REDUCTION OF THE SHEAR STRENGTH OF SOILS IN THE NIGER DELTA AREA OF NIGERIA DUE TO CRUDE OIL PRODUCTION

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ABSTRACT

The research was targeted at finding out if crude oil polluted soils in the Niger Delta Area of Nigeria will still retain their original values of geotechnical properties. If not, establish, the effect of crude oil pollution on the geotechnical properties of the crude oil polluted soils and determine the shear strength of the affected soils. This was achieved by carrying out soil investigations at randomly selected crude oil polluted sites and also carrying out another set of soil investigations at nearby locations which enabled the geotechnical properties of the crude oil polluted soils to be compared with those of unpolluted soils. Evaluation of the effects of crude oil pollution on the engineering properties of the affected soils and comparison with the engineering properties of unpolluted soils of similar soil structure within the same zone was carried out. Decrease in values of un-drained cohesion, un-drained angle of internal friction, optimum moisture content, maximum dry density, coefficient of consolidation, coefficient of permeability of the polluted soils were established from the study. The mathematical interrelationship (Mohr-Coulomb equation) between these soil properties and shear strength and soils was used to establish the reduction in shear strength of polluted soils.

Keywords: crude oil, shear strength, engineering properties of soils, Niger Delta.

1. INTRODUCTION

There is a high frequency of oil spill in Nigeria ad other oil producing countries. The impact of these spill on soil is not yet quite understood. There are studies on the impacts of crude oil on ground water [1], fauna and flora [2-4] and so [5] but known yet on the geotechnical properties of soil [7,8]. Hence, this study is aimed at investigating the effect of crude oil on the engineering properties of soil. The result of this study will not only enhance proper understanding of crude oil imparted soil but will also facilitate utilization of more effective remediation strategies and reuse for engineering purposes.

2. SHEAR STRENGTH

One of the prime parameters of structures on soil masses in the shear strength of the soil. Evaluation and assessment of these shear stresses still remains the Mohr-Coulomb strength criteria given by equations (1(a) and 1(b)) reproduced below.

$$\vartheta = C + \Phi \tan M \qquad \ldots\ldots 1(a)$$

$$\vartheta = C + (\Phi - :_1) \tan (M - :_2) \qquad \ldots\ldots 1(b)$$

Where c = intrinsic cohesion of the soil material

M = angle of internal friction of the soil

$:_1$ and $:_2$ = are the reduction factors for the shear strength and angle of internal friction respectively as a result of crude oil pollution.

It must be mentioned here that c and M are referred to as the "shear strength parameters" of the soil.

Values of the angles of friction (M) for fine-grained soils in the Niger Delta area of Nigeria, varies from as low as 2 - 3° to a high of about 8 - 10° depending on the amount of coarse particles included within the soil materials. For coarse-grained soils, values of angles of friction (M) vary between 15 - 30° [5].

3. PHASE RELATIONSHIP FOR THE UNPOLLUTED AND POLLUTED SOILS

The major components of soil are solids, water and air as shown schematically in fig 1(a). In the Niger Delta area of Nigeria that is susceptible to crude oil pollution, the phase structure of the soil changes when a fourth phase is introduced into the system as shown in fig. 1(b). The fourth phase mentioned above is crude oil or any other pollutants like diesel oil or chemicals used for clean up operation of polluted soils.

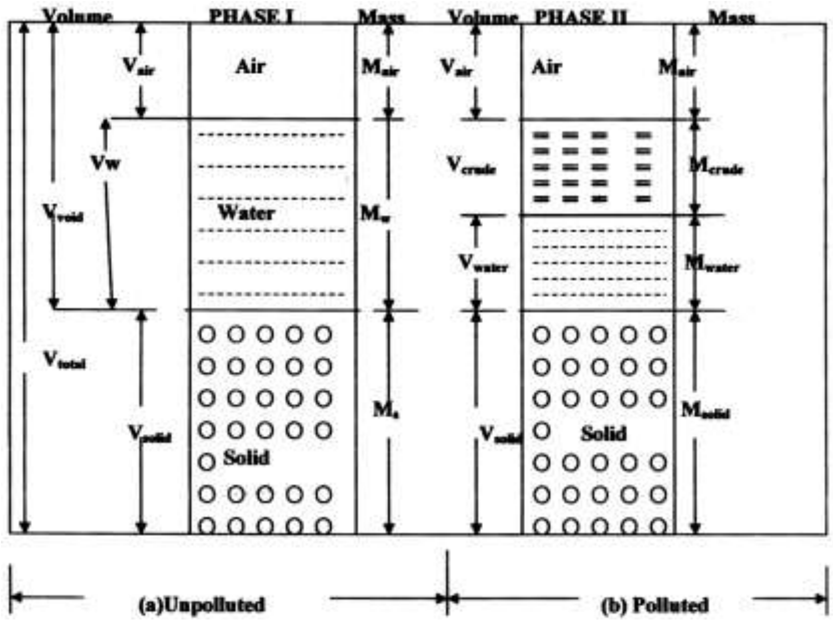
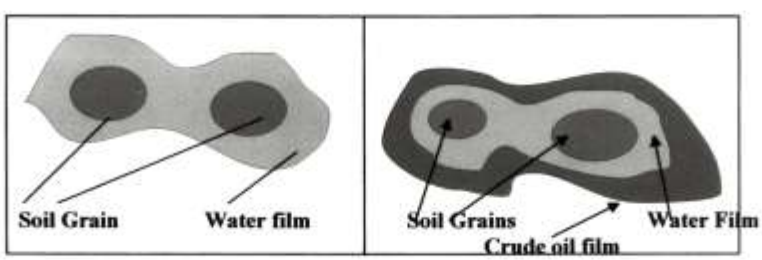


Fig. 1(a)and (b): Phase relationship for the unpolluted and polluted soils

4. SOIL GRAIN – WATER – CRUDE OIL CONFIGURATION BEFORE AND AFTER CRUDE OIL POLLUTION

Before crude oil pollution, the soil grains are separated by only films of water as shown in fig. 2(a). After crude oil pollution, the soil grains and water films are further coated by a thin slimy layer of crude oil as shown in fig. 2(b).

Understanding the phase relationships for the unpolluted and polluted soils as well as the soil grain-water-crude oil configuration before and after crude oil pollution is very beneficial in understanding the next phase of this technical paper which illustrates how the shear strength of crude oil polluted soils are affected, as a result of the reduction in engineering properties of the affected soils.



2a Before crude oil pollution 2b After crude oil pollution

5. METHODS

Soil samples were collected from crude oil polluted sites in the following towns in Rivers State of Nigeria, (Apara, Bomu, Ebubu, Oporoma and Oshika).

At each site, one or two borings were made within the crude oil polluted areas and one boring was made in the unpolluted (control) areas but usually not more than half a kilometre from each other.

From each boring, disturbed samples were collected in polythene bags. Also from each boring, undisturbed samples were collected in polythene bags using open ended tube samplers and block sampling equipment.

Borings were sampled at depths of between 0.40 – 0.50m intervals from the ground level to the termination of the boreholes. Depths of borings ranged from 0.20m – 2.0m.

To check if the polluted soil samples obtained at distances of about 0.5km apart were comparable in terms of soil index, previous results of soil tests carried out by Shell Petroleum Development Company Nigeria Ltd, were used to determine how the indices compare.

The review established clear and comparable soil samples for the polluted and unpolluted sites. Furthermore, at each depth (polluted sites) sampled, special samples were collected in polythene bags. These samples were used for the analysis of the hydrocarbon content of the polluted soils. This offered the opportunity to establish a proper correlation between the effect of crude oil pollution on the geotechnical properties of the soils and the extent of pollution.

Index tests were done for each single sample collected. Laboratory analyses of the polluted and unpolluted soils were carried out to obtain the following soil properties:

- Grain size distribution
- Atterberg limits
- Strength parameters (e.g. shear strength, proctor compaction, CBR, tri-axial compression).
- Compressibility indices.

As previously mentioned, the hydrocarbon content of the polluted and unpolluted soil samples was also analysed in order to compare how the extent of pollution affects the engineering properties of soils analysed after the soil investigation.

6. TRIAXIAL STRENGTH TESTS

6.1 Results of the Undrained Triaxial Strength Tests

It is important to mention that all the tests for the various soil indices were carried out in the triaxial. Only the results of the parameters that are related to shear strength will be re-produced in this paper for brevity.

CBR - California Bearing Ratio of crude oil polluted soils experienced increases and a different paper has been published highlighting the fact that crude oil polluted soils are good for road and air-field pavement construction as a result of increased CBR values over and above the CBR values of the unpolluted soils.

7.0 RESULTS

7.1 Shear Strength (Triaxial Test)

Table 1(a) Result of Triaxial Tests

Location	Borehole No.	Depth (m)	Undrained cohesion Cu/(KN/m^2)	Undrained Angle of internal friction M (°)	Remarks
1) Bomu	1A	0.5 – 0.65	20	38	Firm dark grey oily Silty SAND
	2A	1.6 – 1.75	18	38	Firm dark grey oily Silty SAND

	1B	1.0 – 1.2	40	39	Firm greyish brown Sandy CLAY
	1B	1.0 – 1.40	20	37	Firm greyish brown Sandy CLAY
2) Ebubu	1A	1.0 – 1.10	18	24	Firm to soft light Grey oily silty CLAY
	1A	1.5 – 1.65	38	25	Soft grey oily Silty CLAY
	1A	1.92 – 2.0	20	23	Soft grey oily Silty CLAY
	2A	0.5 – 0.65	60	26	Firm grey silty Oily CLAY
	2A	1.0 – 1.20	45	27	Firm grey oily silty Sand.
	2A	1.90 – 2.10	40	21	Firm yellowish brown Sandy silty CLAY.
	1B	0.6 – 0.65	60	29	Firm yellowish brown Sandy silty SAND
	1B	1.30 – 1.45	100	21	Firm yellowish brown Sandy silty SAND
3) Apara	1A	0.60 – 0.65	22	27	Firm yellowish grey Sandy silty CLAY
	1A	1.0 – 1.15	30	24	Firm yellowish grey Silty CLAY
	2A	1.0 – 1.15	20	25	Firm yellowish grey Sandy silty CLAY.
	1B	0.5 – 0.65	30	25	Firm brown sandy CLAY (lateritic).
	1B	1.0 – 1.15	30	28	Firm brown sandy CLAY (lateritic).
4) Oshika*	1A	0.45 – 0.50	40	39	Very stiff grey brown sandy silty CLAY.
	1A	0.30 – 0.45	18	25	Soft yellowish brown sandy CLAY.
5) Oporoma	1A	0.5	32	22	Soft to firm brown grey Silty CLAY/organic
	1A	1.0 – 1.14	30	22	Firm grey mottled silty CLAY with organic
	1A	1.50 – 1.55	25	23	Stiff grey mottled brown silty CLAY with organic.
	1B	1.5 – 1.95	44	26	Soft to firm light grey

Note: Values of undrained angle of internal friction are high because most of the soils in question are SANDY clay.

Table 1(b) Average values of Cu and M_u

LOCATION	POLLUTED		UNPOLLUTED	
	Cu (KN/m^2)	M_u (°)	Cu (KN/m^2)	M_u (°)
BOMU	19	38	30	38
EBUBU	36.8	24.3	80	25
APARA	24	25.3	30	26.5
OSHIKA	40	39	18	25
OPOROMA (Nun River)	29	22.3	44	26

Table 2(a) Values of c_v for Apapa, Ebubu and Oporoma Fields

LOCATION	PRESSURE RANGE (KN/m^2)	POLLUTED (c_v, m^2/yr)	UNPOLLUTED (cv, m^2/yr)
1. APARA	25 – 50	25.16	25.7
	50 – 100	24.25	26.21
	100 – 200	19.52	28.00
	200 – 400	16.68	19.69
	400 – 800	12.12	17.18
2. EBUBU	25 – 50	21.32	28.81
	50 – 100	18.45	22.61
	100 – 200	13.00	15.14
	200 – 400	12.35	14.50
	400 – 800	13.35	15.40
3. OPOROMA (NUN RIVER)	25 – 50	29.55	32.60
	50 – 100	27.13	28.30
	100 – 200	29.38	31.05
	200 – 400	15.74	18.70
	400 – 800	12.82	15.40

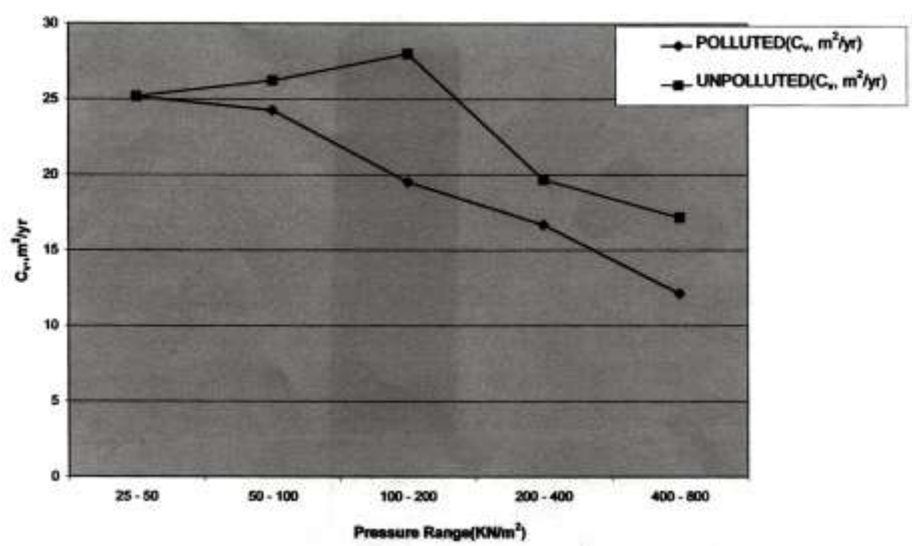


Fig 3(a): Plot of pressure range vs coefficient of consolidation (c_v)(Apara)

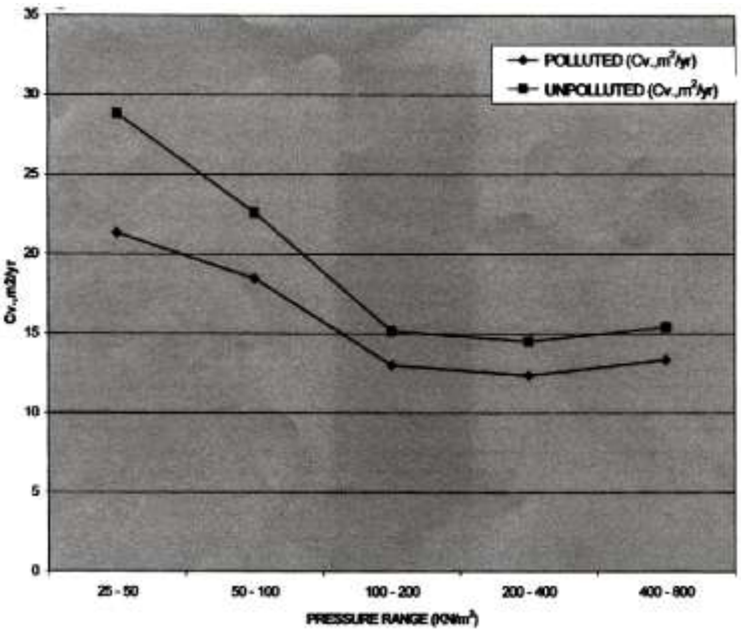


Fig. 3(b): Plot of pressure range vs coefficient of consolidation (c_v) (Ebubu)

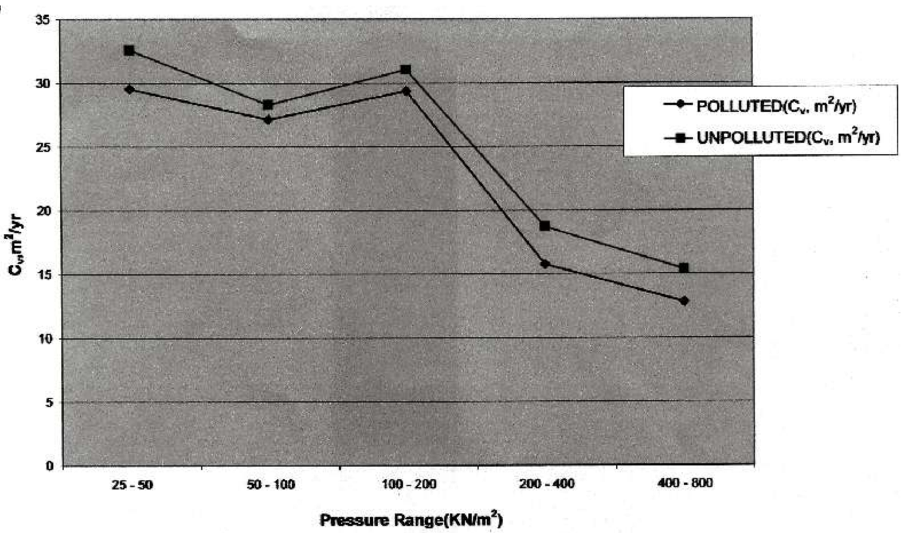


Fig. 3c: Plot of pressure range vs coefficient of consolidation (c_v)(Oporoma)

Table 2(b) Values of k (Coefficient of permeability for APARA, EBUBU AND OPOROMA FIELDS)

LOCATION	PRESSURE RANGE (KN/m^2)	POLLUTED (k, cm/sec)	UNPOLLUTED (k, cm/sec)
1. APARA	25 – 50	16.1 H 10^{-9}	16.0 H 10^{-9}
	50 – 100	39.03 H 10^{-9}	10.30 H 10^{-9}
	100 – 200	16.11 H 10^{-9}	5.60 H 10^{-9}
	200 – 400	9.90 H 10^{-9}	3.50 H 10^{-9}
	400 – 800	4.27 H 10^{-9}	4.27 H 10^{-9}

2. EBUBU	25 – 50	2.36 H 10^{-7}	6.75 H 10^{-7}
	50 – 100	2.10 H 10^{-7}	3.12 H 10^{-7}
	100 – 200	1.66 H 10^{-7}	1.91 H 10^{-7}
	200 – 400	0.85 H 10^{-7}	1.03 H 10^{-7}
	400 – 800	0.69 H 10^{-7}	1.03 H 10^{-7}
3. OPOROMA (NUN RIVER)	25 – 50	0.02 H 10^{-7}	0.61 H 10^{-7}
	50 – 100	2.30 H 10^{-7}	2.80 H 10^{-7}
	100 – 200	1.90 H 10^{-7}	2.10 H 10^{-7}
	200 – 400	0.65 H 10^{-7}	0.80 H 10^{-7}
	400 – 800	0.38 H 10^{-7}	0.52 H 10^{-7}

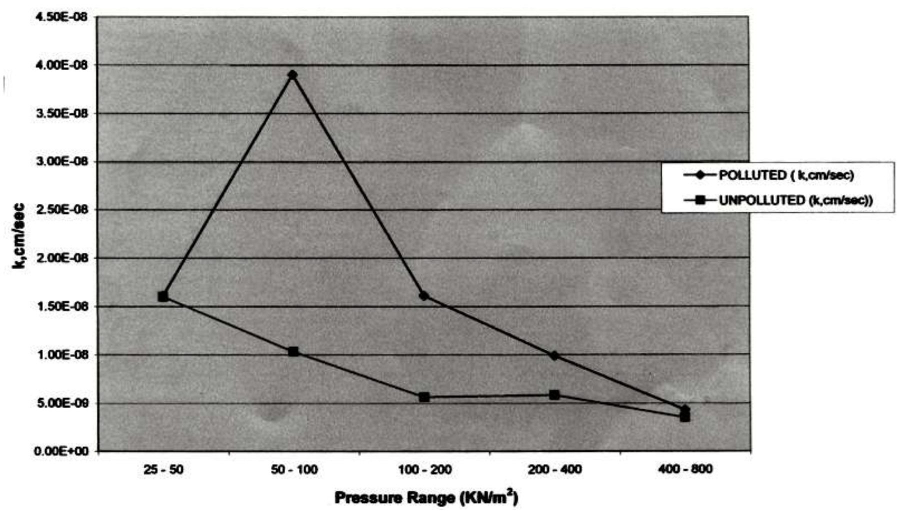


Fig 4(a): Plot of pressure range vs coefficient of permeability (k) (Apara)

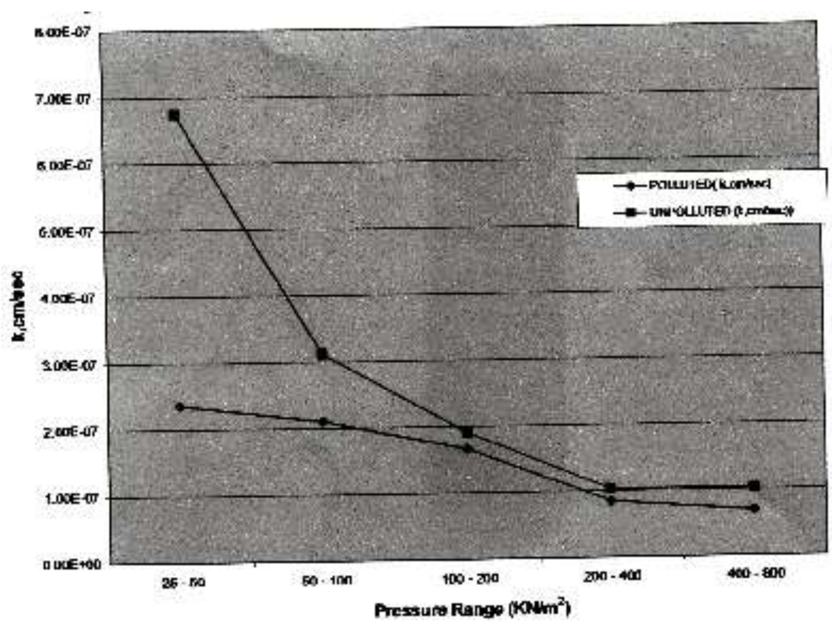


Fig. 4(b): Plot of pressure range vs coefficient of permeability (k) (Ebubu)

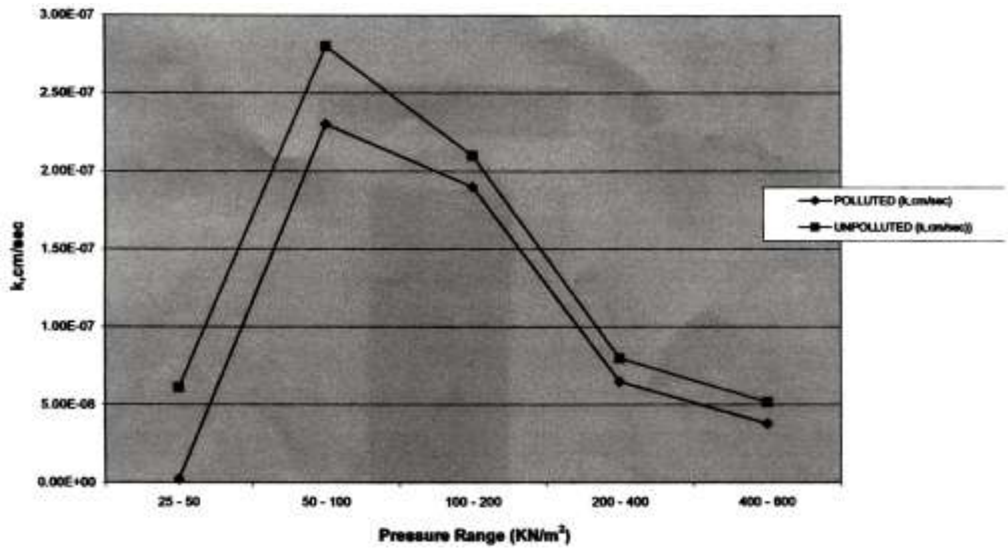


Fig. 4(c): Plot of pressure range vs coefficient of permeability (k) (Oporoma)

7.2 Hydrocarbon Content Analysis

Table 3: Results of hydrocarbon content analysis for polluted soil samples

Location	Borehole No.	Depth (m)	Hydrocarbon content concentration (ppm)
1) Bomu	1A	1.5 – 10.65	2063.24
	2A	0.0 – 0.50	1522.06
	2A	0.5 – 1.0	1575
	2A	1.0 – 1.70	1623.53
	Borehole B unpolluted	All depths	10 – 50*
2) Ebubu	1A	0.0 – 0.40	131911.76
	1A	0.40 – 1.00	44647.06
	1A	1.00 – 1.10	22661.76
	1A	1.92 – 2.10	19482.35
	2A	0.0 – 0.30	287500.0
	2A	0.30 – 0.50	111617.65
	2A	1.0 – 1.20	23000.00
	Borehole B unpolluted	All depths	10 – 50*
3) Apara	1A	0.40 – 0.50	703.53
	1A	0.7 – 1.0	33.82
	1A	0.8 – 1.0	300
	2A	0.0 – 0.10	1183.82
	2A	0.5 – 1.0	70
	2A	0.50 – 1.0	94.71
	2A	1.0 – 1.15	16.91
	Borehole B unpolluted	All depths	10 – 50*
2) Oshika*	1A	0.40 – 0.50	50.74
	Borehole B unpolluted	All depths	10 – 50*

2) Oporoma	1A	0.0 – 0.50	372.06
	1A	0.50 – 0.875	300
	1A	0.40 – 1.0	405.88
	1A	1.15 – 1.50	175.88
	Borehole B	All depths	10 – 50*

* For unpolluted soil samples, the hydrocarbon content was measured and found to be equal to the natural hydrocarbon content of a soil in the Niger Delta region of Nigeria (10 – 50 ppm).

8.0 ANALYSIS OF RESULTS

8.1 Shear Strength (Triaxial) Test

From Tables 1(a) and 1(b) it can be observed that crude oil pollution reduces the values of both undrained cohesion and undrained angles of internal friction of affected soils.

The reduction of the undrained angle of internal friction is due to the inter-grain lubrication of the soil particles by the crude oil which still remained intact in the soil at Bomu and Ebunu sites several years after the pollution occurred. Also crude oil pollution enhances soil degradation which destroys the inter-molecular forces between soil grains and consequently results in lowering of values of undrained cohesion.

The reduction in values of shear strength can be mathematically illustrated using the Mohr-Coulomb equation with the reduced values of both undrained cohesion and undrained angle of internal friction for crude oil polluted soils as follows;

Shear strength of a soil is defined by Mohr-Coulomb equation as:

$\vartheta = C + \Phi_n \tan M$

Where ϑ = shear strength

C = cohesion

Φ_n = normal pressure

M = angle of internal friction (undrained)

From the above equation, it can be deduced that crude oil pollution lowers the shear strength of affected soils, since $\vartheta(p)$ is lower in value compare to $\vartheta(up)$ as calculated below.

This is illustrated below with the values for Apara field in Table 1(b).

$\vartheta(p) = 24 + \Phi_n \tan 25.3°$

Assume $\Phi_n = 100KN/m^2$

$\vartheta(p) = 24 + 100 \tan 25.3° = 71.3KN/m^2$

$\vartheta(up) = 30 + \Phi_n \tan 26.5°$

Assume $\Phi_n = 100KN/m^2$ (for both polluted and unpolluted cases)

$\vartheta(up) = 30 + 100 \tan 26.5° = 79.8KN/m^2$

$\vartheta(p) < \vartheta(up)$

Note $\vartheta(p)$ is the shear strength of polluted soils and $\vartheta(up)$ is the shear strength of the unpolluted soils. Approximately 11% reduction in shear strength of crude oil polluted soils from Bomu field was obtained from the calculated shear strength values above.

8.2 Oedometer Consolidated Tests

The consolidation test for Ebubu, Apara, Oshika and Oporoma sites were done using five pressure ranges, (25 – 50KN/m^2), (50 – 100KN/m^2), (100 – 200KN/m^2), (200 – 400KN/m^2), and (400 – 800KN). For each pressure range values of, c_v (coefficient of consolidation) and k (coefficient of permeability) were calculated.

8.2.1 c_v Coefficient Of Consolidation

For all pressure ranges considered, the general observation is a decrease in values of (coefficient of consolidation) for polluted soils, from Table 2(a) and figs 3(a) – 3(c), it is noticed that values of coefficient of permeability for crude oil polluted soils are generally lower than those of the unpolluted soils.

The lower values of coefficient of consolidation noticed for crude oil polluted soils are related to the lower values of coefficient of permeability for crude oil polluted soils. The consolidation process fro crude oil polluted soils is thus achieved in a longer time compared to that for non-polluted soils. Furthermore, the decrease in values of coefficient of consolidation c_v for polluted soils can be explained mathematically as follows: Since c_v is expressed mathematically in terms of m^2/year. From Table 2(a) and Figs 4(a) – 4(c), it is observed that c_v values for polluted soils are lower than those of the unpolluted soils. This means that less area (m^2), will be consolidated for a given year than for the unpolluted soils. This tends to suggest, however, that the soil is less prone to consolidation when polluted than when unpolluted.

8.2.2 k Coefficient of Permeability

From Fig 2(b) and Figs 4(a) – 4(c), it can be observed that coefficient of permeability of crude oil polluted soils are lower than those of unpolluted soils.

The only exceptions are values for of coefficient of permeability for Apara field which had higher values for polluted soils when compared with those of unpolluted soils. This deviation was ignored because the polluted soil for Apara site is soft silty sandy clay while the unpolluted soil is firm sandy clay. Moreover, the hydrocarbon content analysis (Table 3), shows that the extent of pollution was high only at the top soil region (0.0 – 0.50m). At other depths, the hydrocarbon content was in the region of the natural hydrocarbon content values (10 – 50 ppm). The analysis was based on the phenomenon for Ebubu and Oporoma, since the extent of pollution was more severe on these sites and the soil profiles are similar to the polluted and unpolluted boreholes. The reduction in values of coefficient of permeability of crude oil polluted soils is due to the fact that when soil and water are mixed together, a total or complete mixture of oil and water is not easily achievable. There is usually a boundary layer of soil and water mixture present. Crude oil in soils will trap some of the water, consequently lowering the coefficient of permeability of polluted soils. Fig 2(b) illustrates how crude oil layer impedes flow of pore water thereby leading to reduction of permeability.

9.0 Conclusion

Crude oil pollution reduces the values of undrained cohesion, undrained angle of internal friction, consequently reducing the shear strength of affected soils. The only exceptions were the soil samples for Apara (the reverse being the case as a result of the fact that soils in the polluted areas were silty sand in nature). The reduction in values of undrained cohesion is as a result of the destruction of the inter-molecular forces between soil grains, while the reduction of the undrained angles of internal friction is due to the inter-grain lubrication by the greasy crude oil.

A decrease in values of between 20 – 55%, between 2.8 – 14.2 and between 11 – 35% was noticed for values of undrained cohesion, undrained angle of internal friction and shear strength of polluted soils respectively.

Approximately 11% reduction in shear strength of crude oil polluted soils from Bomu field was obtained from the calculated shear strength values above.

Correlation coefficients of 0.66 and 0.87 was obtained for unpolluted and polluted values of undrained cohesion and undrained angle of internal friction.

The result of this research therefore buttresses the need for soil remediation if buildings, oil and gas facilities and other structures are to be erected on crude oil polluted sites. It follows from this study that the foundation design of crude oil polluted soils will need to carefully consider the pollution indices established in order to ensure that the structures will withstand the intended loads. Foundation design for structures to be erected on crude oil polluted that does not consider the reduction in shear strength of such soils may result in bearing capacity failure.

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