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Laboratory Studies on the Influence of Crude Oil Spillage on Lateritic SoilShear Strength: A Case Study of Niger Delta Area of Nigeria

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Abstract

Short term laboratory studies on the influence of crude oil spillage on lateritic soil shear strength were performed for a period of six months. Two samples of lateritic soil were investigated, samples A and B (uncontaminated and contaminated). Soil sample B contains 10% by weight (10kg) of crude oil. Sieve analysis, Atterberg limits, compaction test and shear strength tests were performed for a period of 168 days. The results of the shear strength test for sample A showed that the values of its cohesion ($\mathbf{kN/m^2}$) and angle of internal friction (°) are 51 and 14 for the 7th day test period respectively. For soil sample B, the value of cohesion ($\mathbf{kN/m^2}$) decreased from 49 for a 7th day test period to 44 in the 168th day test period while the corresponding values of the angle of internal friction (°) decreased from 11.0 to 7.0. Important geotechnical parameters measured for other tests performed were also affected as a result of the spill. The observed reduction in the shear strength parameters indicates that the vestige of crude oil had appreciable effects on soil shear strength.

Keywords: Laboratory studies, Crude oil spillage, Lateritic soil, Shear strength.

1 Introduction

1.1 Crude Oil Spillage and Niger Delta Area of Nigeria

The Niger Delta Area of Southern Nigeria as shown in Figure 1 has witnessed in recent years intense oil and gas exploration and production with its attendant environmental problems, such as crude oil spillage and pollution. Between 1976 and 1996 Nigeria recorded a total of 4835 oil spill incidents, which resulted in a loss of 1,896,960 barrels of

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oil to the environment [1]. In some cases, the spills are accompanied by a fire outbreak resulting in degradation of surrounding soil and air, and water.

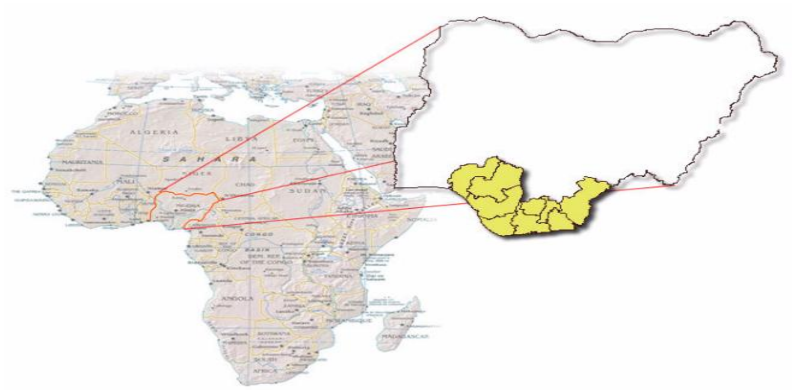

Figure 1: Map of Nigeria (with Niger Delta area delineated), extracted from the map of Africa [2]

Physio-chemical analysis of soil samples at an oil spill site of the Niger Delta Area of Nigeria showed that the total hydrocarbon content of top soil layers ranged from 0.8 to 12.4ppm in the heavy impact zone and the oil had penetrated to a depth of 7.2m. Hydrocarbon concentration in the medium impact zone ranged from 0.02 to 0.40ppm while hydrocarbons were not detected in 75% of samples from the un-impacted reference zone [3]. The causes of these oil spills has been attributed to flow-line leakages, hose failures of tankers loading systems, manifold malfunctioning, blowouts, sabotage to well heads and flow lines, overpressure failures and overflow of process equipment. It should be noted that large percentage of these spills are still lying down there in the affected areas where tendency for its migration and residential development is very high.

The obvious effects of oil spillage are environmental contamination and degradation. However, among the most affected civil engineering construction materials in southern Nigeria is the lateritic soil.

1.2 Soil Contamination and its Effects on Soil's Properties

Soil contamination is one of the most widespread and serious environmental problems confronting nations, most especially the oil producing nations. Different contaminants have different chemical properties which influence the geochemical reactions induced in the soil as it gets contaminated [4]. Nevertheless, the extent of contamination depends on the chemical composition of the contaminant and the properties of the soil [5]. It arises from variety of sources, which include crude oil spillage, acid rain, hazardous liquid and solid waste from industries, animal waste, and salt water intrusion amongst others. Among these sources of contamination, crude oil spillage and pollution are the most obvious concerns of the industrial age.

Several studies ([6], [7], [8], [9]) have shown that major changes in geotechnical properties of soils can occur in a chemical aggressive environment. Onshore and offshore oil spills contaminate soil. In addition to environmental concerns for ground water pollution and other possible effects, the geotechnical properties of the contaminated soil

such as the shear strength and the hydraulic conductivity are also altered[10]. Similar results were obtained in clayey and sandy soils, and Basaltic residual soil [11, 12]. Oil leakages from damaged pipelines, oil storage tanks, and processing plants may also cause oil contamination in the surrounding soils [13].
More recently, Youdeowei [14] concluded that crude oil spill and fire outbreak did not have a significant impact upon the soil or alter its geotechnical characteristics such as index properties, Shear strength and load bearing capacity. Elisha [15] studied the effects of crude oil contamination on the geotechnical properties of soft clay soils of Niger Delta Region of Nigeria and concluded that porosity and swelling pressure of contaminated clay decrease with increase in both sorption time and crude oil content, while its untrained shear strength fluctuates. However, neither Youdeowei nor Elisha research work consider a short or long term effects of crude oil spillage on the geotechnical properties of soil most especially its shear strength. It does appear, however, that further studies are necessary to quantify parameters of interest to geotechnical engineers because of high tendency for crude oil spill to remain uncleaned from its spill site (for example Ogoni land in Niger Delta, Nigeria) thereby prolonging its likely effects on the geotechnical properties of soil. The purpose of this paper is to present the variation of the geotechnical properties of lateritic soil most especially its shear strength due to the vestige of crude oil spillage using Niger Delta Area of Nigeria as a case study.

2 Methodology

The lateritic soil sample (about 120kg) was air dried to minimum moisture content. The air dried sample was sieved with 4.75mm BS sieve to remove dirt and particles greater than the sieve size leaving behind well graded samples of lateritic soil suitable for the tests. The sieved sample of the soil was then stored temporary inside an air tight container to avoid further moisture absorption. About 70kg of the sieved sample of lateritic soil was thoroughly mixed with 7kg (9 liters representing 10% degree of contamination) of crude oil as pollutant for 40 minutes as shown in Figure 2. The contaminated sample was then stored inside a container.

2a 2b

Figure 2: Preparation of the contaminated sample of lateritic soil

The contaminated sample of lateritic soil was stored for a period of six months during which its geotechnical properties were measured. The tests were performed on 7, 14, 21, 28, 56, 84, 112, 140, 168 days of contamination thus simulating the process of short-term soil-crude oil interaction that occurs during industrial oil and gas activities. The following laboratory tests were carried out on the lateritic soil samples, in accordance with BS1377

(1975) [16] and ASTM (1979) [17]:

- Particle Size Distribution Test (Sieve Analysis)
- Atterberg Limits (Consistency Limits)
- Compaction Test
- Shear Strength Test (Triaxial)

In each case, the tests were performed on both samples (A and B) of lateritic soil. The uncontaminated sample of lateritic soil (sample A) served as a control experiment.

3 Main Results and Discussion

Results of the various tests carried out in order to investigate the influence of crude oil spillage on the lateritic soil are presented below and discussed accordingly.

3.1 Particle Size Analysis

Particle size analyses were performed on the two samples of lateritic soil (uncontaminated and contaminated).

From the result of the particle size analysis for soil sample A (uncontaminated sample),

(a) Coefficient of uniformity (C_u)

$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.2}{0.013} = 15.38$$

(b) Coefficient of curvature (C_c)

$$C_c = \frac{(D_{60})^2}{(D_{10})(D_{60})} = \frac{0.06^2}{(0.013)(0.2)} = 1.38$$

Also, the values of C_u and C_c for soil sample B (contaminated sample) are 16.67 and 1.50 respectively.

Since the values of C_u are > 15 while that of C_c falls with the range of 1 and 3 and more than 50% of its grains passed through No. 200 sieve, hence the sample is a well graded soil [18]. In addition, since the values of C_u and C_c, for the uncontaminated and contaminated samples of lateritic soil tested are close (15.38, 1.38), (16.67, 1.50), therefore, the vestiges of crude oil in the soil did not have significant effect on the soils grain sizes.

3.2 Compaction

The compaction test results of soil sample B (contaminated sample) are shown in Table 1. In addition, the curves for moisture content - test day and dry density - test day relationships for the soil sample are shown in Figures 3 and 4.The OMC values were used for the preparation of the specimens for the shear strength tests. From Table 1 and Figure 4, results of the compaction tests performed on the lateritic soil investigated showed that the MDD of the contaminated soil decreased as the period of contamination advances. The uncontaminated sample of lateritic soil has the highest value of $17.25\ \mathrm{kN/m^3}$ as its MDD. This is due to the natural state of the soil which makes it possible for the development of its strength to the maximum value.

The MDD values obtained from contaminated sample of lateritic soil decreased with increasing days of contamination from $17.15\ kN/m^3$ to $16.98\ kN/m^3$. This is due to the presence of crude oil as pollutant which inhibited the development of the density of the soil to the normal value. The absorption of higher molecular weight components, such as hydrocarbon chains of crude oil onto the lateritic soil surfaces caused wettability to change from water-wet to oil-wet. The absorption of these components created an adsorbed layer around the particles. This adsorbed layer is not water soluble, and is not displaced by water. The organic content coats and agglomerates the lateritic soil particles thereby reducing the specific surface area. This in turn led to the reduction in the bonding strength of the lateritic soil.

Table 1: Summary of Compaction Test Results for contaminated Sample of Lateritic (Soil Sample B)

Test Day (Days)	MDD (KN/m^3)	OMC (%)
7	17.15	13.90
14	17.13	14.00
21	17.12	14.00
28	17.11	14.50
56	17.09	15.00
84	17.08	15.84
112	17.05	16.50
140	17.00	18.80
168	16.98	18.90

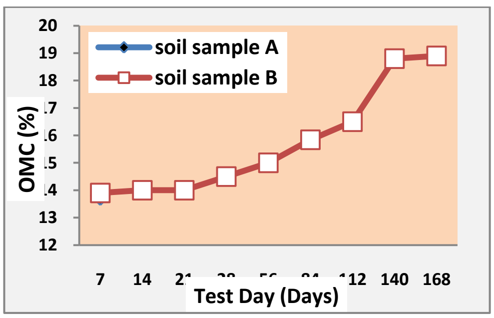

Figure 3: Relationship between OMC (%) and Test Day (Days)

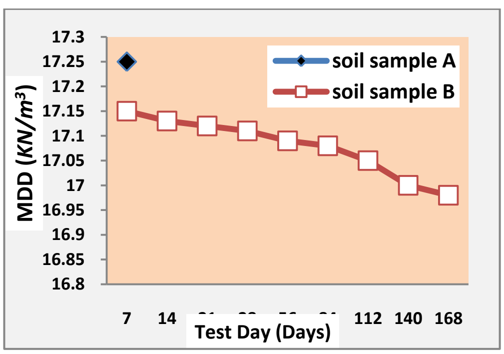

Figure 4: Relationship between MDD (kN/m^3) and Test day (Days)

3.3 Atterberg Limits

The results of the Atterberg limits mainly liquid limit (LL), plastic limit (PL), shrinkage limit (SL) and plasticity index (P1) are shown in Table 2. From Table 2, the liquid limit (LL) of soil sample A is 62.7%, hence the soil is of high plasticity since it is >50%. The plastic limit (PL) decreased from 23.5 to 21.9 and the liquid limits (LL) decreased from 62.7 to 49.3, from high plasticity to low plasticity [18].
The decrease in the values of PL and LL is due to the alteration of the cohesive bonds and forces that exists between the particles of the lateritic soil. The decrease in the values of LL, PL and PL is also due to reduction in the Cation Exchange Capacity (CEC) of the soil.
The composition of cations on the exchange complex of soils was affected by the disposal of wastes during petroleum extraction and operations [19]. Cations are attached and held onto the surfaces and the edges to preserve electrical neutrality. These cations are exchangeable cations because they are replaced by cations of another type. CEC is a measure of the isomorphous substitution. This substitution gives a net negative charge to the lateritic soil particles. CEC reduced considerably in the presence of organic molecules such as crude oil. The molecules blanket or coat exchange sites, thus inhibiting the measured exchange potential thereby reducing the ability of the lateritic soil particles to be bonded with each other.

Table 2: Results of the Atterberg Limit Test

	Test day	Plastic Limit (PL)	Liquid Limit (LL)	Plasticity Index (PI)	Shrinkage Limit (SL)
Soil sample A	7	62.7	23.5	39.2	15.7
Soil sample B	21	49.3	21.9	27.4	12.5

3.4 Shear Strength Parameters

The specimens for the shear strength tests were loaded to failure. At failures, for soil sample A (uncontaminated soil sample) with Cell pressures of 20 kN/m^2, 40 kN/m^2 and 80 kN/m^2, the values of the loads and deformations are (102, 2195), (116.5, 2414), (144, 2693) for the 7th day test period. The detailed values of the load and deformation dial gauge for soil sample B are shown in Tables 3.

Table 3: Detailed Values of Load and Deformation Soil Sample B

Test Day	Cell Pressure (kN/m^2)					
	20		40		80	
	Load	Defor.	Load	Defor.	Load	Defor.
7	102	2482	117	2615	144	2693
14	99	2360	118	2991	143	3189
21	93	2461	105	2486	127	2682
28	96	2730	108	3073	126	3085
56	85	2519	95	2345	115	2653
84	79	1840	88	2118	104	2450
112	81	1930	91	2315	109	2675
140	82	1995	93	2415	114	2910
168	89	1840	95	3252	112	3122

The values of the cohesion (kN/m^2) and angle of internal friction (°) for soil samples A and B are (51, 14) and (49, 11) respectively for the 7th day test period while the summary of the results of the shear strength tests for cohesion and angle of internal friction of soil sample B are shown in Table 4.

Table 4: Summary of Shear Strength Test Results for Soil Sample B

Test day	Cohesion	Angle of Inter. Fric.
7	49	11.0
14	48	10.0
21	47	9.0
28	46	8.5
56	45	8.0
84	44	8.0
112	44	8.0
140	44	8.0
168	44	7.0

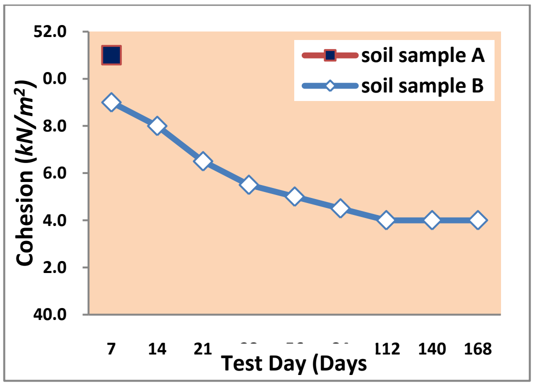

Figure 5: Relationship between Cohesion (kN/m^2) and Test day (Days)

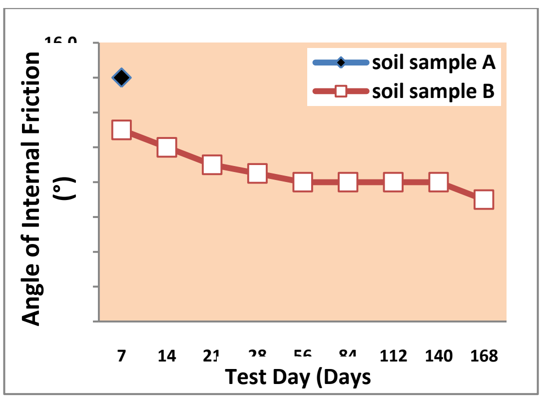

Figure 6: Relationship between Angle of Internal Friction (°) and Test Day (Days)

From the results in Figures 5 and 6, the values of cohesion (kN/m^2) and the angle of internal friction (°) decreased with increasing days of contamination.The shear strength of soil depends on two main factors namely:

- Friction between the soil particles - Angle of internal friction
- Strength of bond between the soil particles - Cohesion

The decrease in the shear strength of the lateritic soil sample tested is due to the reduction in the values of the cohesion (kN/m^2) and the angle of internal friction($°$). The sharp initial decrease in the value of angle of internal friction and cohesion is due to the reduction in friction and bond that holds the lateritic soil particles together. The decrease in the cohesion of the lateritic soil is due to the reduced value of surface tension and the rate of diffusion of the crude oil compared to water.

Surface tension is due to the forces of attraction between the molecules of the fluid. Crude oil being more viscous and less dense than water tends to possess lower value of surface tension. When crude oil spilled on lateritic soil, it infiltrate into the voids between the particles of lateritic soil, forms thin film of coats around its particles thereby inhibits the maximum development of the intermolecular cohesive forces responsible for the bond between the cohesive particles of the lateritic soil.

The reduction in the cohesion of the lateritic soil can also be explained in terms of the viscosity and the rate of diffusion of the crude oil. Viscosity is the internal friction between the layers of the fluid in motion. It is also associated with the ease of movement of the fluid particles (diffusion). Diffusion is the tendency of the molecules of fluids to migrate and fill the empty spaces due to their random thermal motion. Crude oil being a more viscous fluid, when spilled on the lateritic soil, it travels at a slower pace to the voids between the particles of the lateritic soil, thus inhibit the ability of the lateritic soil particles to become mobile and bond with each other.

The reduction in the cohesion of the soil can also be explained from the chemistry of the reaction of the lateritic soil particles.

$$2Al_2O_3 + 8H_2O \rightarrow 4Al(OH)_3 + 2H_2O \quad (1)$$

$$Al_2O_3 + \text{Crude Oil} \rightarrow Al^{3-} + {O_2}^{2+} + \text{Crude Oil} \quad (2)$$

When water mix with lateritic soil as shown in Equation 1, it enhances the process of strength development by strengthening the bond between the particles of lateritic soil through the formation of a compound of $Al(OH)_3$ from Al_2O_3. However, with the addition of crude oil instead of water as shown in Equation 2, the fluid contains more of carbon and hydrogen instead of oxygen and hydrogen. The Aluminum oxide (Al_2O_3) dissociate without having sufficient hydroxides (OH) to form the bonds with, the requirement for the enhancement of the intermolecular forces (Cohesion) of lateritic soil.

The decreases in the value of the angle of internal friction is due to the presence of crude oil (as oil reduces friction) in the lateritic soil, providing layers of coats on the particles of the soil which in turn weakens the bonding strength between the soil particles. Angle of internal friction of the soil is a function of the intermolecular frictional forces (the forces that inhibit the relative motion) between the particles of lateritic soil. Generally, it has been established that oil reduces friction, the fact that makes man slips easily on oil spilled on ground. However, when crude oil is spilled and infiltrate into the lateritic soil, it occupies the voids between the particles of the lateritic soil and tends to form a film of coats around the lateritic soil particles which makes the particles to glide over each other more frequently thereby reducing the relative internal friction that exists between the particles of lateritic soil.

As the period of contamination advances, the gaseous content of the crude oil (CH_4 and C_2H_2) escaped (diffused) into the atmosphere and the absorption of the crude oil by the lateritic soil particles increases. This in turn brought about declination in the rate of reduction in the shear strength of the lateritic soil. The influence of crude oil as contaminant on lateritic soil geotechnical properties most especially, its shear strength is not significant due to lack of feasible chemical reaction between the chemical constituents of crude oil and that of lateritic soil.

Results of different hydrocarbon analysis of samples of Nigeria's crude oil revealed that Nigeria's crude oil is low in sulfur content and has isomers of pentane; hexane and heptane as its major chemical components. However, carbon and hydrogen are the chemical constituents of these major components.

The reaction between the chemical constituents of lateritic soil and the isomers of pentane, hexane or heptane is not feasible as shown in Equations 1, 2, 3 and 4 below.

$$O_2 + C_xH_y \rightarrow SiO_2 + C_xH_y \quad (3)$$

$$Al_2O_3 + C_xH_y \rightarrow Al_2O_3 + C_xH_y \quad (4)$$

$$Fe_2O_3 + C_xH_y \rightarrow Fe_2O_3 + C_xH_y \quad (5)$$

$$CaCO_3 + C_xH_y \rightarrow CaCO_3 + C_xH_y \quad (6)$$

The equations show non feasible chemical reactions between the lateritic soil and major crude oil chemical constituents.

If the chemical reaction between crude oil chemical constituents and the lateritic soil particles is feasible, the effects of crude oil on the shear strength of lateritic soil will be more pronounced and there will be a need for further research into an applicable stabilization method for the soil in question.

4 Conclusion

The vestige of crude oil did not have appreciable effects on the grain size distribution of the lateritic soil investigated.

The soil sample B (contaminated sample) tested showed a sharp declination in the values of its MDD and OMC. The decrease in the values of MDD is due to the presence of crude oil as contaminant which inhibited the development of the density of the soil to the true normal value. The organic content coats and agglomerates the lateritic soil particles thereby reducing the specific surface area which in turn led to the reduction in the bonding strength of the lateritic soil.The soil sample B also showed reduction in the values of the Atterberg limits parameters (PL and LL). The decrease in the values of LL and PL is due to reduction in the cation exchange capacity (CEC) of the soil.

From the results of the shear strength test for soil sample B, the values of its cohesion (kN/m^2) reduced from 49 for 7th day test period to 44 for 168th day test period while its corresponding values of angle of internal friction (°) reduced from 11.0 to 7.0.The reduction in the values of angle of internal friction is due to the formation of a film of coasts of oil around the lateritic soil particles which made the particles to glide over each other more frequently thereby reducing the relative internal friction that exists between the lateritic soil particles.

The decrease in the cohesion of the lateritic soil is due to the reduced value of surface tension and the rate of diffusion of the crude oil compared to water. when crude oil spilled on lateritic soil, it infiltrate into the voids between the particles of lateritic soil, forms film of coats around its particles thereby inhibits the maximum development of the intermolecular cohesive forces responsible for the bond between the cohesive particles of the lateritic soil. Since the results of the shear strength tests showed reduction in the values of the cohesion and angle of internal friction, hence the vestige of crude oil on the lateritic soil sample indeed reduced its shear strength.

References

[1] O.T. Badejo and C.P. Nwilo, "Management of Oil Spill Dispersal Along the Nigerian Coastal Areas, "http://www.isprs.org/proceedings/XXXV/congress/comm7/papers/241.pdf (Accessed on January 10, 2013).
[2] C. P. Enueme and V. Onyene, Youth Restiveness in the Niger Delta of Nigeria: Implication for Education and Leadership, *Euro. J. Soc. Sc.*, 18(2), (2010), 286-296.
[3] M. O. Benka-Coker and J. A. Ekundayo, Effects of an Oil Spill on Soil Physio-Chemical Properties of a Spill Site in the Niger Delta Area of Nigeria, *J. Env. Monitoring and Assessment*, 36(2), (1995), 93-104.
[4] S. Ghosh.,Geotechnical Evaluation of Soil Contaminated with Toxic Chemicals,*Seattle Annual Meeting of the Geological Society of America*, 35, (2003), 313.
[5] P. Fine, E. R. Graber and B. Yaron,Soil Interactions with Petroleum Hydrocarbons: Abiotic Processes, *J. Soil Technol.*,10(2), (1997), 133– 153.
[6] B.M. Sunil and S. Shrihari, *Effects of Wastewaters on the Geo-Technical Properties of Laterite In: Integrated Management of Groundwater and Contaminated Land*, Thomas Telford, 2004.
[7] J. Park, C. Vipulananda, J. W. Kim and M. H. Ho, Effects of Surfactants and Electrolyte Solution on the Properties of Soil,*J. Env. Geology*, 49(7), (2006), 977-989.
[8] V. Murugaiyan and R. Saravanane, Influence of Pharmaceutical Effluent on the Physico – Chemical Behavior and Geotechnical Characteristics of Clayey and Silty Soils, *Int. J. Soil, Sediment and Water*, 2(3), (2009), 1- 15.
[9] I. B. Gratchev and I. Towhata, Effects of Acidic Contamination on the Geotechnical Properties of Marine Soils in Japan,*Proceedings of the 19th International Offshore and Polar Engineering Conference*, (2009), 151-155.
[10] E. C. Shin, J. B. Lee, and B. M. Das, Bearing Capacity of a Model Scale Footing on Crude Oil-Contaminated Sand, *J. Geotech. Geolog. Engineering*, 17 (2), (1999), 123-132.
[11] M. Khamechiyan, A. H. Charkhabi, and M. TajiK, Effects of Crude Oil Contamination on the Geotechnical Properties of Clayey and Sandy Soils, *J. Engineering Geo.*, 89(3), (2007), 220-229.
[12] Z. A. Rahman, U. Hamzah, M. R. Taha, N. S. Ithnain and N. Ahmad, Influence of Oil Contamination on Geotechnical Properties of Basaltic Residual Soil, *Am. J. Applied Sc.*, 7(7), (2010),954-961.
[13] E, Evgin and B.M. Das, *Mechanical Behaviour of Oil-Contaminated Sand In: Environmental Geotechnology*, Balkema, Rotterdam, 1992.
[14] P. O. Youdeowei, The Effects of Crude Oil Pollution and Subsequent Fire on the Engineering Properties of Soils in the Niger Delta,*Bull. Eng. Geol. Environ.*, 67 (1), (2008),119-121.
[15] A. T. Elisha, Effect of Crude Oil Contamination on the Geotechnical Properties of Soft Clay Soils of Niger Delta Region of Nigeria,*Electronic J. of Geotech. Eng.*, 17

(M) (2012), 1929-1938.
[16] ASTM, *Annual Book of American Society for Testing and Material Standards*, ASTM Tech Publications, 1979.
[17] BS 1377, *Methods of Test for Soils for Civil Engineering Purposes*, British Standards Institution (BSI),1975.
[18] Virginia Department of Transportation, *Unified Soil Classification System*, Virginia Department of Transportation, Virginia, 2003.
[19] J. M. Arocena and P. M. Rutherford, Properties of Hydrocarbon and Salt-Contaminated Fare Pit Soils in Northeastern British Columbia (Canada), *J. Chemosphere*, 4 (60), (2005), 567-575.