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Permeability Model for Nigerian Oil Sand as Candidate CO_2 Storage Reservoir

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Abstract

This research examines the challenges associated with storing captured CO_2 in the Niger-Delta reservoirs by examining the effect of the stored gas on the reservoir rock sample. Mitigation against increasing CO_2 in the atmosphere is uppermost in environmental research due to its negative effects and therefore there is need to explore all possible reservoirs, apart from abandoned crude oil reservoirs, for CO_2 storage. In this research, a model was developed to study permeability variation during CO_2 injection to oil sand as a candidate CO_2 storage reservoir. Four existing permeability models of Tixier, Timur, Coates-Dumanoir and Aigbedion were employed together with a proposed model. The proposed model was a combination of irreducible water saturation equation from Timur model and the Coates-Dumanoir permeability equation. The proposed model took cognizance of changing porosity phases, since the injected CO_2 is reactive and affects the properties of the reservoir rock. The model equation obtained is the model gave permeability value ranging from 16.94 to 2.74 mD for Imeri oil sand. In comparison, the Timur model gave permeability values from 1.45 to 0.002 mD; Tixier value ranges from 42.85 to 0.01 mD; Coates-Dumanoir value of 287.72 to 7.49 mD while value given by Aigbedion rangs from 9.01 to 2.6 mD. In the course of the research it was discovered that Imeri oil sand formation, though has very high porosity which could be a pointer to early stage leakage, is highly reactive with the injected CO_2. This reactivity is a good condition for permanent storage of the injected gas and is therefore recommended, with reservation, as a potential CO_2 storage reservoir. The proposed model will also give the expected CO_2 gas mobility with increasing period of injection.

Key words: CO_2 storage; Oil sand; Porosity variation; Permeability; Permeability model

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INTRODUCTION

Investigation was made of the possibility of CO_2 storage in the Nigerian oil sand sub-surface as candidate CO_2 storage reservoir adjacent to Egbin, Omotosho and Olorunsogo power generation plants and the Lagos/Ogun industrial complex in Nigeria. This is because the power plants and the industrial complex are possible CO_2 captured sources. The research was laboratory based. The instability in the reservoir structure after CO_2 storage was investigated by considering the possibility of alteration of the porosity.

Some studies proved that biofuels are carbon pollutants just like the fossil fuel[1] although they have the advantage of less pollution than the equivalent fossil fuel. It was discovered that ethanol made from corn has CO_2 emissions about 50 percent lower than those of the corresponding weight of gasoline. This ascerttion is not conclusive. This is because pollution rate comparison is relative, and is based on the fact that equal amount of fuels, been compared, are required for same purpose. If the amount of biofuel, like ethanol, required is twice that of equivalent fossil fuel, both will all end up with the same amount of pollution.

Every country contributed to CO_2 emission and yet not all have abandoned oil reservoir for CO_2 storage. This necessitated the consideration of other readily available potential CO_2 storage reservoirs, such as oil sand, as a potential CO_2 storage reservoirs[2]. This is due to the fact that oil sand vast deposit abound in the world. Moreover, Ehlig-Economides and Economides estimated from calculations that the volume of CO_2, either in liquid or supercritical gas form, to be disposed cannot exceed more than 1% of the available oil reservoir pore space[3]. Hence, the need to look beyond abandoned oil reservoirs and consider other underground rocks that can serve as potential storage facility.

1. EXPERIMENTAL CONSIDERATIONS/ ASSUMPTIONS

Assumptions were made on the possibility of a variation in reservoir porosity of the oil sand with CO_2 injection. This experiment was carried out bearing in mind the presence of five thermal power generation plants located within a 70 km radius of the deposit, which are regarded as industrial CO_2 capture sources.

2. LIMITATIONS OF RESEARCH

The limitation in this research is the in ability to attain very high pressure, which is the condition for deep wells. The 40 ^oC (104 ^oF) temperature and 8,270 KN/m^2 (1,200 psi) pressure used represented shallow wells in that field. The oil sand used in this research is from shallow depth of an outcrop at Imeri village, Ijebu east, Ogun State, Nigeria. Though, two boreholes were previously sunk by Nigerian Federal Government with only one partially successful, yet there were no available rock samples from the boreholes due to non-preservation of the drilled samples. Hence, this research used shallow depth samples as a representation that will give a pointer to what is to be expected at this reservoir, with respect to effects of CO_2 contact with the oil sand reservoir rock during the gas storage.

3. ANALYSIS EQUIPMENT

The analysis was carried out with Compressed CO_2 gas of over 90% purity, core holder, Delta 17-959 L core drilling machine, porosimeter and S-series Atomic Absorption Spectrometer (AAS). CO_2 gas was employed to replace the N_2 gas normally used for porosity experiment so that the core samples would not be contaminated with nitrogen but with the desired CO_2.

The procedure followed is as follows:

a. Experimental determination of variation of porosity of Imeri oilsand with time as CO_2 is injected. This injection of CO_2 gas into Imeri oil sand serves as a representation of the sub-surface rock underlining possible sources of CO_2 capture candidates such as Olorunsogo I and II and Omotosho thermal power generation plants and various cement complexes at Papalanto/Ibesse axis.

b. Experimental determination of the irreducible water saturation for Imeri oilsand using the drying rate method.

c. AAS analysis of the Imeri oilsand to determine the heavy metal composition as a possible determination of metals involved in reaction with injected CO_2 gas.

d. Permeability modelling for the Imeri oil sand samples. The steps for proposed permeability model with time of CO_2 injection is as follows:

For the permeability computation, porosity-time plots from measured data were made.

(a) Best-fit curves/lines and equations for the plots were obtained.

(b) Average porosity was computed giving an average porosity variation with time.

(c) With the average porosity, a Modified Coates-Dumanoir permeability was computed with the Timur's S_{wirr}.

(d) Best fit curves and equations from the Modified Coates-Dumanoir permeability curve were obtained. This described the permeability variation with time of CO_2 injection.

The porosimeter was calibrated in order to have accurate determination of the porosity values. With the calibration, the expected maximum error reading from the Porosimeter is $\pm$ 0.259%.

In the research, two Imeri oil sand samples were used. The Imeri oil sand sample 1 was used for the permeability modeling while sample 2 was used to study the observed change in compressive strength with CO_2 injection. Imeri oil sand sample 1 was used for the permeability model analysis during CO_2 injection and storage in the oil sand.

4. RESULTS

It was observed that the porosity changes during CO_2 injection is in phases (Figure 1). It is expected that the two major factors that can influence porosity variation on injection of CO_2 is the pressure of injection and also reaction between the injected gas and the formation rock. In this research, injection pressure was kept at 1,200 psi, so that its effect on the rock porosity is minimized and the reaction of the rock with the injected gas will then have the dominant effect on the porosity variation. This is because, the effect of pressure of injection will mostly be felt at the rock's environment near the point of injection while away from this point, there is going to be a minimal pressure differential between injection pressure and the formation pressure, and so the porosity variation will actually be determined by some other factors apart from the injection pressure factor.

There was 49.52% reduction in the porosity from high value of 75.83% to 26.31% at the end of 20 days (Figure 2). The initial high porosity must have been due to the fact that the oil sand existed together with large water mass.

Table 1
Measured Porosity for Imeri Oil Sand 2

DAY	Grain volume	Corrected porosity
1	10.08427	0.7583
2	6.9568	0.7564
3	7.738667	0.6997
8	11.9412	0.6685
9	4.924418	0.6076
12	14.2053	0.6234
20	32.29856	0.2631

Note. Bulk volume was 48.7cc and Porosimeter constant was 58.64.

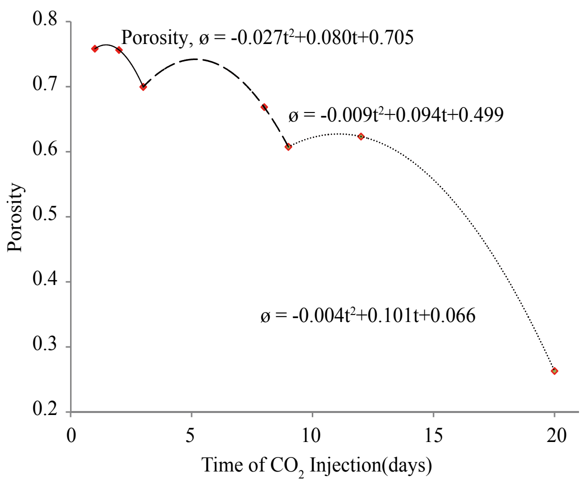

Figure 1
Phases of Porosity Variation With Time of CO_2 Injection for Imeri Oil Sand 2

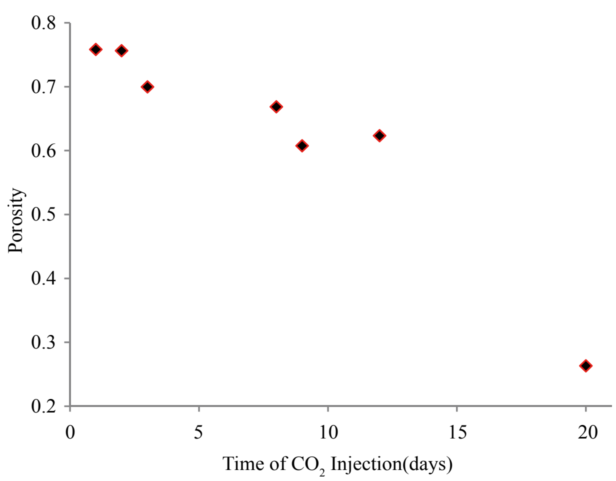

Figure 2
Porosity Variation for Imeri Oil sand Sample 2 With Time of CO_2 Injection

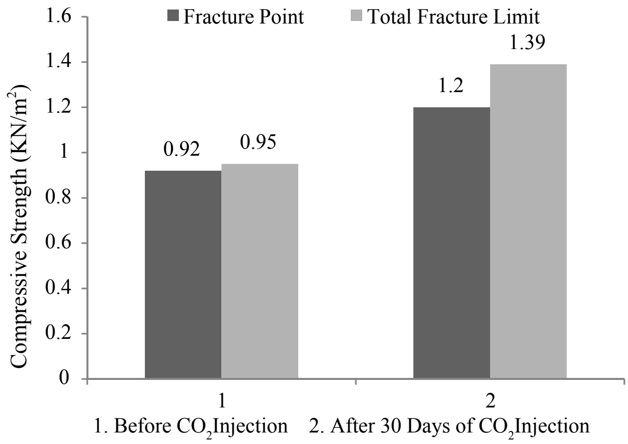

Figure 3
Measured Compressive Strength of Imeri Oil Sand Sample 2 Before and After CO_2 Injection

For the Imeri oil sand sample 2 that was used for the study of the compressive strength, the porosity variation trend was also noted. This observed reduction in the measured porosity after the 16^{th} day could be attributed to the observed hardening of the core sample after 30 days of CO_2 injection. This was also confirmed by increase in the measured compressive strength (Figure 3). Physical observation of the oil sand core outer surface showed a more slippery surface which is believed to have resulted in formation of seals of some sort that could have resulted into the reduction in measured porosity. The physical hardening of the oil sand core sample resulted in a 30.43% increase in the measured compressive strength of the core after 30 days of contamination with CO_2.

5. PERMEABILITY MODELLING

In order to carry out the permeability modeling, irreducible water saturations, S_{wirr} were computed with the Tixier, Timur and Coates-Dumanoir models. The most accurate being Timur S_{wirr} was then applied in Coates-Dumanoir model to obtain a proposed model (modified Coates-Dumanoir model).

In all the computations, it was observed that the Aigbedion model[4] is not applicable in CO_2 injection as it gave very low permeability values at high porosity and all irreducible water saturation value range from low to high values (Table 2).

As the irreducible water saturation, S_{wirr}, increased, the calculated permeability reduced and this is because the increasing immobility of the formation water will create a restriction in the path of flow and hence a lower permeability. On the average, the proposed model gave values that are closer to published measured permeability values for Kwale sand while other methods gave permeability values that are either too low or too high. This is an indication that those other models are not applicable for permeability analysis for the Niger-Delta region when there is CO_2 injection.

Table 2
Permeability Variation for Imeri Oil Sand 1

Time (hours)	Porosity φ	Computed S_{wirr}	Timur Permeability	Coates Dumanoir Permeability	Tixier Permeability	Aigbedion Permeability	Proposed Model Permeability
0	0.7584	0.1666	1.4512	287.72	42.85	9.06905	16.9624
24	0.7583	0.1667	1.4487	287.44	42.76	9.06775	16.9541
48	0.7564	0.1671	1.4258	285.17	41.92	9.04293	16.8868
72	0.6997	0.1806	0.8659	222.05	22.47	8.30243	14.9015
172	0.6685	0.1891	0.6467	191.66	15.60	7.89496	13.8442
216	0.6076	0.2080	0.3509	140.54	7.27	7.09961	11.8551
288	0.6234	0.2028	0.4136	152.81	8.92	7.30595	12.3615
480	0.2631	0.4804	0.0017	7.49	0.01	2.60044	2.7361

The general observation is that the Tixier and Coates-Dumanoir model gave unreasonable values at high S_{wirr} while the Aigbedion values are not affected by S_{wirr} but gave too low values for low S_{wirr} and too high values for high S_{wirr}. The Timur model gave values that are either too low or too high permeability values for the Kwale sandstone while the proposed model gave values ranging from 2.46 to 99 mD at low sand porosity to high porosity which is in line with observed permeability values for Kwale sands.

6. AAS ANALYSIS OF TRACES OF HEAVY METALS IN THE SAMPLES

It was discovered that the iron content is much larger than other heavy metallic content (Figure 4). The Imeri oil samples digested in water have Fe, Cu, Ni, Mn contents in order of reducing volumetric content.

From the Figure 5 above, the S_{wirr} is at the point of rapid decline in drying rate after a constant drying rate and this correspond to 90 minutes drying time and a water saturation of 0.16667. The maximum possible S_{wirr} at the present porosity and temperature/pressure conditions is therefore 0.16667.

Table 3
S_{wirr} Determination for Oil Sand by Drying Rate Method

Time (mins)	Oil sand Weight (g)	Water loss (g)	Drying rate (g/min)	S_w
0	11.2	0	0	1
30	10.8	0.4	0.01333	0.33333
40	10.7	0.5	0.0125	0.16667
60	10.7	0.5	0.00833	0.16667
70	10.7	0.5	0.00714	0.16667
75	10.7	0.5	0.00667	0.16667
90	10.7	0.5	0.00556	0.16667
150	10.6	0.6	0.004	0

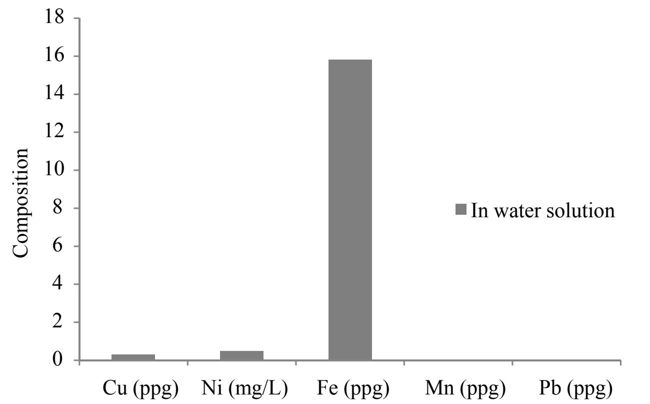

Figure 4
AAS Analysis for Imeri Oil Sand Sample

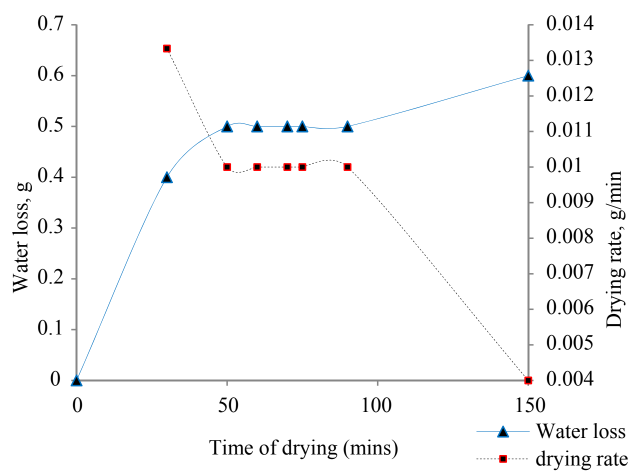

Figure 5
S_{wirr} Determination for Imeri Oil Sand Sample

7. PERMEABILITY ANALYSIS FOR IMERI OILSAND SAMPLE

The result obtained for the calculated permeabilities for the Imeri Oil sand samples for the models of Timur, Tixier, Coates-Dumanoir and Aigbedion and the proposed permeability model at various irreducible water saturations are as shown in Figure 6. Due to observed hardening of the oil sand sample after CO_2 injection, the compressive strength of another sample of Imeri oil sand was measured before CO_2 injection and at the end of 30 days of CO_2 injection. This is as shown in Figure 3.

From the graph above, the best fit equation for the proposed permeability model is:

$$K = 0.0000003t^3 - 0.039t + 17.56$$

Where permeability, K is in mD and time, t is in hours.

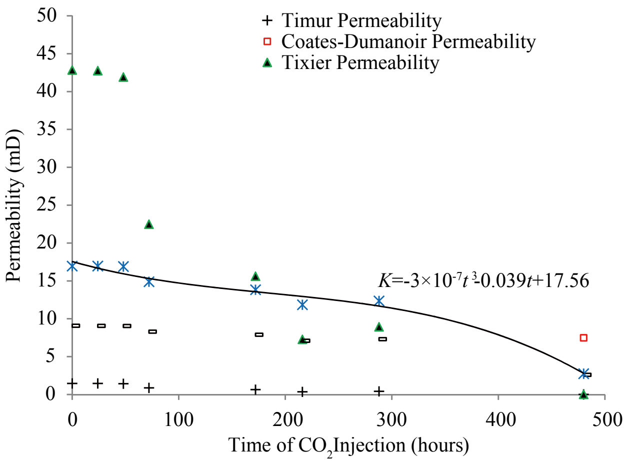

Figure 6
Permeability Variation With Time of CO_2 Injection for Imeri Oil Sand for Various Models

CONCLUSION

Timur model was observed to be the most relevant in the computation of the irreducible water saturations, S_{wirr}, among the three models of Tixier, Timur and Coates-Dumanoir. The Coates-Dumanoir was observed to give the most appropriate permeability values for Kwale sands with no CO_2 injection. Hence, a model was proposed which was a merger of the Timur's S_{wirr} equation and the Coates-Dumanoir permeability equation to describe CO_2 injection influence on the Kwale reservoir permeability. The proposed model was observed to give values that are closest to published permeability values for Kwale sands than the Tixier, Timur, Coates-Dumanoir and the Aigbedion models. The proposed model gave permeability values ranging from 2.47 to 92.46 mD for the Kwale sandstones and 0.04 - 9.62 mD for the shales. The models gave permeabilities of 17.58 - 85.2 mD when the S_{wirr} model of Kwale sandstone was applied and 2.9 - 10.21 mD when various values of constant S_{wirr} were assumed for the Ota Kaolinitic clay. The proposed model gave 15.166 - 1.3155 mD at various assumed S_{wirr} for the Imeri oil sand samples. For all the samples, Timur model gave permeability values from 0.0 to 634 mD while Tixier values ranges from 0.0 to 10,053 mD. Coates-Dumanoir gave wide range values of 6.68 - 8,550 mD while Aigbedion gave values ranging from -3.7 to 5.94 mD. The published measured Kwale sand permeability ranges from 0.8 to 87 mD. Though the proposed model gave slightly higher permeability than the published measured permeability, this is expected and is as a result of the average increase in porosity due to the CO_2 gas injection.

It was observed that Imeri oil sand formation is too porous for storage purpose. Though there was observed reduction in porosity as injection continues due to possible reaction between the oil sand and the injected gas but the gas will be lost to nearby formation initially until this reaction progress to a level where the oil sand property was distorted to form a material with higher compressive strength and lower porosity. This projected initial loss of the CO_2 to nearby formation has made the injection objective unrealistic.

It was observed that there is no single equation to describe the permeability variation with time for the considered samples since the porosity variation is divisible into three zones for each sample. Hence, permeability equation modeling can only be applicable to each type of reservoir and this is highly dependent on its reactivity with the injected CO_2 gas. Most common equation is similar to that of the sandstones where the permeability is a 2nd degree polynomial in time and porosity, immediately after injection but has an exponential relationship with the time/porosity after some days of injection.

Lastly, any form of leakage from a stored reservoir will cause CO_2 gas kick in the nearby reservoir and will create drilling problem due to its side effect on drilling mud and must be specially design against possible effect of CO_2 gas kick. Moreover, from the results obtained in this study, it was discovered that any CO_2 leakage into nearby producing reservoir will affect the property of the producing oil negatively and there may be need for further treatment of the crude at the surface.

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