Development of Predictive Model for Concentration Distribution of Crude Oil in Polluted Soil Medium

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Authors' contributions

This work was carried out in collaboration between the two authors. Author DKK designed the study, managed the introduction section and discussed result from the developed model. Author OOA developed the predictive model, run the simulation in MATLAB, plot the simulation results and managed literature search. Both authors read and approved the final manuscript.

Original Research Article

ABSTRACT

This research deals with the development of predictive model for the concentration distribution of Nigerian crude oil in porous soil media. Three (3) different soil media were considered: sand, loam and clay. Oil spillage has been the most prominent source of ground water contamination, so, a model has been predicted to access the risk of ground water contamination by crude oil in Niger Delta regions. The migration of crude oil in the soil is only by diffusion and this enables us to predict a model of concentration distribution of naphthalene, benzene and toluene (NBT) using an approach called Buckingham's π theorem. With the theorem, parameters that affect the migration of crude oil in the soil such as viscosity, density, porosity were considered. The predicted model results were compared with experimental results obtained from literature and it showed reasonable agreement. Simulations of different components with different soil types (sand, clay and loam) were performed and it showed that sand has the highest porosity followed by loam and least in clay. In all, Benzene shows the highest effect on the depth of soil followed by the double ringed naphthalene.

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DEFINITION OF VARIABLES

C_i = concentration of key component "i" in the hydrocarbon (kg/m³); V = Volume of hydrocarbon (m³); Q = Quantity of hydrocarbon discharged (m³/s); R = Porosity - $R_i \rightarrow 1$; D_i = Diffusion coefficient of key component (m²/s); t = Migration time (s); x = Direction of hydrocarbon migration (m); ρ_i = Density of key component (i) (kg/m³); μ_i = Viscosity of key component (i) (kg/ms); σ_i = Surface tension of key component in the hydrocarbon (kg/s²); g = gravity (m²/s); ρ_B = Bulk density of the soil (kg/m³); C_{oi} = Initial concentration of key component "i" in the hydrocarbon (kg/m³); S = maximum depth of hydrocarbon migration.

1. INTRODUCTION

Crude oil is a complete hydrocarbon predominantly consisting of aliphatic polycyclic and aromatic compounds. Petroleum products are extremely harmful for our environment because when it spills on ground surface can penetrate deeply into the ground and the soluble constituents constitute a very great threat to flora, fauna and underground water [1].

Specifically, crude oil contains constituents such as the benzene, xylene, toluene, naphthalene, anthracene and so on. Benzene is a known human carcinogen and it is identified by Occupational safety and Health Administration (OSHA) and International Agency for Research on Cancer (IARC) as group of carcinogen. Toxicity of crude oil and its fractions results from their physical and chemical properties. Also, the health risk of Volatile Organic Compounds (VOCs) such as benzene, toluene and xylene (BTX) even at low concentration have most serious effects [2].

BTX are natural constituent of crude oil containing 0.1 – 3% benzene, and 1% for toluene, xylene and naphthalene (%wt) [3]. Benzene exposure has the most serious effects. It is a volatile compound of a ring structure characteristic of homologous series of the aromatic hydrocarbon. It is a natural constituent of crude oil with the percentage share in all distillation below 1%. To reduce knocking, more hydrocarbons were added to petrol including benzene whose share rose to 5%. The areas exposed to the highest benzene contamination are filling stations and their surrounding [4,5].

An alternative approach towards modeling the transport of polycyclic aromatic hydrocarbons (PAHs) is shown in literature [6]. In the work, the authors proved the effect of adsorption upon petroleum hydrocarbons dispersion in the porous matrix containing dissolved organic matter (DOM). The dissolved organic matter present in the matrix containing silicon-dioxide (SiO_2) increases the retardation factor ($R_i > 1$) [6].

Characteristic and rate of crude oil migration are dependent on the properties of the sub-surface medium in which it is released. Porosity and permeability are the two most important media specific properties of a natural geological material such as sedimentary rocks. Hence, porosity characterizes the ability of a medium to store fluids while permeability is the rate at which the fluid passes to the next soil strata [4,7]. If the volume of crude oil spilled or released is small in relation to the porosity of the soil, then, hydrocarbons will tend to adsorb onto the soil particles and essentially the entire mass will be immobilized [8].

All aspects of the petroleum industry, from the prospecting stage to the distribution of the final products degrade the environment in one way or the other [8]. The constituents that enter the soil becomes part of the biological cycles that affect all forms of life (plants and animals) [8]. Also, shape and size of pores are of utmost importance in quantifying contaminants transport and entrapment in soil.

The difference in flow profiles of the spilled petroleum in the three soil types (sand, loam and clay) is also due to fractional wet-ability of the soil. Loamy soil with the highest organic matter and water content allow only a portion of the total surface area to be preferentially wetted by spilled petroleum [6].

Polycyclic Aromatic Hydrocarbons (PAHs) are likely to be retained in soil for many years and may even enter the aquatic environment inducing further hydrosphere pollution due to their hydrophobicity. The accumulation of multiple source PAHs in the soil may lead to the contamination of vegetables in food chains

thereby posing a great health risk to humans. However, most of previous studies focused on surface soil pollution with little attention paid to vertical distribution of contaminants [9].

Previous works have not really dealt with the parameters that affect the vertical migration of crude oil in the soil. The aim of this work is to develop a predictive model using dimensional approach (Buckingham pi (π) theorem) to predict concentration distribution of crude oil spill in different soil medium. This will go a long way to enable us determine the maximum depth a spilled petroleum will diffuse into the soil at migration time (t) from the onset of spillage.

The aim of this work is to predict using a model, the concentration distribution of crude oil in different soil medium (sand, loam and clay). The model will be predicted using dimensional approach and solved using Buckingham's theorems. This will be used to confirm the hypothesis of crude oil penetrating the ground following diffusive model of hydrocarbon contaminants migration.

2. MATERIALS AND METHODS

Distribution of Nigeria crude oil migration in the soil has been discussed by many authors [3,9]. Nigeria crude being free of sulphur and relatively low in benzene, toluene xylene (BTX) or Polycyclic Aromatic Hydrocarbons (PAHs) constituents are considered. A more precise and different approach is needed to explain the concentration distribution of crude oil in the soil.

2.1 Model Development

Fick's law was used in formulating a diffusive model of hydrocarbon transport in the hydrocarbon-sand system. When a fluid flow diffuses vertically in the soil, taking one end of the flow as origin and the other end as the direction of flow (z – direction) as shown in Fig. 1. The continuity equation for the mass balance was used to develop a mathematical model to predict the concentrations of crude oil in soil medium.

Model assumptions

The following assumptions were made in the derivation of the model

1. Diffusion is uni-directional (downward spread only)

2. No reaction between hydrocarbon and soil constituents.
3. Sand, loam and clay soil were considered
4. Naphthalene, benzene and toluene were chosen as prominent contaminants based on Nigeria crude oil; there high toxicity and relatively good solubility.
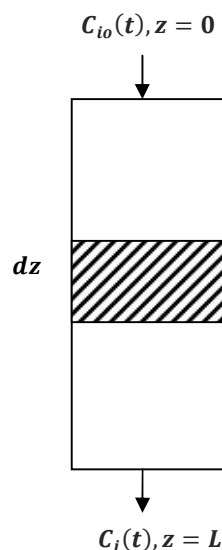
$$C_{io}(t), z = 0$$

$$dz$$

$$C_i(t), z = L$$

Fig. 1. Hypothetical representation of crude oil migration in one-dimension

The crude oil is assumed to spread from a region of higher concentration to lower concentration. The material balance for the crude oil migration in the soil in 3-dimension incorporating Fick's law of diffusion is given as;

$$\frac{\partial c_i}{\partial t} = -D_i \left(\frac{\partial^2 c_i}{\partial x^2} + \frac{\partial^2 c_i}{\partial y^2} + \frac{\partial^2 c_i}{\partial z^2} \right) \tag{1}$$

Although, spatial distribution of crude oil in soil medium both in horizontal and vertical direction is a function of the quantity of spilled crude oil. The more the volume of the spilled petroleum, the greater the distance migrated by the oil. This effect is more evident in the vertical downward spread as the horizontal spread converges within a few centimeters often spill irrespective of the volume spilled. Therefore, in this model, crude oil migrates into the soil vertically (unidirectional) by gravity. Slope dependent form of the 3-dimensional Fick's equation (1) is negligible. It is assumed that the model does not take into consideration quasi-random motions of the soil particles in which the crude oil migrates.

Therefore, approximating equation (1) into one-dimension, concentration gradients in y and z directions are negligible since the major consideration is to determine the vertical distribution of crude oil as it affects water-table. One-directional Fickian's diffusion equation is represented in equation (2).

Assuming the concentration of the hydrocarbon diffusing vertically into the soil at any time t at depth x from the starting point of diffusion to be $C_i(x, t)$. Fick's law equation is proposed thus;

$$\frac{\partial C_i}{\partial t} = D_i \frac{\partial^2 C_i}{\partial x^2} \tag{2}$$

The diffusion equation in equation (2) is of fundamental importance in environmental fluid mechanics. In this model, we seek a solution for the diffusion of crude oil on vertically in time due to vertical migration alone.

C_i is the initial concentration of hydrocarbon species "i", i represents components of the hydrocarbon (Benzene, Toluene and Naphthalene). x represents the depth of migration, and D_i is diffusion coefficient of key component and t is the migration time.

Equation (2) is a Partial Differential Equation (PDE) which resembles that of heat equation with a solution of $C_i(x,t)$. Using:

$$C_i(x,t) = X(x)C(t \tag{3}$$

where X is a function of x and C is a function of t

Defining the boundary conditions:

As one-dimensional, (gradients of the other two axes equals zero) unsteady assumption as been made, two boundary conditions and one initial condition are required. As a boundary condition, it is imposed that the concentration at (+/-) infinity remains zero. The initial condition is that the crude oil is assumed to spread uniformly across the cross section of soil (sand, clay and loam) in x- direction alone.

$$C_i(x,0) = 0 \quad for \ 0 < x < S$$
$$C_{oi}(0,t) = C_{oi} \quad for \ t \geq 0$$
$$\frac{\partial C_i}{\partial x} = 0 \quad for \ t > 0, x = S$$

Differentiating equation (3), applying the boundary conditions and substituting in equation (1) gives;

$$C_i(x,t) = \frac{C_{oi}S}{(4\pi D_i t)^{1/2}} \exp\left(\frac{-x^2}{4D_i t}\right) \tag{4}$$

Where, S is the maximum depth of migration and C_{oi} is the initial concentration of species "i". From the point of spillage, the maximum depth at which hydrocarbon can penetrate at time 't' can be determined. With this, the extent of the effect it has on ground water can be promptly attended to.

Dimensional approach

The transport of crude oil is most influenced by concentration, density, quantity, bulk density, viscosity, surface tension and gravity.

Buckingham's pi theorem assumes m-dimensional variables and n set of different dimensions (Length, Mass and Time). The theorem states that there are 'm-n' independent non-dimensional groups that can be formed from the governing variables [10].

In this model, there are six (6) dimensional variables and three (3) set of dimensions. A quantity π is to be determined in terms of six (6) measurable quantities. Where "f" is an unknown function of the quantities.

This model can be mathematically dimensioned as;

$$\pi = f(C_i, Q, \rho, \mu, g, \sigma, V) \tag{5}$$

There exist three (3) dimensional quantities (M, L, and T) with seven (7) variables (concentration and bulk density has the same dimension). With this, a unique solution cannot be found within variables. So, the Buckingham π theorem is applicable.

Assuming,

$$f(\pi) = 0 \tag{6}$$

$$\pi = C_i^{a_1} Q^{a_2} \mu^{a_3} \sigma^{a_4} g^{a_5} V^{a_6} \tag{7}$$

Representing π with any of the measurable quantities, the dimensionless quantity denoted by [π] is a product of powers of the fundamental dimensions as shown in equation (7).

The dimensional vector of the measurable quantities in order of length, mass and time (L, M, T) is shown in Table 1;

Table 1. Dimensional vector of the measurable quantities

Quantities	Units	Dimension
C_i	Kg/m^3	$L^{-3}M^1T^0$
Q	m^3/s	$L^3M^0T^{-1}$
μ	Kg/m.s	$L^{-1}M^1T^{-1}$
σ	Kg/s^2	$L^0M^1T^{-2}$
g	m/s^2	$L^1M^0T^{-2}$
V	m^3	$L^3M^0T^0$
ρ_b	Kg/m^3	$L^{-3}M^1T^0$
R	-	-

Forming a dimensional matrix 'M' from the quantities and variables gives (8).

Row – Dimension M, T, L
Column – Dimensional variables

$$M = \begin{bmatrix} -3 & 3 & -1 & 0 & 1 & 3 \\ 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & -1 & -1 & -2 & -2 & 0 \end{bmatrix} \quad (8)$$

A kernel of "Ma"; matrix M with exponential coefficients a_1, a_2 a_3...a_7 in the sets of equations k is a set;

A quantity $[\pi]$ is said to be dimensionless if it is equal to 1. Solving for the exponents (a1, a2, a3, a4, a5, a6) in equation (7) using MATLAB compiler, gives a vector form as shown in equation (9.1). Also, Gauss Jordan elimination was performed on "M" to get its row echelon form. A product of the reduced row echelon form of "M" on vector "a" yield the zero vector [0, 0].

$$N(M) = Null(M) = Ker(M = \{x \in k^n : Mx = 0\} \quad (9)$$

Where *"0"* denotes the zero vector with "m" components. The matrix equation Ma = 0 is equivalent to a homogeneous system of linear equations used to form dimensional matrix "M" in equation (8) [10].

$$So, \ a = \begin{bmatrix} 1 \\ 1 \\ -1 \\ -1 \\ 1 \\ -1 \end{bmatrix} \quad (9.1)$$

In fundamental terms,

$$\pi = C_iQ\sigma R(Vg\mu\rho_b)^{-1} = 1 \quad (10)$$

$$\pi = \frac{C_iQ\sigma R}{Vg\mu\rho_b} \quad (11)$$

Substituting (3) in (11) gives the developed model in dimensionless approach.

$$\pi = \frac{C_{oi}QR\sigma S}{Vg\mu\rho_b(4\pi D_it)^{1/2}} \exp\left(\frac{-x^2}{4D_it}\right) \quad (12)$$

π is the concentration in dimensionless term, R is the porosity of soil, σ is the surface tension of hydrocarbon species, Q is the quantity of discharged hydrocarbon, ρ_b is the bulk density of soil, g is the acceleration due to gravity, μ is the viscosity of hydrocarbon species and V is the volume of discharged hydrocarbon.

2.2 Operating Parameters

Table 2 shows the initial concentration of hydrocarbon species.

Table 2. Initial concentration (C_{oi}) of hydrocarbon species (kg/m^3)

Naphthalene	Benzene	Toluene	Reference
1380	1500	1420	[11]

Table 3 shows the physiochemical properties of the hydrocarbon species (Naphthalene, Benzene and Toluene) such as diffusion coefficient, viscosity, surface tension and density obtained from literatures. Also, Table 4 shows the physiochemical properties of the soil medium (clay, sand and loam). These parameters were substituted in (12) to obtain the dimensionless concentration of the hydrocarbon as it migrates vertically along the depth of the soil.

3. RESULTS AND DISCUSSION

Tables 5, 6 and 7 show that the dimensionless concentration of naphthalene, benzene and toluene obtained from equation (12). The migration days used for simulation were 1, 2, 5, 8 and 12 respectively. The result in Tables 5, 6 and 7 were obtained at a crude oil discharge rate of 2 m^3/s. When the results obtained from the predictive model were compared with that of literature [12] at the different migration time, both results showed that 3 m was the maximum depth of crude oil migration. Also, the trend of graphs obtained from results of the predicted model is similar with that of the literature [12].

As depicted in Figs. 1 and 2, when the predictive model results were compared with that of

literature [12], it was also evident that the concentration distribution at migration time of 8 days and above show a slow concentration distribution of crude oil into the soil while migration time below 8 days showed a rapid concentration distribution of crude oil into the soil. Also at low migration time, crude oil does not migrate to a maximum depth of 3 m while at long migration time; the effect of the crude oil could still be felt at maximum depth of migration.

Figs. 1 (a, b, c) and 2 (a, b, c) depict the comparison between the model prediction of equations (4 and 12) for the actual concentration and dimensionless concentration respectively with that of the experimental result [12]. From the figures, it is obviously seen that concentration of benzene and toluene decrease along the depth of the soil. These results are in agreement with previous work done [16].

From Fig. 1a, at migration time of 1, 4 and 8 days, the concentration of benzene in Kg/m^3

decreases from 7299, 3649, and 2580 at 0 m to 372.2, 1734, 1779 at 0.6m respectively. When compared with the result of experimental data from Fig. 1c at migration time of 1, 4 and 8 days, the concentration in Kg/m^3 decreases from 94.5, 49.5, 34 at 0m to 0.005,13 and 22 at 0.6 m respectively. This trend is also observed for toluene concentration from equation (4). The percentage decrease in concentration of the model results and that of the experimental results was calculated to be 4% at all the migration time from 0 to 0.6 m.

From the simulation results, it was evident that the extent to which spilled oil spreads along the soil surface and migrates downwards depends on the quantity of oil spilled, the physical properties of spilled oil (density and viscosity, porosity). At longer migration time, the crude oil will migrate deeply into the soil under the influence of gravity and capillary force until it reaches water-table.

Table 3. Physiochemical parameters of the hydrocarbon species

Parameters	Symbols	Hydrocarbon species			Units	Reference
		Naphthalene	Benzene	Tolune		
Diffusion coefficient	D_i	3.0×10^{-7}	3.5×10^{-7}	3.8×10^{-7}	m^2/s	[12]
Viscosity	μ	2.3×10^{-3}	0.61×10^{-3}	1.18×10^{-3}	kg/ms	[13]
Surface tension	σ	29.14×10^{-3}	28.88×10^{-3}	28.40×10^{-3}	kg/s^2	[14]
Density	ρ	820	873	862	Kg/m^3	[11]

Table 4. Physiochemical parameters of the soil medium

Parameters	Symbols	Soil type			Units	Reference
		Sand	Loam	Clay		
Bulk density	ρ_β	1600	1400	1100	kg/m^3	[15]
Porosity	R	0.40	0.47	0.58	-	[15]

Table 5. Naphthalene dimensionless concentration (sandy soil at 2 m^3/s discharge)

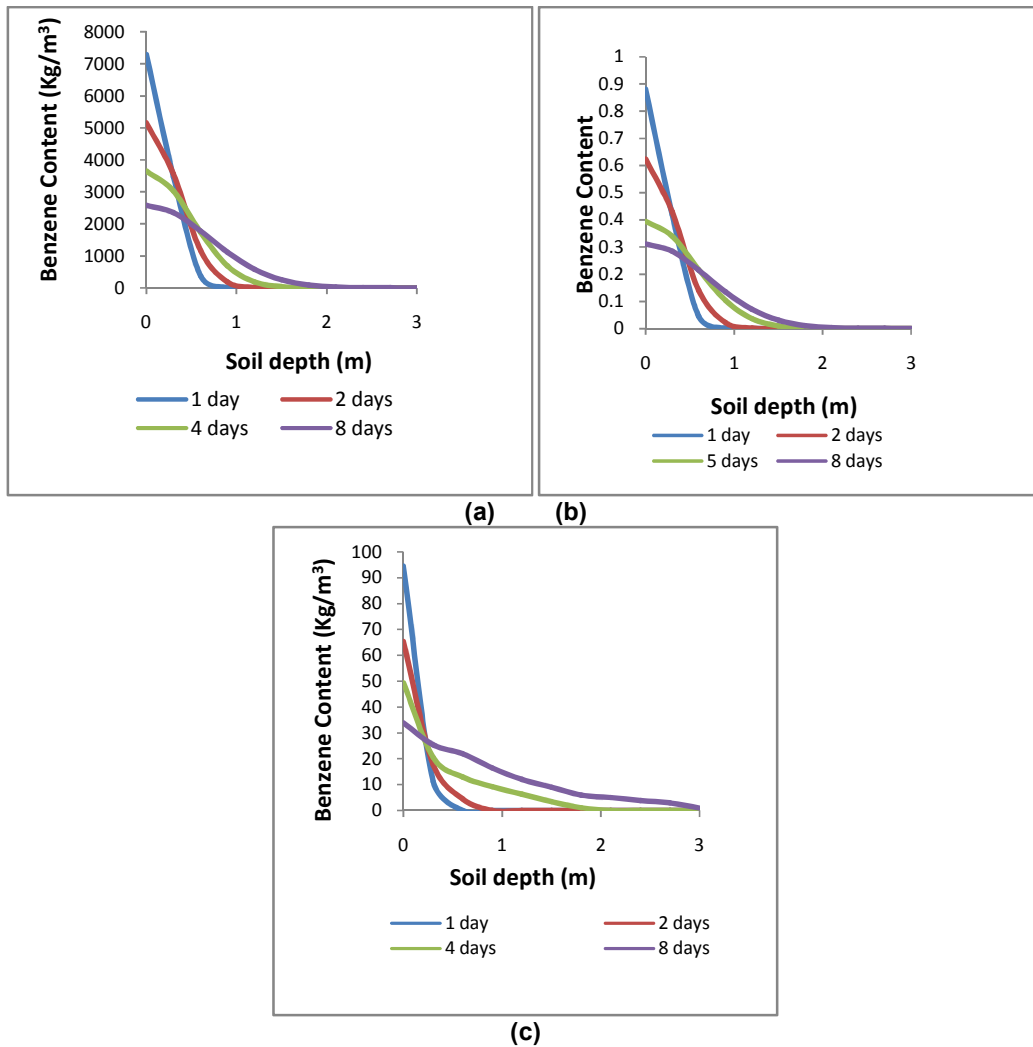|	Dimensionless constant in relation to variables				
X(m)	1 day	2 days	5 days	8 days	12 days
0	0.256	0.181	0.114	0.090	0.074
0.3	0.107	0.117	0.096	0.081	0.069
0.6	0.008	0.032	0.057	0.059	0.055
0.9	0	0.004	0.024	0.034	0.039
1.2	0	0	0.007	0.015	0.023
1.5	0	0	0.002	0.006	0.012
1.8	0	0	0	0.002	0.005
2.1	0	0	0	0	0.002
2.4	0	0	0	0	0.001
2.7	0	0	0	0	0
3	0	0	0	0	0

Fig. 1. Comparison of the; (a) benzene concentration (Kg/m^3) from equation (4) (b) benzene dimensionless concentration from equation (12) (c) benzene concentration (Kg/m^3) from experiment [12]

Table 6. Benzene dimensionless concentration (sandy soil at 2 m^3/s discharge)

X(m)	Dimensionless constant in relation to variables				
	1 day	2 days	5 days	8 days	12 days
0	0.882	0.623	0.394	0.312	0.255
0.3	0.419	0.429	0.340	0.284	0.239
0.6	0.045	0.140	0.217	0.215	0.199
0.9	0.001	0.022	0.103	0.135	0.146
1.2	0	0.002	0.037	0.070	0.094
1.5	0	0	0.010	0.030	0.054
1.8	0	0	0.002	0.011	0.027
2.1	0	0	0	0.003	0.012
2.4	0	0	0	0	0.005
2.7	0	0	0	0	0.002
3	0	0	0	0	0

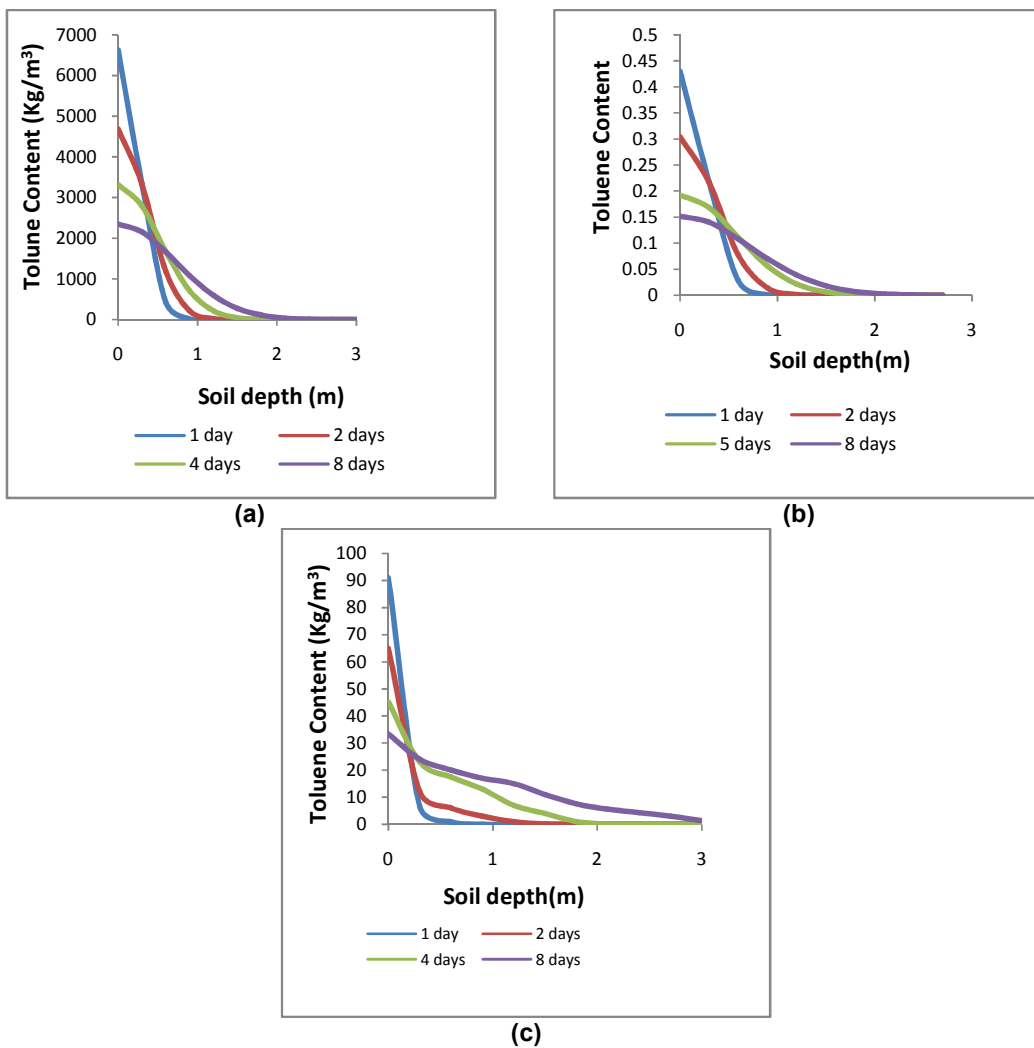**Table 7. Toluene dimensionless concentration (sand soil at 2m³/s discharge)**

x(m)	1 day	2 days	5 days	8 days	12 days
0	0.430	0.304	0.192	0.152	0.124
0.3	0.216	0.216	0.168	0.140	0.117
0.6	0.027	0.077	0.111	0.108	0.099
0.9	0	0.014	0.056	0.070	0.074
1.2	0	0.001	0.022	0.039	0.049
1.5	0	0	0.006	0.018	0.030
1.8	0	0	0.001	0.007	0.016
2.1	0	0	0	0.002	0.008
2.4	0	0	0	0.001	0.003
2.7	0	0	0	0	0.001
3	0	0	0	0	0

(a)

(b)

(c)

**Fig. 2. Comparison of the; (a) toluene concentration (Kg/m³) from equation (4)
(b) toluene dimensionless concentration from equation (12) (c) toluene concentration (Kg/m³)
from experiment [12]**

For different soil (sandy, loam and clay) migration speed differs. It can be easily noticed from the result that the distribution of crude oil was slow for clay compared to sand. The concentration was seen to decrease as it diffuses into the soil.

Fig. 3 shows the distribution of naphthalene content of the hydrocarbon as it migrates vertically downward along the depth of the soil medium at low hydrocarbon discharge of 2 m^3/s. The dimensionless concentration is seen to range from 0.255 - 0. From the figure, it is obvious that concentration decreases along the depth of the soil. Also, migration time of 12 days have a larger effect on the soil.

Fig. 4 shows the naphthalene content distribution along the depth of sandy soil. The simulation was done for 1,2,5, 8 and 12 days respectively. A discharge of 5m^3/s shows that the higher the discharge, the higher the extent of migration. Comparing Figs. 1 and 2, the only changed parameter is the discharge. The concentration of naphthalene content at a depth of 3 m (0.000211) is lower than that of 5 m^3/s discharge (0.00527). Summarily, the higher the flow rate and migration time, the higher the concentration impact on the depth of soil.

Fig. 5 displays the distribution of naphthalene content of hydrocarbon (sandy, loamy and clay) at a flow rate of 5 m^3/s and migration time of 5 days. The above showed that sandy soil is more porous compared to loamy and clay. Sandy soil

has highest porosity and lower bulk density followed by clay soil and then loamy soil. Therefore, the decreasing order of porosity is sandy- loamy-clay. This means that clay soil medium is the least porous. This is obvious since at a depth of 1.5 m, the dimensionless concentration of sand, loam and clay are 0.0037, 0.0053 and 0.0078 respectively.

Fig. 6 depicts the distribution of benzene content on sandy soil medium at a flow rate of 2 m^3/s in relation to migration time. The same with naphthalene content at low discharge, the dimensionless concentration of benzene ranges from 0.88-0.000516 (0.1 m at 1 day to 3 m at 12 days). The extent of migration increases with migration time but reduces at the surface of the soil. Benzene has a larger effect on the polluted soil medium than naphthalene. At low migration time, the crude oil would not have enough time to migrate deeply into the soil medium. So, the longer the migration time, the deeper the crude oil diffuses into the soil.

Fig. 7 displays the distribution of benzene content of hydrocarbon on sandy soil at a discharge of 5 m^3/s in relation to migration time. The result shows that higher discharge has more impact on sandy soil. At lower discharge, benzene content ranges from (0.88-0.001) at 1 day migration time and (0.25-0.00516) at a depth of 3 m, also 1 day migration time. When higher discharge of 5 m^3/s was used. The concentration of benzene was highest and reduces as migration time increases but has
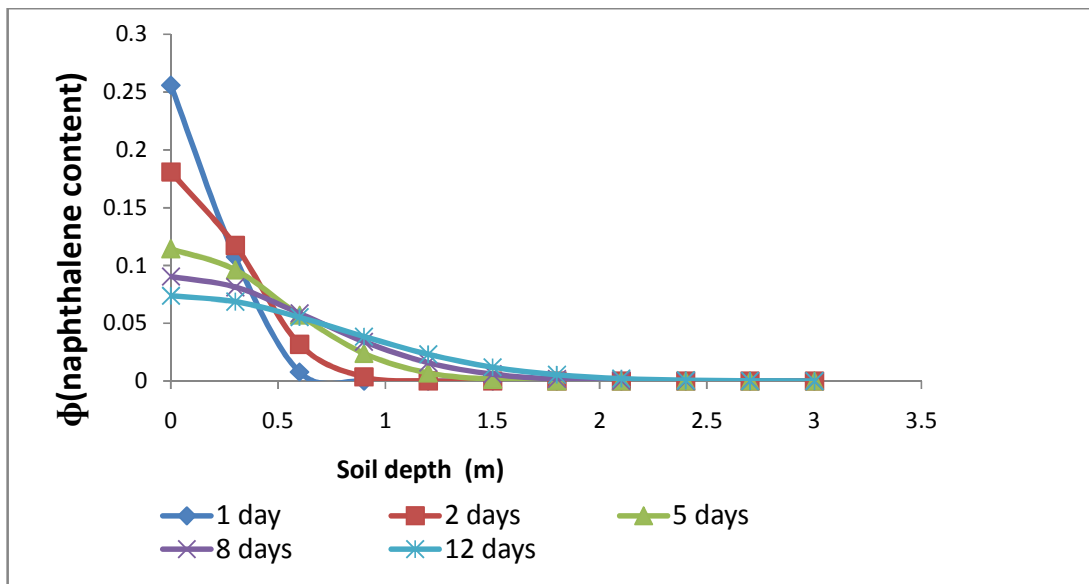

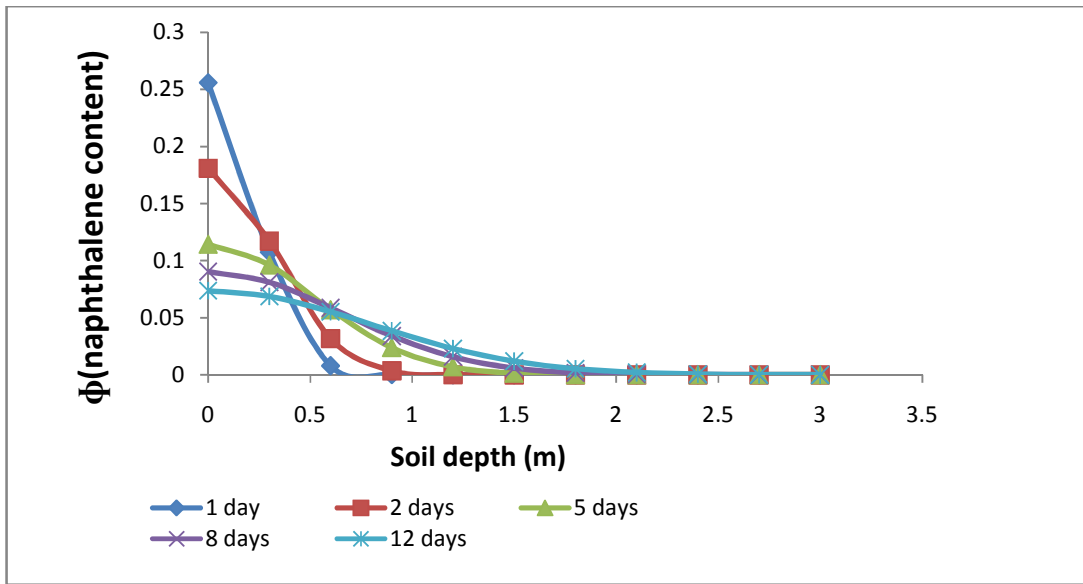**Fig. 3. Distribution of naphthalene content in relation to migration time**

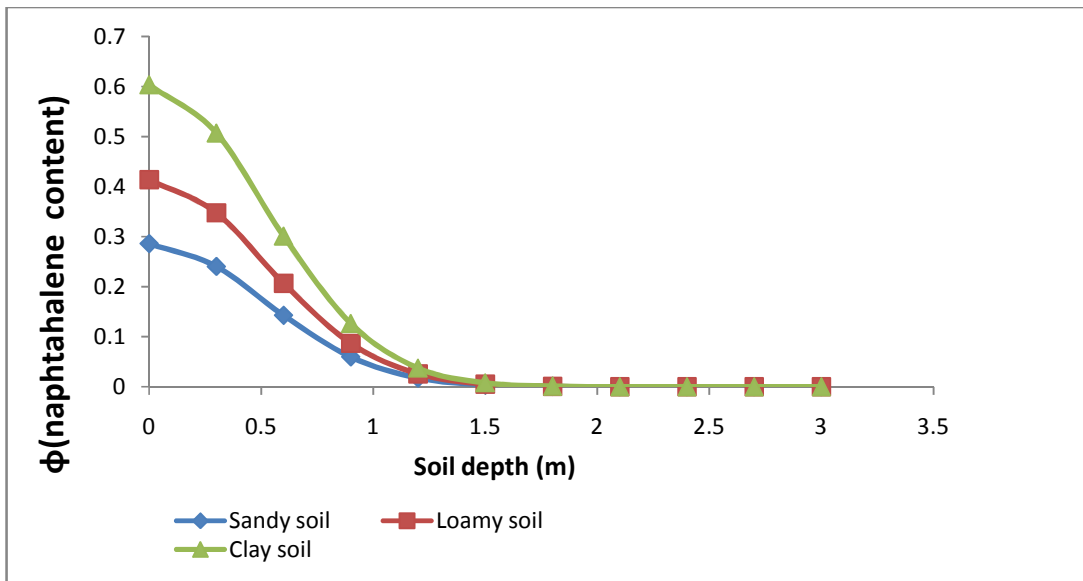**Fig. 4. Distribution of naphthalene content in relation to migration time**

Fig. 5. Distribution of naphthalene content in relation to soil types at 5 days migration time

more effect on the depth of migration. This means that out of the three (3) species of crude oil considered, benzene has the highest effect on the soil despite its low diffusion coefficient. This is possibly as a result of its high concentration in the crude oil.

Fig. 8 depicts the simulation result of benzene content distribution at discharge of 5 m3/s, migration time of 5 days in relation to soil types (sandy, loamy and clay). It is obvious from the graph that sandy soil is readily porous, followed by loamy and then clay being the least porous. This is because the particles of sandy soil are not as compacted as loam and clay, leading to its high permeability. Loamy soil with the highest organic matter allows only a portion of the total surface area to be prefentially wetted by spilled petroleum, hence low concentration of the petroleum in the soil compared to clay and sand soil.
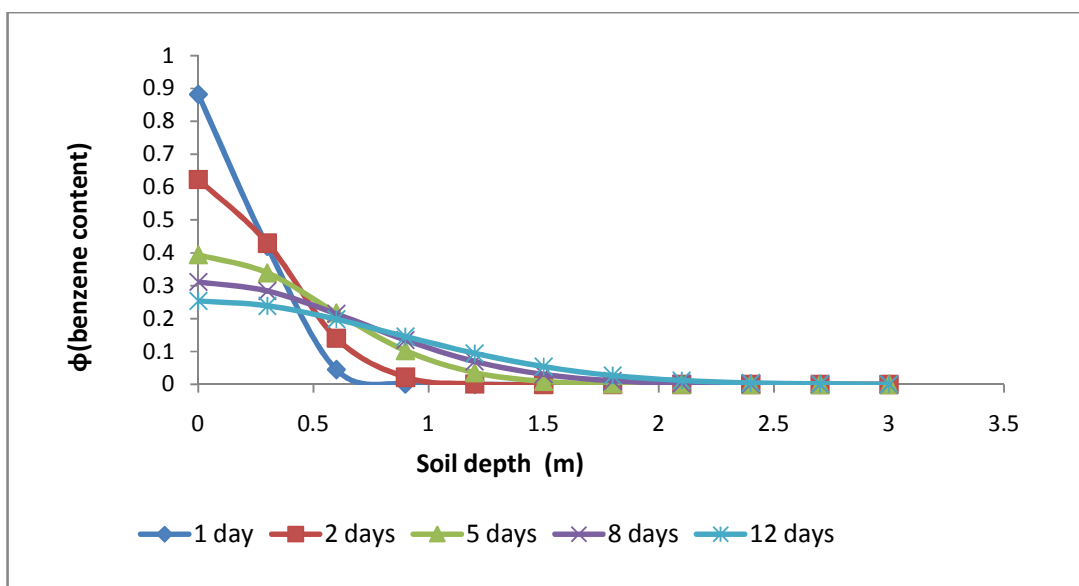
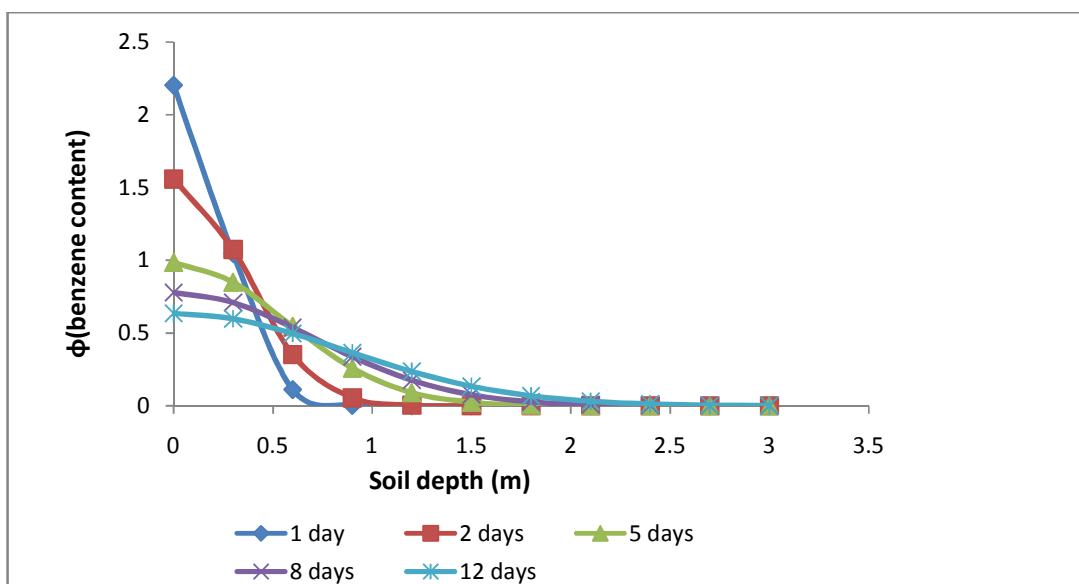**Fig. 6. Distribution of benzene content in relation to migration time**

Fig. 7. Distribution of benzene content in relation to migration time

Fig. 9 shows the distribution of toluene content against migration depth in sandy soil at a discharge of 2 m^3/s. From the result, at 0.1 m, concentration in dimensionless constant ranges from (0.43 - 0.124) to (7.43E-31-0.000411) at a depth of 3 m. This depicts that toluene content of hydrocarbon decreases along the depth of the soil. This is because, the volume of the crude oil decreases as it diffuses into the soil thereby reducing concentration.

Fig. 10 shows the distribution of toluene content in relation to migration time. This was simulated at higher flow rate which can be seen having greater impact in the soil. As can be seen from the graph, at migration time of 1 and 2 days, it has not had serious effect on the soil (in terms of depth). It has not diffuse deep into the soil but as the time increases, the effect is felt deep down the depth of the soil. For all the tested species of hydrocarbon, the effect of concentration of pollutants is greatest at migration time of 12 days.
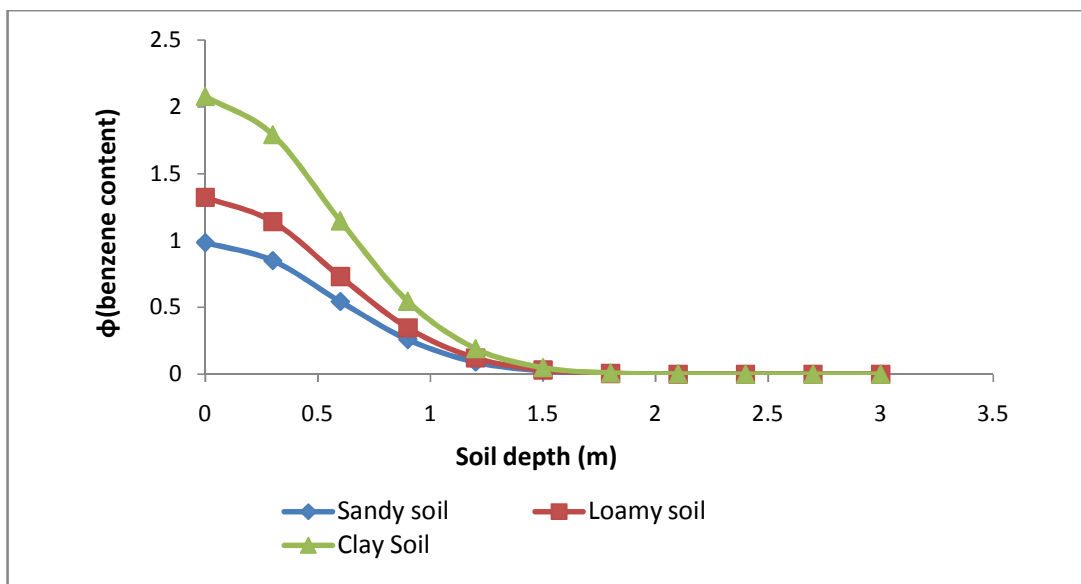
Fig. 8. Distribution of benzene content in relation to soil types at 5 days migration time
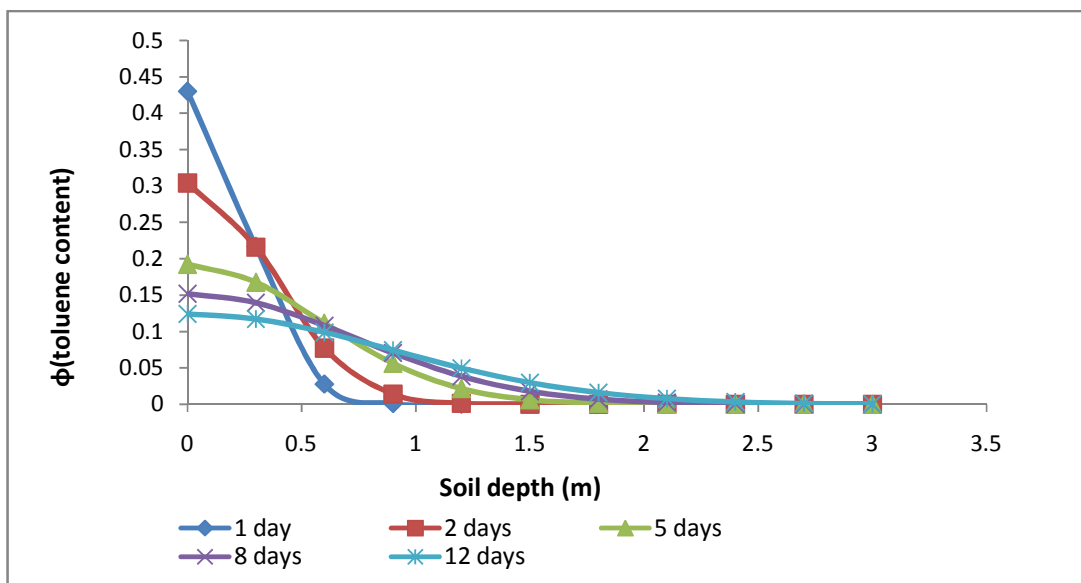

Fig. 9. Distribution of toluene content against migration depth

Generally, Benzene showed the highest effect on the hydrocarbon mixture followed by toluene and naphthalene. To investigate the concentration distribution of crude oil in the soil, the residence time of penetration is a function of the depth of distribution. Also, the quality of leakage from the source to the soil is also very crucial. These are evident from simulation results knowing the impact of the leaked crude oil in the soil.
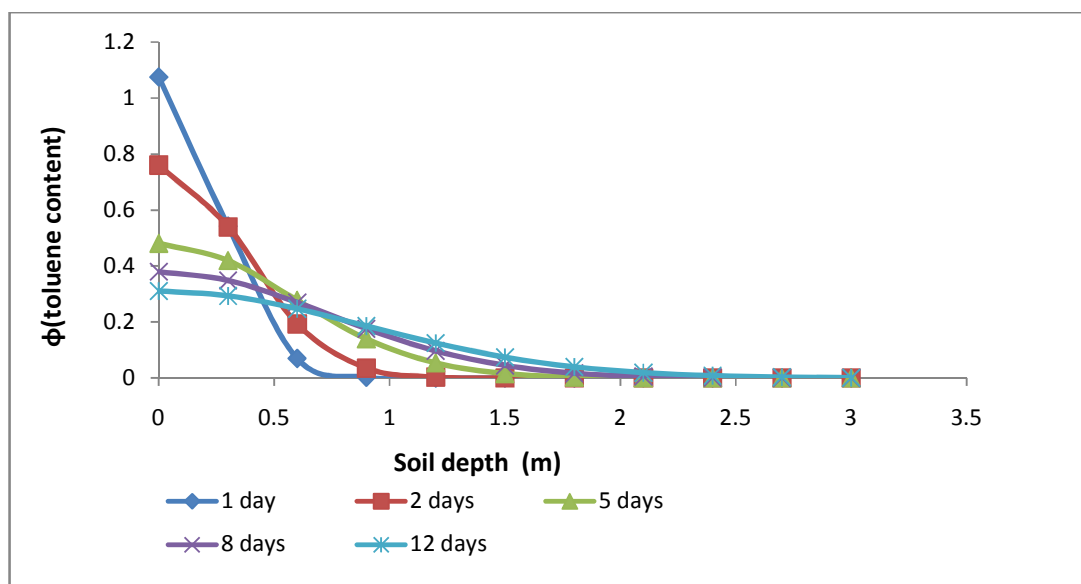
Fig. 10. Distribution of toluene content in relation to soil types at 5 days migration time

4. CONCLUSION

This work has been able to develop a predictive model for the concentration distribution of crude oil in polluted soil media. With this, the maximum depth spilled oil will diffuse through the soil at migration time "*t*" from the onset of leakage can be predicted. The results obtained from the predictive models were compared with that of literature and there was reasonable agreement. So, preventive measures (a proactive approach) should be commenced as soon as possible to assure that oil spillage areas would not be a threat to human health.

The predicted model for concentration distribution of crude oil in porous soil media using Buckingham π model was achieved. Predicting the concentration from Fick's law directly will not effectively take into account parameters that affect the molecular diffusion of hydrocarbon in the soil, thereby necessitating the introduction of the dimensionless approach. The concentration of considered species in dimensionless unit was seen to reduce as the crude oil diffuses down the soil. Simulating the different parameters involved in the developed model showed that the transportation of spilled oil by molecular diffusion is a function of distance migrated, quantity of spilled petroleum, density, surface tension, gravity, viscosity, porosity, bulk density of the soil and time of migration. The result of this work gave an insight of the transport behavior- of spilled hydrocarbon on sub-surface.

It is likely that ground water would be contaminated by vertical migration of petroleum by diffusion if proper remedial action is not carried out immediately after spill to restore the affect area to base-line level.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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