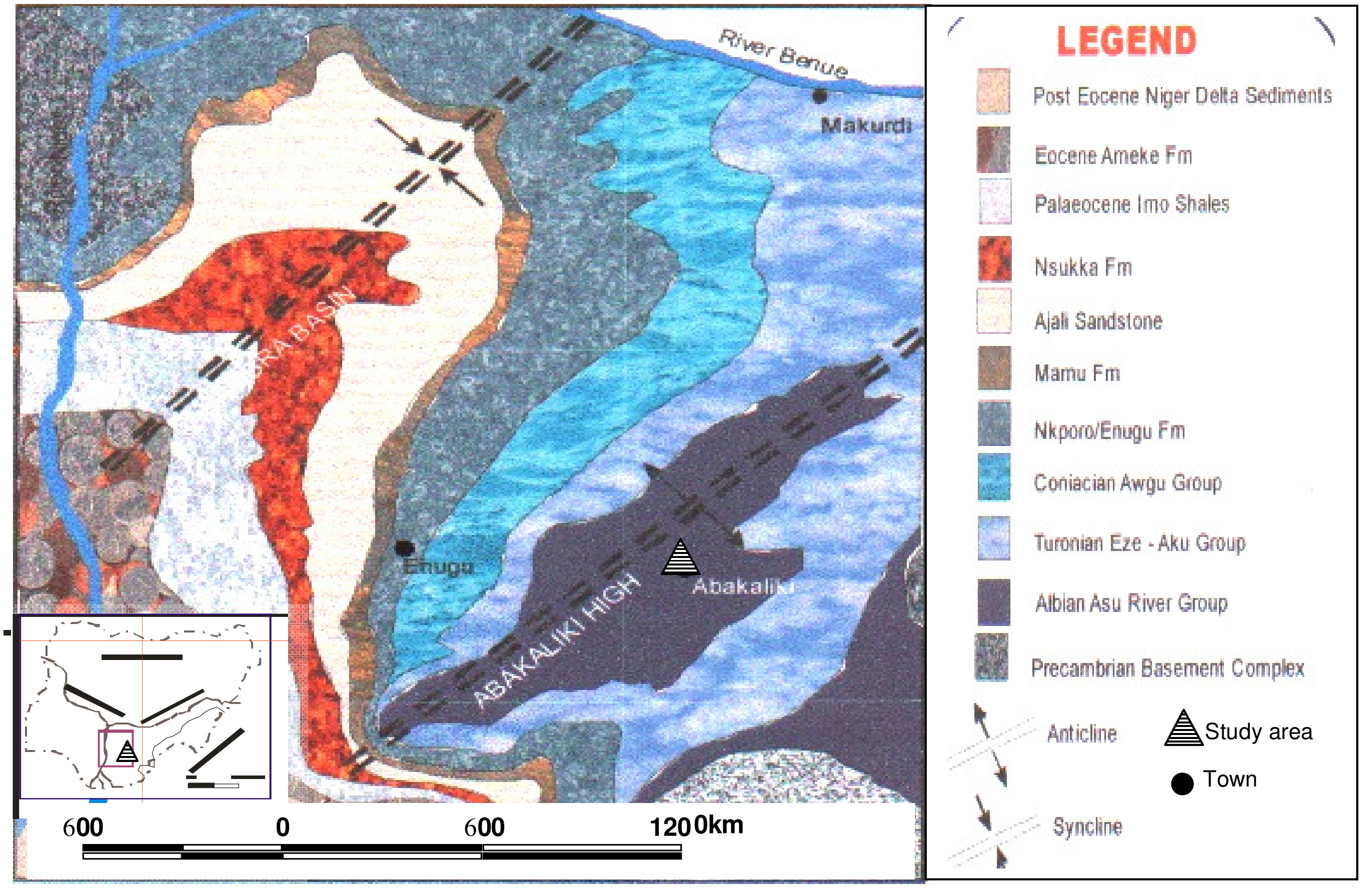

Figure 2. Generalized Geological map of southeastern showing the distribution of the Asu River Group and other lithologic units (Modified after Okogbue and Aghamelu, 2010a).

tests were performed on compacted samples in both unsoaked and soaked conditions, following the procedure of Bailey (1976). However, soaking was done overnight (24 h) in a water-filled bathtub. Samples for the shear strength tests were prepared and tested following the BSI 1377 (1990) standard. The test type was the triaxial compression strength test (consolidated undrained). However, the triaxial cell for the tests was the 76 mm diameter type, hence, the tested samples were proportionately scaled down to 152 by 76 mm, height by diameter, respectively. Pressured water was also used for confining the samples inside the cell.

Hydrogeochemical

Since the aim of the study was partially to ascertain any noticeable ionic enrichment in the concentration of groundwater samples from the area, few basic parameters that could provide such insight were tested for in the water samples. They included pH, TDS, hardness and basic ions; while Ca^{2+}, Mg^{2+} and Na^{+}, were the cations tested for, Cl^{-}, HCO_3^{-} and NO_3^{-} were the anions determined in the water samples (all ions measured in mg/l). Apart from pH, which was determined in the field using HACH portable pH meter, the rest of the parameters in the water samples were analyses in the laboratory adopting analytical procedures specified by the American Association of Public Health (APHA, 1985) standards. All the water samples were, however, analyzed within 24 h of collection, at the Analytical Laboratory of the Department of Geology, University of Nigeria, Nsukka, Nigeria.

Statistics

For both the geotechnical and the hydrogeochemical analyses, values of each of the parameters recorded were obtained after repeated tests on portions of the same sample for at least thrice. In other words, test for each parameter was repeated at least thrice and the average value of at least two consistent results then recorded as the value for the parameter. However, statistical mean and range for each of the parameter represent the average and extreme that is (lowest and highest) values, respectively, for the parameter when all the tested samples from all sample locations are considered.

RESULTS AND DISCUSSION

Geotechnical properties

Atterberg limits, natural moisture content and specific gravity

The summary of the geotechnical properties of the Abakaliki shale is presented in Table 1. As shown in the table, the Abakaliki shale recorded values of Liquid Limit (LL) which ranged from 49 to 54, Plastic Limit (PL) 15 to 18. The difference between LL and PL, termed the

Table 1. Summary of the geotechnical properties of the tested samples of the Abakaliki Shale.

Property	Ntezi Abba	Sampled location		Statistical analysis	
		Iyiokwu River	Juju Hill	Range	Mean
Liquid limit, *LL*	54	53	49	49 – 54	52
Plastic limit, *PL*	18	15	15	15 – 18	16
Plasticity Index, *PI*	36	38	34	34 – 38	36
Specific gravity, G_s	2.28	2.25	2.42	2.25 – 2.42	2.32
Natural moisture content, %	17	23	20	17 – 23	20
Maximum dry density, MDD (Mg/m^3)	1.85	1.89	1.83	1.83 – 1.89	1.86
Optimum moisture content, OMC (%)	12.1	12.0	12.5	12.0 – 12.5	12.2
California bearing capacity, $^a CBR_u$ (%)	22	16	22	16 – 22	20
California bearing capacity, $^b CBR_s$ (%)	11	10	12	10 – 12	11
Angle of shearing resistance, ϕ (°)	23	30	31	23 – 31	28
Cohesion, c (kN/m^2)	30	50	55	30 – 55	45

[a]Unsoaked condition. [b]Soaked (24 h soaking) condition.

plasticity index (PI), represents the range in the water contents through which the soil is in the plastic state (Seed and Woodward, 1964). The PI was considerably high (ranged from 34 to 38). Sowers and Sowers (1970) note that PI >31 should be considered high and indicates high content of expansive clays, most probably montorillonite and/or illite. Obiora and Umeji (2004) notes predominance of montmorrilonite, illite and mixed layer clay minerals in the Asu River Group sediments. Natural moisture content (W_n) of a material is a measure of the water-holding ability of the material, usually reflecting clay content and type of the material (Sowers and Sowers, 1970). W_n of the shale samples ranged from 17 to 23 %.

On the basis of LL and PI values, the Abakaliki shale could be classified as high plasticity soil; a soil with PI >31 is described as highly plastic (Sowers and Sowers, 1970). Such a soil usually has the ability to retain appreciable amount of total moisture in the diffuse double layer, especially by means of absorption. This fact was buttressed by a significant mean value (20%) of natural moisture content recorded by the shale samples (Table 1). High plasticity materials are usually susceptible to high compressibility (Seed and Woodward, 1964; Sowers and Sowers, 1970; Coduto, 1999). An increase in plasticity of material also decreases its permeability and hydraulic conductivity (Sowers and Sowers, 1970).

In this study the specific gravity (G_s) of shale, a dimensionless parameter, is the weighted average of the soil minerals (excluding air and water). Results indicated that the Abakaliki shale has mean G_s value of 2.32 (Table 1); a value less than that of a potentially durable construction aggregate, which should have G_s value of 2.625 or above, according to Reidenouer (1970). A comparison of specific gravity values of rock aggregates that serve well in construction project with the Abakaliki shale (Table 2) points out the fact that the shale is unlikely to be durable in most construction projects. Ezeribe (1994) on the basis of slake durability assessment, rates shale samples collected from two locations on the Asu River Group (Ishiagu and Amenu Okposi areas) as very low durability shales.

Compaction and California bearing ratio (CBR)

Compaction test seeks to simulate the right combination of moisture (optimum moisture content) and load (compactive effort) on a soil that would result in increased density (maximum dry density) of such soil; thus improving its appropriateness in construction projects. Results indicated that the compacted Abakaliki shale achieved mean Maximum Dry Density (MDD) value of 1.86 Mg/m^3 at mean Optimum Moisture Content (OMC) of 12.2 (Table 1). The MDD was considerably high; MDD of other shales from Southeastern Nigeria ranges from 1.50 to 1.68 Mg/m^3 (Okogbue and Aghamelu, 2010b). In addition to compactive effort, Okogbue and Aghamelu (2010b) point out that calcite cementation, nature of the compacted sample and moisture condition of the sample may have also contributed to the relatively high MDD recorded by the Abakaliki shale.

CBR is the ratio (expressed as percentage) of the actual load required to produced a 2.5 mm deflection to that required to produce the same deflection in a certain standard crushed stone (Yoder, 1959; Sowers and Sowers, 1970; Mannering and Kilareski, 1998; Wignall et al., 1999). Results of the laboratory CBR tests showed that the mean CBR values of 20 and 11%, for soaked and unsoaked conditions, respectively, were recorded in the Abakaliki shale. The CBR values showed a reduction in the stability of the shale to about 45%. The reduction in CBR suggested that moisture influx would be detrimental to subgrades of pavements constructed with the Abakalki shale. Clay mineralogy in the shale, might also be responsible for reduction in CBR, which was a geotechnical signal for cautions when used as pavement material.

Table 2. Average specific gravity of various rock types.

Rock type	SG[a]
Igneous	
Andesite	2.22
Basalt	2.77
Gabbro	3.0
Granite	2.67
Rhyolite	2.4
Sedimentary	
Limestone	2.69
Sandstone	2.58
Shale[b]	2.3 – 2.4
Metamorphic	
Gneiss	3.12
Marble	2.73
Slate	2.77

[a]apparent specific gravity data adapted from Krynine and Judd (1957). [b]bulk specific gravity data from this study

Triaxial shear strength

Shear strength of a material denotes the ability of such material to resist shearing deformational stresses (Sowers, 1963). It is expressed in terms of two parameters, angle of shearing resistance (ϕ) and cohesion (c). Laboratory analysis showed that ϕ for Abakaliki shale ranged from 23 to 31°C, while c ranged from 30 to 55 kN/m^2. Coduto (1999) and Punmia et al. (2005) remark that shales that are predominated only by clays and are as well non-cemented, most often, record very low values of ϕ (close to 10°C). Reasonable values of c recorded denoted a cohesive material, similar to consolidated clay and other materials with high clay content.

The fact that values of c were significantly greater than 10°C and c reasonably high would suggest that the Abakaliki shale as subgrade and construction material would have considerable strength, and is likely to withstand shear stresses. Moisture influx, however, would deteriorate its constituent minerals, especial clays, resulting in strength reduction and perhaps, bearing capacity loss, during the engineering life of such project. CBR values reduction have already clued-up such suspicion.

Water analysis

Table 3 gives the result of a hydrogeochemical investigation conducted in the area, while Table 4 shows the results of statistical analysis on the parameters. Average pH values for both hand dug wells and boreholes were almost equal. Mean pH for all the tested water samples, however, showed neutrality (6.9 on the pH scale). A comparison of the concentrations of the tested water samples with normal concentrations of elements in unpolluted fresh water (data presented in Table 5) showed the tested water samples had high values of ions, with HCO^-_3 and NO^-_3 being exceptionally high (above normal range). Probable source of the ions in the water included dissolution of calcite and other rock salts, as well as mica and organic matters within the shale (Table 5). Occurrences of siltstone, sandstone and limestone beds have also been noted in the Abakaliki shale (Reyment, 1965). NO^-_3 source might also be anthropogenic that is (due to activities of human beings in the area).

A borehole in the Southwestern part of the area at (Abiaji Ogharaugo) recorded highest enrichment of Ca^{2+}, HCO^-_3 and carbonate hardness. This may be either due to the fact that the borehole tapped deeper shaley bed that have secondary enrichment due to effects of leaching or that static that is (steady) and deeper water table in boreholes aided more dissolution. Most hand dug wells, and even some boreholes, in the Abakaliki area dry up in the middle of dry season leaving the town with acute shortage of portable water. In the Abakaliki area, ground water generally exists in the following ways:

(1) Fractured zones within the Asu River group.
(2) Sandstone and limestone layers or members.
(3) Weathered zones
(4) Bedrock interfaces with the shale group.

Usually, the yields are poor. According to Ismael (1990), the fractured and weathered zone shale-aquifer systems have specific yields values as follows; range 1.26×10^{-3} to 1.60×10^{-3} litre per second (l/s) and 1.22×10^{-3} to 1.81×10^{-3} l/s, with average values of 1.48×10^{-3} l/s and 1.59×10^{-3} l/s, respectively. Both shale-aquifer systems have only served for the establishment of hand-pump boreholes and hand-dug wells.

All the water sources recorded considerable amounts of Total Dissolved Solids (TDS) and appreciable hardness. Hardness in water is caused by the presence of any polyvalent metallic cations (Kiely, 1997) but principally Ca^{2+}, Mg^{2+} and, less so, Fe^{2+} and Mn^{2+}. Kiely (1997) notes that total hardness is usually computed based on the concentration of Ca^{2+} and Mg^{2+} and is usually expressed in mg/l as $CaCO_3$. Details on the softening processes and other physical, chemical and microbiological techniques that can be utilized to achieve acceptable standard for the groundwater in the Abakaliki area are presented in American Water Works Association (AWWA) (1990), Thomas and King (1991) and Kiely (1997).

All the water samples, from both hand dug wells and boreholes, could be classified as ‘fresh’, due to the fact that their TDS values all fall within the range of 0 – 1000 mg/l (Freeze and Cherry, 1979; Fetter, 1990). On the

Table 3. Hydrogeochemistry of the water resources of the Abakaliki Area.

Sample location	Source type	Parameter[a]					HCO^-_3	NO^-_3	Hardness[b]	TDS
		pH	Ca^{2+}	Mg^{2+}	Na^+	Cl^-				
Mgbado Achara	Hand dug well	6.2	8.0	0.2	4.9	7.0	21.8	15.0	17.9	56.9
Mgbado Achara	Borehole	6.7	88.0	3.0	10.1	4.0	392.0	15.0	322.2	512.1
Azu Isuma, Ogharaugo	Hand dug well	7.4	8.0	0.6	2.0	2.0	37.0	15.0	30.4	64.6
Abiaji, Ogharaugo	Borehole	6.8	134.0	3.3	10.7	71.0	1176.1	20.0	966.6	1415.0
Okposi, Umuogharu	Hand dug well	7.2	26	3.3	5.7	3.0	67.52	20.0	55.5	125.5

[a] all in mg/l, except pH. [b] hardness as $CaCO_3$ concentration.

Table 4. Normal ranges of concentrations of elements in unpolluted fresh water.

Element	Range	Av. value for hand dug wells (mg/l)	Av. value for boreholes (mg/l)	Mean
pH	6.2 – 7.4	6.9	6.8	6.9
Ca^{2+}	8.0 – 134.0	14.0	111.0	52.8
Mg^{2+}	0.2 – 3.3	1.37	3.15	10.4
Na^+	2.0 – 10.7	4.2	20.8	6.7
Cl^-	2.0 – 71.0	4.0	37.5	17.4
HCO^-_3	21.8 – 1176.1	42.1	784.1	338.9
NO^-_3	15.0 – 20.0	16.7	17.5	17.0
TDS	56.9 – 1415.0	82.3	963.6	434.8
Hardness	17.9 – 966.6	22.77	644.4	278.5

Table 5. Normal ranges of concentrations of elements in unpolluted fresh water.

Element	Concentrations (mmol/l) (Appelo and Postma, 1993)	Mean value in water samples (mmol/l)	Remarks	Probable source
Na^+	0.1 – 2	1.3	High	Rock salt
Mg^{2+}	0.05 – 2	0.4	High	Mica
Ca^{2+}	0.05 – 5	0.2	High	Calcite
Cl^-	0.05 – 2	0.5	High	Rock salt
HCO^-_3	0 – 5	5.6	Above	Calcite
NO^-_3	0.001 – 0.2	0.3	Above	Organic matter

basis of mean TDS values, however, water samples from hand dug wells would classify as moderately hard, while those from boreholes would classify as very hard (Sawyer and McCarty, 1967).

Conclusions

This study on the Abakaliki shale formation has provided insights into the probable causes of widespread and persistent occurrence of pavement, foundation and embankment failures, as well acute shortage of quality groundwater especially in the middle of dry season, flooded and waterlogged terrain, especially in the middle of rainy season, as experienced in the Abakaliki area.

Geotechnical assessment showed that the Abakaliki shale is of high plasticity, most probably, due to its content of expansive clay minerals. Attributes of material with high plasticity, like the Abakaliki shale, include swelling on moisture influx, high compressibility, low bearing capacity and low permeability that is (low drainage). These properties, most probably, would negate few favourable properties, like high MDD and high shear strength parameters (Table 6), recorded by the shale and ultimately render it unsuitable for use for most construction purposes, especially where moisture influx cannot be effectively controlled. Aggregates sourced from extrusive and Intrusive rock, as well as laterites from some parts of Southeastern Nigeria (Okagbue, 1986), may prove better alternatives.

Table 6. An engineering evaluation of some physical properties of the Abakaliki Shale.

Physical properties				
Laboratory test and *in-situ* observations	**Average range of values (Underwood, 1967)**		**Abakaliki Shale**	**Remarks**
	Unfavourable	**favourable**		
Cohesive strength (kN/m^2)	35 – 700	700 – 10,500	30 – 55	Favourable
Angle of internal friction (°)	10 – 20	20 – 65	23 – 31	Favourable
Dry density (Mg/m^3)	1.13 – 1.76	1.76 – 2.56	1.83 – 1.89	Favourable
Natural Moisture content (%)	20 – 35	5 – 15	17 – 23	Unfavourable
Predominant clay minerals	Montmorillonite, illite	Kaolinite, chlorite	*Montmorillonite, illite	Unfavourable

*data from Obiora and Umeji (2004).

Hydrogeochemical analyses indicated that the water samples from the area near neutrality, but showed high concentration of cations and anions, resulting in high values of hardness and TDS. Dissolution of the constituent minerals, especially calcite and organic matter, might likely be the source of these particles in the water. Enrichment of calcium and carbonate ions was observed in one of the tested boreholes within the area and probable explanations to this would be either that the effect of element leaching mechanism was most in the area or that steady water table in the borehole (depths of boreholes are generally higher than that of hand dug wells) necessitated higher degree and persistent dissolution of minerals in the borehole area.

Although a general situation of high HCO^{-3}, TDS and hardness was observed in the water samples, it requires comparison with established standards, for example World Health Organization (WHO, 2006) guidelines, to ascertain the appropriateness of the water samples for use for various purposes. Treatment of groundwater hardness in the area is possible and could follow standard procedure by American Water Works Association (AWWA) (1990), Thomas and King (1991) and Kiely (1997).

On the issue on environmental hazards in the area; high affinity of plasticity material that is (the Abakaliki Shale) for water, its low permeability, topography of the area and high volume of rainwater and runoffs, result to waterlogging and flooding in the middle of the rainy season, while the same affinity of plasticity material for water, highly reduced volume of rainwater and increased evapotranspiration result to hand dug well and some borehole dry-ups, as well as differential settlement and structural damages of engineering projects founded within the shale formation.

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