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Correlations for Oil Recovery Efficiency of a Niger Delta Well under Emulsion Flooding Operations: A core Sample Analysis

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Abstract: *This study presents a core sample analysis of emulsion flooding for enhanced oil recovery in Niger Delta reservoirs using palm oil mill waste materials (oil palm mills effluent and palm bunch). The experiment investigates the effect of emulsion viscosity on oil recovery efficiency. Results show that increasing emulsion viscosity improves oil recovery, with the 40/60 emulsion ratio yielding the highest recovery efficiency of 55.2%. A predictive model was developed, and the predicted recovery efficiencies were in good agreement with experimental values with 95.2% accuracy.*

Keywords: Palm oil mill effluent, Empty palm oil bunch, Emulsion flooding, Oil recovery efficiency, Predictive Model.

INTRODUCTION

Chemical flooding is a technique used to improve oil recovery from reservoirs. It involves injecting chemicals, such as surfactants, polymers, and alkalis, to enhance oil mobility and displacement. Types of Chemical Flooding. surfactant flooding reduces interfacial tension between oil and water, improving oil flow (Demirbas, Alsuami, and Hassanein 2015). Polymer flooding increases viscosity of displacing fluid, improving sweep efficiency (Mohammadi, Khodapanah, and Tabatabaei-Nejad 2019). Alkaline flooding alters pH level, reducing oil adsorption onto rock surfaces (Alvarado & Manrique, 2010). Surfactant-Polymer (SP) flooding combines surfactant and polymer to reduce interfacial tension and improve displacement efficiency (Al-Sabagh, Kandile, El-Ghazawy, Noor El-Din, El-Sharaky 2016).

Emulsion flooding is a chemical enhanced oil recovery method that involves injecting a stable mixture of hydrocarbon, brine, and emulsifying agent into a petroleum reservoir to mobilize trapped oil (Alvarado, Wang, and Moradi, 2011). Emulsions are mixtures of two immiscible liquids, with one phase dispersed in the other (Maaref, Ayotollahi, Rezaei, and Masihiet, 2017). Oil-in-water (O/W) emulsions have shown better performance and higher oil recovery (Gogarty, 1967). Emulsion flooding works through the improvement of waterflooding through selective plugging, reducing water cut and increasing oil recovery factor (Zohoorparvaz & Arastoo, 2013). Advantages. Applications of emulsion flooding has been successfully applied in various oil fields, with reported increases in oil production and sweep efficiency (McAuliffe, 1973b; Wei, Lu, Li, and Ning, 2018).

Several studies have investigated the effectiveness of green surfactants and local materials in enhancing oil recovery. Azdarpour, Noroupour, Santos, & Mohammadian (2023) found that adding sodium salts to a green surfactant extracted from Avena sativa (oat plant) improved oil recovery, with recovery factors ranging from 7.98% to 88.45%. Rad, Alizadeh, Takassi, and Mokhtary (2023) synthesized a fresh eco-friendly surfactant that produced additional 15% oil from water-wet reservoir and 11% from oil-wet reservoir formation. Nanofluids for Enhanced Oil Recovery Onwukwe et al. (2022) investigated the effectiveness of nanofluids formulations from a blend of nanoparticles and oil extract from Irvingia gabonensis (bush mango) in boosting recovery from oil porous media. The results showed oil recoveries of 38.9% and 42.8% for aluminium oxide and zinc oxide nanofluids, respectively. Local Materials for Chemical Flooding Uzoho, Onyekonwu, and Akaranta (2019) screened local resources for chemical flooding operations in the Niger Delta oil reservoirs and found that alkali, surfactant, and polymer produced additional recovery efficiencies. Oyatobo, Muoghalu, Ikeokwu, and Ekpotu (2021) found that starch produced the utmost oil recovery due to viscosity increase of the displacing fluid.

METHODOLOGY

Preparation of emulsion samples

The palm oil mill effluent was characterized using the conventional technique of quantitative chemical analysis of heating the sample in a water bath to a temperature 60^{o}C was done by making the sample suitable for AAS analysis. Ten millilitres of the sieved palm oil mill effluent were injected into the graphite furnace cuvette, controlled electrical heating process of the cuvette dried the sample and removed the matrix before atomization, the hollow cathode lamps provided exact elemental output of light focused through the centre of the graphite furnace cuvette to activate measurement as atomization was ongoing. The sample was found to contain (oil, sodium, potassium, magnesium, phosphate, calcium, and ammonium). The oil, and water elements of the sample were separated using a separating funnel. Furthermore, ash was obtained from the empty palm fruit bunch by burning the bunch, then blending the ash and finally filtering the ash with a sieve, 350g of the filtered ash was dissolved in 500ml of distilled water to form an ash solution. The oil extracted from the palm oil mill effluent and the ash solution from the empty palm fruit bunch were mixed at room temperature in ratios of 5/95, 10/90, 15/85, 20/80, 25/75, 30/70, 35/65, 40/60, 45/55 (milliliters), An electric mixer was used in homogenizing the mixtures in order to create smaller droplets of the oil within the surfactant solution for increase of emulsion stability. By placing the emulsions formulated respectively in a Biobase Bk-VX1 electric mixer. The samples were put into the tube and put in place through the test tube holder rod by pressing into the mixing head. The formulated samples were used in a core flooding experiment

Core Flooding Experiment with emulsion samples

The core flooding experiment was conducted using a flood scheme apparatus housing the core, accumulator, and core scheme injector. Oil-in-water emulsions with varying ratios (15/85, 25/75, 30/70, 35/65, and 40/60) were prepared and used for secondary flooding, along with a control emulsion. The core samples were saturated with brine and then injected with oil to displace the brine, determining the original oil in place. Water was injected into the core holder at a flow rate of 2cc/60sec until brine breakthrough occurred, and the oil recovered was recorded. Finally, each emulsion sample was injected into the core holder at a flow rate of 2cc/60sec to recover additional oil not recovered by water flooding. The injection continued until emulsion breakthrough occurred, and the volume of oil recovered was recorded.

The volume of oil recovered from each core sample using respective emulsion samples was recorded, and observations were noted. This process was carried out for five emulsion samples (15/85, 25/75, 30/70, 35/65, and 40/60) . The objective of this experiment was to evaluate the effectiveness of different oil-in-water emulsions in enhancing oil recovery from core samples.

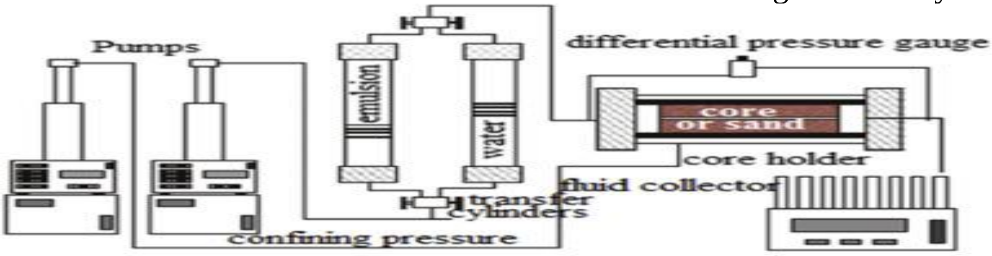

Plate 1: Core Samples Experimental Setup

Sensitivity analysis

A sensitivity analysis was carried out using excel to determine the paraments that influence oil recovery efficiency during emulsion flooding operation. The following parameters were investigated:

Table 1. Range of parameters investigated

Parameter	Lowest	Median	Highest
Reservoir Temperature ^oF	122	189	250
Oil Viscosity, μ_o (cp)	0.4	1	2
Emulsion Viscosity, μ_e (cp)	0.5	5	10
Surface temperature ^oF	75	84.2	90
Oil specific Gravity	0.97	0.86	0.78

Generation of Proxy Model for the Prediction oil Recovery efficiency

A correlation using reservoir fluid parameters sensitive to oil recovery efficiency was developed by applying linear regression analysis. Regression models are widely used to establish relationships between variables. Linear regression is a statistical method for modeling the relationship between a dependent variable (target variable), and one or more independent variables (predictor variables). the objective is to create a linear equation that best predicts the value of the target variable based on the values of the predictor variables. The model was done through historical gathering of variables of interest, and laboratory experiments. The data-set is organized in excel with independent and dependent variables in separate columns. The proxy model was developed by constructing the linear equation using intercept and coefficients. The experiment revealed that the recovery efficiency depends greatly on oil and emulsion viscosities ratio, reservoir fluids and injection fluid viscosity, therefore the proxy model is based on these factors. The general form of polynomial regression is;

$$Y = \alpha + \beta 1X1 + \beta 2X2 + \beta 3X3 \ldots, + \beta n\, Xn \qquad 1$$

Where
Y is the dependent variable (response variable)
X is the independent variable (predictor variable
β1, β2…. βn are coefficients
n is the degree of the polynomial (order of regression)
Ɛ is the error term (residual)

Validation of proxy Model

The developed proxy model was validated by initially applying it in the prediction of recovery efficiency using the parameters obtained from the experiment. This predicted recovery efficiency was compared to the recovery efficiency derived from core flooding experiments performed earlier. Then, the proxy model was also validated by scaling up the model through application of Placket-Burman range of parameters matrix to design reservoirs with combination of different value range of the sensitive parameters. Lastly the model was validated by comparing it to already published model in the field of enhanced oil recovery. On this last note, the correlation model developed by (Balhasan, Jumaa & Elbagir 2017) published in International Journal of Applied Engineering Research was compared to the proxy equation developed from this work since the two are characterized by same parameters.

$$RE = 0.165 \ln\left(\frac{Tr}{Ts}\right)^{0.88} + 0.0066 \ln\frac{\mu o}{\mu w} + 0.28 \left(\frac{1}{\gamma o}\right)^{1.55} + 0.264 \qquad 2$$

RESULTS AND DISCUSSIONS

Developed Model to predict oil recovery efficiency during emulsion flooding operations

$$\boldsymbol{RE = 0.288\,Tr + 0.063\mu o + 0.051\mu e - 0.046\gamma o - 0.00004Ts}$$

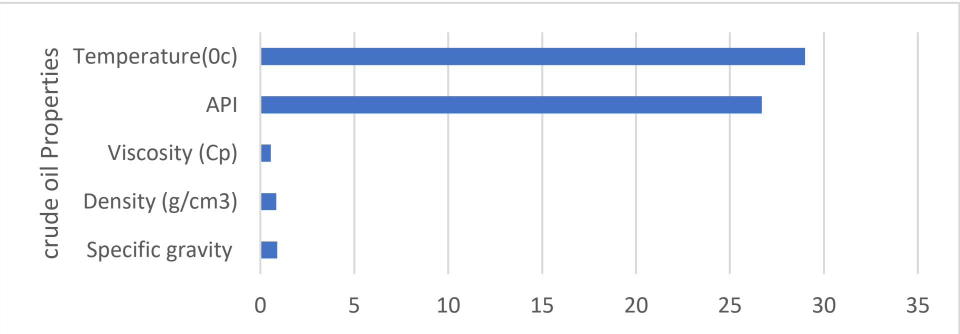

Figure 1: Property of crude oil used in the flooding experiment

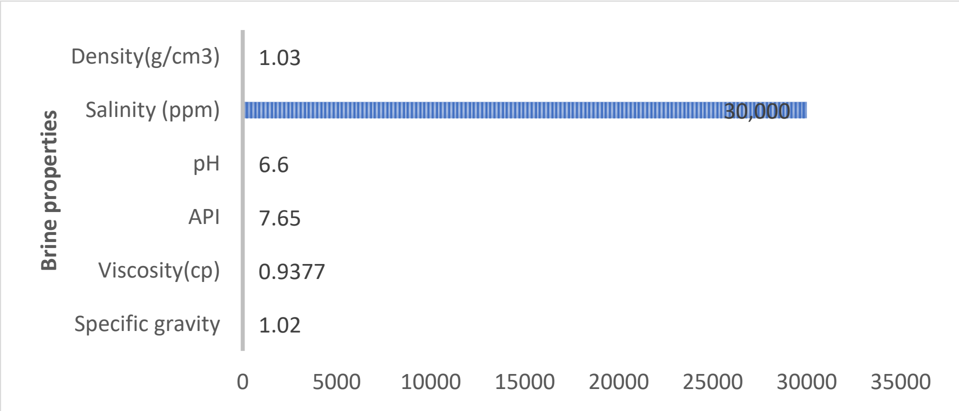

Figure 2: Properties of brine used in the flooding experiment

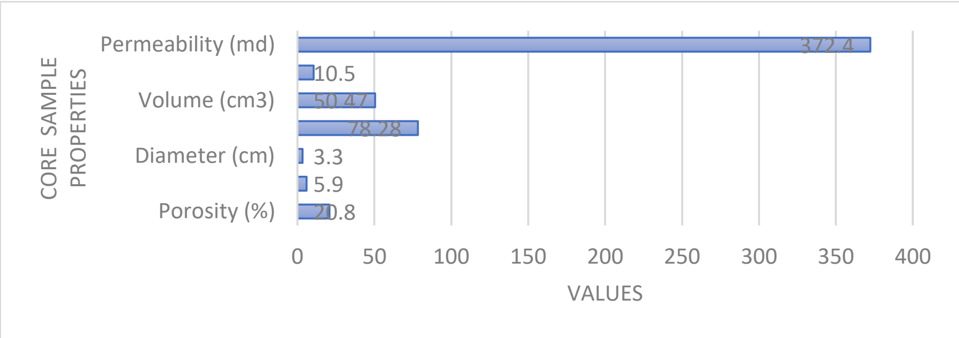

Figure 3: Properties of core samples

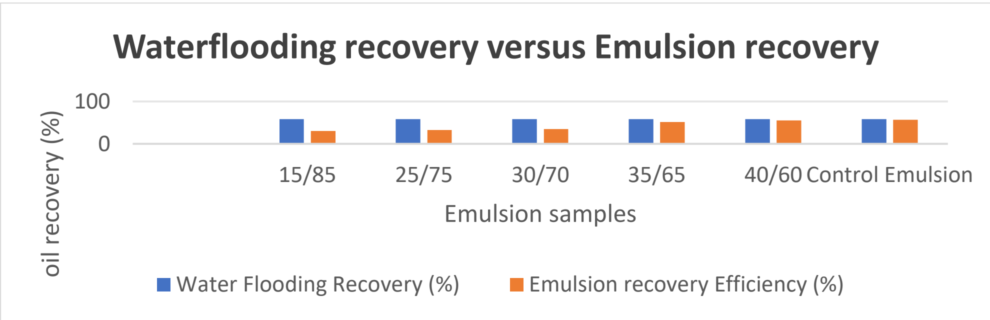

Figure 4: Oil recovery with Water flooding recovery versus Emulsion flooding

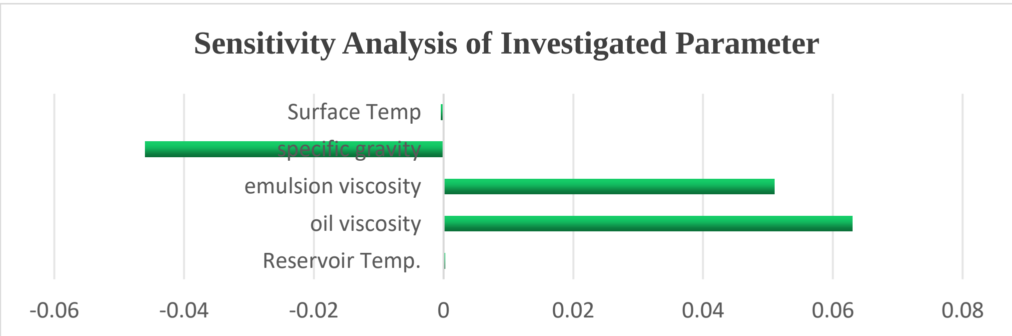

Figure 5: sensitivity analysis of investigated parameters that effect oil recovery under emulsion flooding

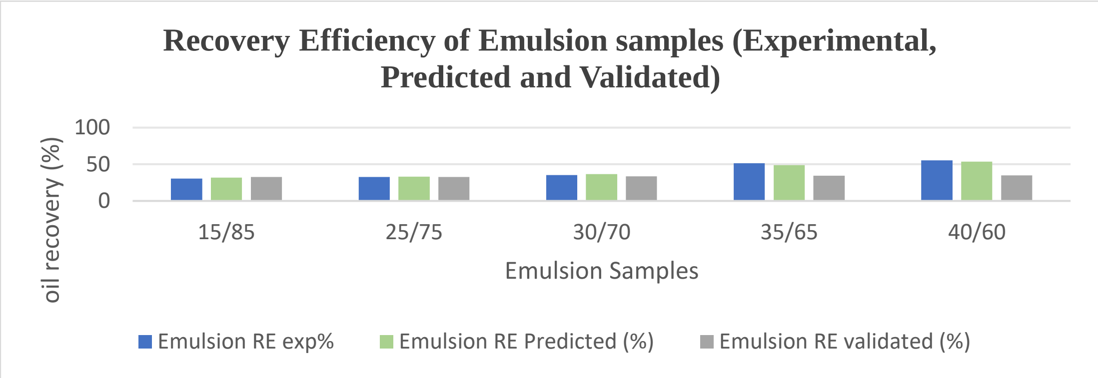

Figure 6: Recovery efficiency of emulsion samples (experimental, predicted and validated)

Table 2. Statistical data of the developed proxy model

R-Squared
0.9520

Table 3: Properties of core samples

Porosity (%)	**length(cm)**	**Diameter (cm)**	**Area (cm^2)**	**Volume (cm^3)**	**Pore volume(cm^3)**	**Permeability (md)**
20.8	5.9	3.3	78.28	50.47	10.50	372.4

Table 4: Oil recovery with water flooding and formulated emulsion samples floodin

Emulsion Sample (ml)	**OOIP (ml)**	**Oil Recovery (water Flooding) (ml)**	**Oil Recovery Emulsion Flooding(ml)**	**Total Recovery (ml)**	**Water Flooding Recovery (%)**	**Emulsion recovery Efficiency (%)**
15/85	6.00	3.50	0.76	4.26	58.33	30.4
25/75	6.00	3.50	0.82	4.32	58.33	32.8
30/70	6.00	3.50	0.89	4.38	58.33	35.2
35/65	6.00	3.50	1.29	4.79	58.33	37.1
40/60	6.00	3.50	1. 39	4.88	58.33	37.3
Control Emulsion	6.00	3.5	1.41	4.92	58.33	37.5

Table 5: oil recovery efficiency for emulsion flooding (experimental, Predicted, and Validated)

Sample	Q (ml/min)	Φ (%)	K (mD)	μ_o, (cp)	μ_e, (cp)	L (cm)	D (cm)	OOIP (ml)	Np (ml)	Emulsion Flooding (Experimental) RE exp%	Emulsion Flooding (Predicted) RE (%)	validated RE (%)
15/85	**2**	0.208	372.4	0.55	0.18	5.9	3.3	6	4.26	30.4	31.8	32.7
25/75	**2**	0.208	372.4	0.55	0.56	5.9	3.3	6	4.32	32.8	33.0	32.8
30/70	**2**	0.208	372.4	0.55	1.70	5.9	3.3	6	4.38	35.2	36.7	33.5
35/65	**2**	0.208	372.4	0.55	5.14	5.9	3.3	6	4.79	51.6	48.7	34.3
40/60	**2**	0.208	372.4	0.55	6,50	5.9	3.3	6	4.88	55.2	53.7	35.0

DISCUSSIONS

Figure 5 shows that crude oil recovery using water flooding recovered 58.33% of the oil-in-place from all crude oil saturated core samples, indicating that water flooding alone is not very effective in recovering oil from the mature fields as represented by the core samples. Emulsion flooding increases oil recovery when compared to water flooding. Though the highest oil recovery is achieved with waterflooding, and the control emulsion sequentially (95.83%) and waterflooding with the 40/60 emulsion sample sequentially (95.63%), however the 25/75 emulsion sample with waterflooding sequentially recovered 91.13% of the oil. It is noteworthy that the optimal ratio in recovering oil from the core sample when the viscosity, and stability of the emulsion samples are compared is 25/75 emulsion sample because an extra cost is needed to increase the viscosity from 0.56cp of 25/75 ratio to 6.5 cp of 40/60 ratio. Emulsion flooding shows significant improvement in oil recovery compared to water flooding, indicating the potential benefits of using emulsion flooding in enhanced oil recovery (EOR) operations.
Figure 6 shows that as the emulsion oil/palm bunch ash solution ratio increases from 15/85 to 40/60, the cumulative oil produced (Np) also increases. This suggests that as the viscosity of the emulsion sample increases, oil recovery increases too. Both experimental and predicted recovery efficiency values increase with increasing oil ratio and decreasing palm bunch ash solution ratio. This indicates that the enhanced oil recovery process becomes more efficient as less water is injected.

Table 2 shows that the predicted recovery efficiency values are generally close to the experimental Recovery Efficiency values, indicating a good match between the model predictions and actual experimental results. R-squared value (0.952) is close to unity, indicating a strong correlation. The model explains approximately 95.2% of the variability in the experimental recovery efficiency indicating a very strong positive linear relationship between the experimental and predicted recovery efficiencies, suggesting that the model is accurately predicting the recovery efficiency

CONCLUSION

- The model was able to predict the oil recovery efficiency of emulsion flooding operation accurately

- Emulsions prepared from Palm oil mill waste recovers trapped oil efficiently

Recommendation

- Field tests should be performed to assess the feasibility of large-scale oil recovery production in field application using this emulsion formulated with palm oil mill waste materials

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