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# Experimental Investigation on the Economic Feasibility of Using Polymer and Nanoparticle Hybrids for Altering Permeability

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***Abstract***— *Polymer solutions are used in chemical chemical-enhanced oil recovery (EOR) method to achieve incremental oil recoveries through obtaining favorable mobility ratios. In this method, the solution viscosity is a key parameter for the polymer flood design, as well as the changes in permeability due to the retention or adsorption. Polymer flooding is a commonly used EOR method, but it has issues with polymer retention and vulnerability to degradation. Polymer nanoparticle hybrid flooding reduces polymer retention resists degradation, and maintains superior rheological properties. This study compares the impact of a bare polymer (polyacrylamide, PAM) solution and a hybrid (polyacrylamide-alumina nanoparticle, PAM/$Al_2O_3$ NP) solution in terms of permeability alteration, oil recovery, and economic analysis. Rheological measurements and sand pack flooding tests were conducted to determine the effects of the solutions on the parameters. The mutual correlation between oil recovery, concentration, and permeability alteration was generated using a statistical model. The results indicate that the hybrid solution showed a higher oil recovery efficiency of 83.81% compared to the bare PAM solution of 72.22% at a concentration of 0.3 wt%. Furthermore, the hybrid solution prevented significant permeability alteration of 510.6mD, while significant permeability alteration of 939.3mD was observed with the bare PAM solution at 0.3wt% concentration. The hybrid solution proves to be more economically feasible than the bare PAM solution, as it leads to an increased oil recovery resulting in a profit boost of ₦205,559,868.70 at 0.3wt% concentration, outweighing the higher production cost of the hybrid solution. Conversely, the bare PAM solution experienced a reduced profit of ₦73,414,656.95 at the same concentration.*

***Keywords***— *Enhanced oil recovery, Polyacrylamide, Nanoparticle, polymer nanoparticle hybrid, Permeability alteration, Sand pack flooding, Economic analysis.*

## I. INTRODUCTION

The growing global demand for energy has led to a heightened focus on enhanced oil recovery (EOR) methods, as a significant portion of the original oil in place remains unrecovered. Traditional primary and secondary oil recovery methods have only been able to retrieve approximately 50% of the original oil in place (OOIP), leaving a substantial volume of oil underground. Therefore, tertiary recovery, also known as improved oil recovery (IOR), and its subset enhanced oil recovery (EOR), are of considerable importance, with the potential to recover between 50-80% of the oil, depending on the type of crude oil and reservoir. This addresses the disparity between the increasing global energy demand and the inadequate recoveries from conventional methods (Odo et al., 2020; Uzoho et al., 2019; Hincapie et al., 2011).

Various enhanced oil recovery (EOR) techniques, such as chemical, thermal, miscible, and microbial flooding, are being researched globally to tackle these challenges and recover residual oil. One key mechanism in enhanced oil recovery (EOR) is polymer flooding, where polymer is injected into the wellbore to increase the oil mobility ratio and prevent viscous fingering of water. This method has shown the potential to recover an additional 30-60% of the original oil in place (OOIP), depending on the reservoir and crude oil type (Sircar et al., 2021; Hincapie, 2011; Sorbie, 1990).

Polymer flooding is a chemical technique used in enhanced oil recovery, involving the addition of polymers to brine to reduce the viscosity gap between the injected fluid and the reservoir fluids (Kumar et al., 2020). Among the various chemical techniques, polymer flooding is widely recognized as the predominant and effective approach for the potential recovery of oil and gas resources (Wever et al., 2011; Sheng et al., 2015).

An essential factor in the efficiency of a polymer is its viscosity at a specific in-situ shear rate. Viscosity, which determines how well-suited a polymer is to produce oil, can be understood as the resistance of a fluid to flow (Mezger, 2011). However, increasing viscosity can lead to injectivity problems and higher chances of retention, with an increased risk of formation plugging at some point (Hincapie et al., 2015; Seright et al., 2009).

The decrease in permeability during a polymer flood is caused by various interactions between the fluid and the porous medium. The decrease in permeability significantly impacts flood productivity, especially in reservoirs with low initial permeability. This reduction results in irreversible damage to the reservoir, reduced production efficiency, and increased operational costs. Factors such as adsorption, mechanical entrapment, and hydrodynamic retention contribute to the reduction in permeability (Thomas, 2016; Manichand and Seright, 2014; Sheng, 2010; Sorbie, 1990). Adsorption refers to the bonding of a polymer to the rock surface through van der Waals and hydrogen bonding, and this bonding increases as the rock surface area increases. It is the only process that removes the polymer from a free powder/bulk solution. Polymers with a high molecular weight have demonstrated elevated levels of adsorption, which can be attributed to an increase in layer thickness (Sorbie, 1990). Furthermore, adsorption depends on the concentration of the polymer solution being used. This can be explained by the growing number of polymer structures (chains) within the solution (Yerramilli et al., 2013).

An experiment conducted by Odo et al. (2020) showed that aluminum oxide ($Al_2O_3$) was the best-performing nanoparticle after an enhanced oil recovery flooding process. An increase in nanoparticle concentration results in an increase in oil recovery and a decrease in the permeability of the reservoir rock. Only $Al_2O_3$ at a concentration of 0.2% by weight is economically feasible compared to other nanoparticles. The ability of nanoparticles to modify certain factors in the formation and oil properties can be advantageous for oil recovery (Odo et al., 2020).

Researchers have observed that the adsorption of nanofluid during flooding increases oil recovery but also significantly reduces permeability after the flooding process (Odo et al., 2020).

Knobloch et al. (2018) conducted a qualitative and quantitative assessment of permeability changes during polymer flooding for enhanced oil recovery using micromodels. A biopolymer, Scleroglucan, was tested and compared to a commonly used polymer, Flopaam, providing a direct comparison of their advantages and disadvantages. According to their results, the primary retention mechanism in the Flopaam flooding experiments was mechanical entrapment, while in the Scleroglucan flooding experiment, it was adsorption. Also, while Flopaam at a concentration of 1000 ppm showed almost no visible plugging, the visible plugging sharply increased for a concentration of 1500 ppm. There appears to be a critical concentration for Flopaam, at which there is a sharp increase in permeability reduction. On the other hand, Scleroglucan appears to exhibit the same level of adsorption at low concentrations. Adsorption has a greater impact on the residual resistance factor (RRF) than mechanical entrapment.

Furthermore, researchers have studied the use of nanoparticles in polymer nanohybrids to potentially improve the rheological behavior of polymer solutions in chemical flooding operations. The reduced size and increased surface area of nanoparticles (NPs) make them suitable for use in polymer flooding (Yadav et al., 2020). Incorporating nanoparticles into the solution can also improve the network structure of polyacrylamide (PAM) solution, leading to enhanced mechanical and thermal properties (Hu et al., 2017).

The aim of this study is to examine the impact of the PAM solution and PAM-$Al_2O_3$ hybrid on permeability alteration and oil recovery efficiency. Additionally, the study aims to conduct an economic analysis comparing the PAM solution to the PAM-Al2O3 hybrid at various concentrations.

## II. MATERIAL

The material and apparatus used to carry out the experiment include polyacrylamide (PAM), alumina nanoparticle ($Al_2O_3$ NP), crude oil, sodium chloride (NaCl), potassium chloride (KCl), prepared laboratory brine (NaCl + KCl), encapsulated plug samples, set-up for flooding/liquid permeameter flow loop, pH meter, Stopwatch, measuring cylinder, magnetic stirrer, and U-tube viscometer.

## III. METHOD

### *3.1 Permeability Determination*

The plug samples A, B, C, D, E, and F were inserted accordingly into the core holder, ensuring that both ends were sealed with stem caps, one end of the plug was connected to the reservoir containing brine, and the other end to the receiving point, as depicted in the experimental set-up (fig. 3.1). The electronic pump was activated and adjusted to achieve a flow rate of 1/60 second using the pressure regulator and stopwatch. The pressure measurement, ΔP, the length of the plug sample, $L_{plug}$, the viscosity of brine, $\mu_{brine}$ was recorded, while, the area of the plug, $A_{plug}$, was calculated using the equation below.

$$A_{plug} = 2\pi r_{plug}\left(r_{plug} + l_{plug}\right)$$

$A_{plug}$ is the cross-sectional area of the plug sample in $cm^2$, $r_{plug}$ is the radius of the plug sample in cm, and $l_{plug}$ is the length of the plug, in cm.

The permeability of the plug, before and after flooding was estimated using Darcy's law for an incompressible fluid, as shown in the equation below.

$$Permeability, K = \frac{Q\mu_{brine} L_{plug}\, 14700}{A_{plug}\, \Delta P}$$

Where K is the permeability of the plug sample in mD, Q is the flow rate in cm/sec, $\mu_{brine}$ is the viscosity of brine in cP, $L_{plug}$ is the length of plug-in cm, $A_{plug}$ is the cross-sectional area of plug-in $cm^2$, and ΔP is the differential pressure in psi.

### *3.2 Preparation of Polymer Solution and Polymer Nanoparticle Hybrid*

Polymer solutions were prepared by blending polyacrylamide (PAM) obtained from Eddy Chemicals, situated in Mile 1 Diobu, Port Harcourt, Rivers State, Nigeria, with brine at different concentrations. The solutions were agitated using a magnetic stirrer until achieving a uniform state, and then left to age for 24 hours at room temperature, approximately 30°C. Following the 24-hour period, alumina nanoparticles (supplied by the Department of Petroleum and Gas Engineering laboratory, University of Port Harcourt, Rivers State, Nigeria) were introduced to the polymer solution and mixed until completely dissolved, resulting in a homogeneous solution. The pH values of each flooding fluid were also determined at various concentrations using a pH meter. Rheological parameters, such as viscosity, were measured for both the PAM solution and the hybrid using a U-tube viscometer at the same temperature.

### *3.3 Sand Pack Flooding Experiment*

The experimental procedure is as follows: The flooding experiment began with a drainage test, during which crude oil was injected using the experimental set-up for flooding (fig. 1). The process displaced the laboratory brine in the sand-pack until irreducible water saturation was achieved, as indicated by the absence of water droplets through the outlet pipe into the measuring cylinder. The time when the first drop of oil was observed through the outlet pipe, known as the oil breakthrough time, was recorded using a stopwatch. Additionally, the volume of brine displaced by the oil within the plug was estimated to be the initial volume of oil in place (OIIP).

Next, the imbibition test was conducted by injecting brine through the inlet pipe into the core holder to displace the oil until irreducible oil saturation was achieved. The volume of oil displaced after water flooding was recorded, and the time for water breakthrough was also noted. The efficiency of oil displacement was calculated and documented. PAM and hybrid solutions were prepared using 100 mL of brine (NaCl + KCl) with polymer (PAM) concentrations of 0.1 wt%, 0.2 wt%, and 0.3 wt%, along with alumina nanoparticles ($Al_2O_3$ NP). The tertiary recovery method involved injecting prepared solutions of both PAM and PAM/$Al_2O_3$ hybrid through the inlet pipe into the core-holder to displace additional oil (fig. 1). The amount of oil recovered was recorded, and the oil recovery efficiency was calculated and documented. Subsequently, the loose sand pack was removed from the core holder and weighed. It is important to note that this process was repeated for each sand pack. The properties of the crude oil sample used in the flooding experiment are presented in table 1.

TABLE 1. Properties of crude oil.

| S/No. | Properties | Values |
|---|---|---|
| 1 | Specific gravity | 0.860 |
| 2 | Density (g/cc) | 0.8880 |
| 3 | Temperature (℃) | 30 |
| 4 | API gravity (°) | 33.99 |
| 5 | Viscosity (cP) | 42.6812 |

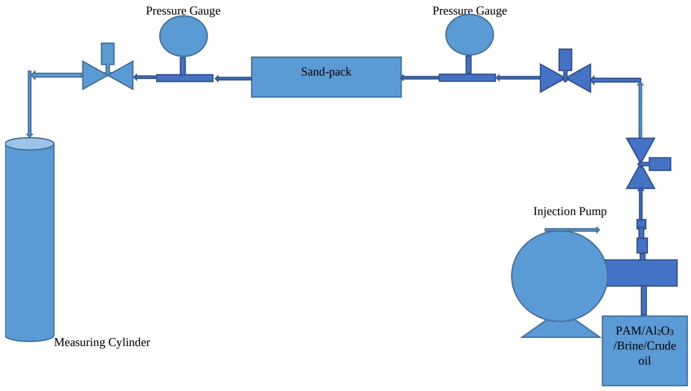

Fig. 1. Experimental Apparatus design for the Flooding Process (Warmate and Mbachu, 2023).

## IV. RESULTS AND DISCUSSION

### 4.1 *The Effect of PAM and Hybrid Solutions on Permeability Alteration*

The impact on the permeability of the formation was evaluated during the sand pack flooding experiments. Polymer flooding, which involves the injection of pure PAM into the formation to enhance oil recovery, was utilized. PAM, being a polymer with a high molecular weight, increases the viscosity of the injected fluid. This, in turn, aids in improving the efficiency of fluid displacement and enhancing oil recovery. However, as the concentration of PAM increased from 0.1 to 0.3 wt%, it adsorbed onto the surface of the rock and obstructed the pore throat, resulting in a decrease in permeability from 583.86 mD to 939.30 mD, respectively.

On the other hand, when PAM was combined with aluminum oxide ($Al_2O_3$) nanoparticles, it formed a hybrid solution known as PAM-$Al_2O_3$. The unique functionality of the alumina nanoparticles mitigated the adverse effects of polymer retention. When injected into the formation, these $Al_2O_3$ nanoparticles interacted with the rock surface, reducing the adsorption and retention of the PAM solution. This, in turn, helped maintain permeability and prevent significant alterations caused by pure PAM flooding. The hybrid flooding technique improved the performance of polymer flooding while minimizing the reduction in permeability from 356.50 mD to 510.58 mD. Therefore, the presence of $Al_2O_3$ nanoparticles enhanced the mobility of the injected fluid, improved fluid displacement efficiency, and potentially increased oil recovery, making it a promising approach for enhanced oil recovery (EOR).

At a concentration of 0.1 wt%, the permeability of the formation experienced a slight decrease to 583.86 mD during the process of PAM solution flooding. However, as the concentration increased from 0.1 wt% to 0.3 wt%, there was a notable reduction in permeability due to the retention of polymer, which hurt the efficiency of the enhanced oil recovery (EOR) process, as indicated in table 2.

TABLE 2. Determination of permeability alteration at 0.1 to 0.3wt% Concentration.

| Plug Sample ID | Dispersing Fluid | Initial Permeability (mD) | Final Permeability (mD) | Change in Permeability (mD |
|---|---|---|---|---|
| A | PAM1 | 1624.53 | 1040.67 | 583.86 |
| B | Hybrid1 | 1597.02 | 1240.52 | 356.50 |
| C | PAM2 | 1423.44 | 806.85 | 616.59 |
| D | Hybrid2 | 1384.62 | 1020.68 | 363.94 |
| E | PAM3 | 1563.87 | 624.57 | 939.30 |
| F | Hybrid3 | 1390.73 | 880.15 | 510.58 |

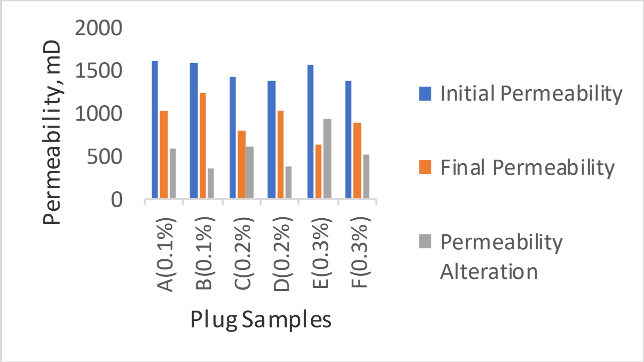

Fig. 2. Effect of PAM solution and hybrid on permeability alteration.

Conversely, the use of PAM/$Al_2O_3$ hybrid flooding helped mitigate this effect. The inclusion of $Al_2O_3$ nanoparticles (NPs) in the PAM solution reduced polymer adsorption and maintained the permeability of the formation, even at a higher concentration of 0.3 wt%. This resulted in a slight decrease in permeability to 510.58 mD (fig. 2). This has the potential to enhance the efficiency of the EOR process by ensuring a stable and optimized flow of the injected fluid.

These findings align with the research conducted by Odo et al. (2020) on the alteration of permeability due to the retention of nanoparticles in porous media during nanotechnology-assisted enhanced oil recovery experiments using core samples made with Niger Delta sand. The results demonstrate that the adsorption of nanofluids during flooding led to an increase in oil recovery but also significantly decreased permeability after the flooding process.

### *4.2 Effect of Permeability Alteration on Oil Recovery*

The chemical flooding experiment induced permeability alteration, which significantly impacted the flow of fluids within the reservoir. Permeability alterations affects the movement of oil and water through the porous rock formations, altering the sweep efficiency and overall recovery of oil.

TABLE 3. Cumulative Oil Recovery of solutions as a function of permeability Alteration on different formations.

| Plug sample ID | Permeability Alteration (mD) | Cum. Oil Recovery (%) |
|---|---|---|
| A (0.1%) | 583.86 | 68 |
| B (0.1%) | 356.5 | 74.36 |
| C (0.2%) | 616.59 | 69.09 |
| D (0.2%) | 363.94 | 82.5 |
| E (0.3%) | 939.3 | 72.22 |
| F (0.3%) | 510.58 | 83.81 |

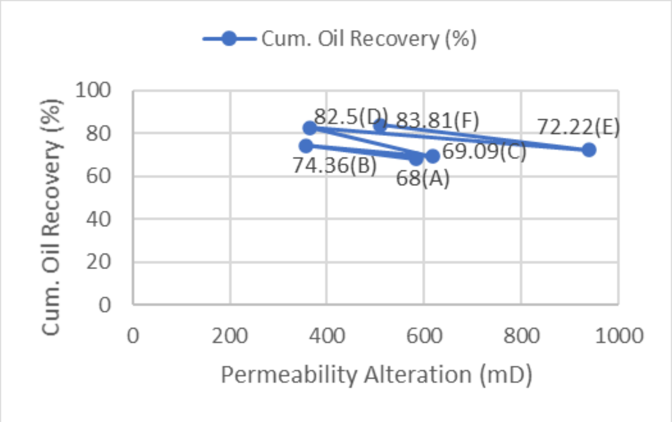

Fig. 3. Correlation between Permeability Alteration and Cumulative Oil Recovery at different formation.

Experiments were conducted using sand pack samples made with Niger Delta sand samples. Polymer solutions and polymer nanoparticle solutions were prepared, with brine as the dispersing medium and 0.1 wt% to 0.3 wt% concentrations were used to flood the plug samples. The results from the experiments were analyzed using charts to check the effectiveness of the process. Also, the differences in the permeability of the plugs before and after flooding were compared. The results show that the PAM/$Al_2O_3$ hybrid solution exhibited a lower permeability reduction, indicating its ability to provide sustained flow control. Higher increase in cumulative oil recovery from 74.36% to 83.81% was observed for the PAM/$Al_2O_3$ hybrid solution with a reduced permeability alteration from 356.50 mD to 510.58 mD at 0.1 wt% to 0.3 wt% concentration. Whereas significant permeability reduction from 583.86 mD to 939.30 mD was observed after the flooding process, leading to a slight rise in cumulative oil recovery from 70.68% to 72.22% for the PAM solution alone at the same concentration.

PAM/$Al_2O_3$ hybrid solution yielded superior cumulative oil recovery compared to the PAM solution as the permeability alteration reduced (table 3 and fig. 3). The enhanced cumulative oil recovery during PAM/$Al_2O_3$ hybrid flooding, as depicted in fig 3, can be attributed to improved sweep efficiency and reduced mobility ratio resulting from the increased viscosity of the PAM/$Al_2O_3$ hybrid solution and the utilization of $Al_2O_3$ nanoparticles. This finding aligns with a study conducted by Odo et al. in 2020, which demonstrated that the inclusion of $Al_2O_3$ nanoparticles slightly increases permeability alteration but subsequently improves oil recovery.

### *4.3 Economic Analysis*

The economic analysis considered the pore volume and tertiary oil recovery when scaling up the data. The approach used for the economic analysis was based on the methodology employed by Odo et al. (2020). Table 4 displays the values of pore volume and tertiary oil recovery. The upscaling data is presented in table 5, with a scaling factor of 1 $cm^3$ = 1 mL = 500 bbl. Table 6 provides the average price of the fluid, sourced from Eddy Chemicals and department of Petroleum and Gas Engineering laboratory in Port Harcourt, Rivers State. The equation for determining the cost of the dispersing particle is given as:

$$\text{Particle Concentration } (\%\text{wt}) \times \text{Density of Brine} \left(\frac{\text{Ib}}{\text{bbl}}\right) \times \text{Particle Price} \left(\frac{₦}{\text{Ib}}\right) \times 1\text{bbl}$$

TABLE 4. Sand-Pack Properties at 0.1 to 0.3%wt concentration

| Dispersing Particles | Pore Volume (cm3) | OOIP (mL) | Secondary Oil Recovery (mL) | Tertiary Oil Recovery (mL) | Cumulative Oil Recovery (mL) |
|---|---|---|---|---|---|
| PAM1 | 24.21 | 19.00 | 12 | 0.92 | 12.92 |
| Hybrid1 | 24.45 | 19.50 | 12 | 2.50 | 14.50 |
| PAM2 | 27.42 | 22.00 | 13 | 2.20 | 15.20 |
| Hybrid2 | 26.00 | 20.00 | 12 | 4.50 | 16.50 |
| PAM3 | 20.66 | 18.00 | 11 | 2.00 | 13.00 |
| Hybrid3 | 26.47 | 21.00 | 12 | 5.60 | 17.60 |

TABLE 5. Upscaling Data for Economic Analysis at 0.1-0.3%wt Concentration.

| Dispersing Particles | Pore Volume (bbl) | Tertiary Recovery (bbl) |
|---|---|---|
| PAM1 | 12,105 | 460 |
| Hybrid1 | 12,225 | 1,250 |
| PAM2 | 13,710 | 1,110 |
| Hybrid2 | 13,000 | 2,250 |
| PAM3 | 10,330 | 1,000 |
| Hybrid3 | 13,235 | 2,800 |

The experimental brine has a density of 1.0174 $g/cm^3$.
To convert this density to pounds per barrel (Ib/bbl), the following conversion factors are used:
1$g/cm^3$ = 8.3454 Ib/US gal, 1bbl = 42 US gal.

Thus, 1g/cm$^3$ is equivalent to 8.3454 × 42 Ib/bbl, which equals 350.5068 Ib/bbl. Therefore, the density of the brine is calculated as 1.0174 × 350.5068, resulting in 356.6056 Ib/bbl. Table 7 provides the comprehensive cost breakdown for preparing 1 barrel of dispersing fluid.

TABLE 6. Price per Pounds of dispersing particles.

| Dispersing Particles | Price (₦/Ibs) |
|---|---|
| PAM | 1602.2716 |
| $Al_2O_3$ | 35,925.7378 |
| Hybrid | 18,764.0047 |

TABLE 7. Total Cost of Producing Dispersing Fluids at 0.1 to 0.3%wt Concentration.

| Dispersing Particles | Price ($\frac{₦}{bbl}$) | 0.5 Pore Volume (bbl) | Total Cost of Production (₦) |
|---|---|---|---|
| PAM1 | 571.3790 | 6052.5 | 3,458,271.398 |
| Hybrid1 | 6,691.3492 | 6112.5 | 40,900,871.990 |
| PAM2 | 1,142.7581 | 6855.0 | 7,833,606.776 |
| Hybrid2 | 13,382.6983 | 6500.0 | 86,987,538.95 |
| PAM3 | 1,714.1371 | 5165.0 | 8,853,518.122 |
| Hybrid3 | 20,074.0475 | 6617.5 | 132,840,009.300 |

0.5 pore volume of the dispersing fluids prepared with brine was injected into the formation. Table 7 displays the overall cost of producing each dispersing fluid at various concentrations. Table 8 provides data on profit and loss, as well as revenue generated, based on the average cost of crude oil and total production cost. An increase in the concentration of dispersing particles leads to a corresponding increase in the total cost of preparing a hybrid solution of PAM (fig. 4). The hybrid solution is more economically viable than the pure PAM solution at concentrations ranging from 0.1wt% to 0.3wt% as shown in fig. 4 and fig. 5 respectively.

This conclusion is based on the current average crude oil price of ₦77,128.54 ($100.690) per barrel, as reported on September 29th, 2023.

TABLE 8. Profit/loss and Revenue Generated at 0.1-0.3%wt Concentration

| Dispersing Particles | 0.5 Pore Volume (bbl) | Tertiary Oil Recovery (bbl) | Revenue Generated (₦) | Profit/loss (₦) |
|---|---|---|---|---|
| PAM1 | 6052.5 | 460 | 35,479,128.4 | 32,020,857.00 |
| Hybrid1 | 6112.5 | 1,250 | 96,410,675.0 | 55,509,803.01 |
| PAM2 | 6855.0 | 1,100 | 84,841,394.0 | 77,007,787.22 |
| Hybrid2 | 6500.0 | 2250 | 173,539,215.0 | 86,551,676.05 |
| PAM3 | 5165.0 | 1,000 | 77,128,540.0 | 68,275,021.88 |
| Hybrid3 | 6617.5 | 2,800 | 215,959,912.0 | 83,119,902.70 |

The hybrid solution, at concentrations of 0.1 wt% to 0.3 wt%, resulted in a higher oil recovery of 74.36% to 83.81% and a profit recovery of ₦55,509,803.01 to ₦83,119,902.70, respectively. These recovered profits significantly exceed the total cost of preparing both the hybrid solution and the bare PAM solution. Notably, the hybrid solution at a concentration of 0.2 wt% yielded the highest profit of ₦86,551,676.05, making it a more economically viable option compared to other dispersing fluids. The inclusion of alumina nanoparticles in the PAM solution enhances its effectiveness, potentially leading to increased production rates and improved overall process efficiency. Furthermore, the presence of alumina nanoparticles improves the stability of the PAM solution by preventing premature sedimentation or aggregation. This enhanced stability reduces costs associated with remixing or redosing the solution and minimizes material waste.

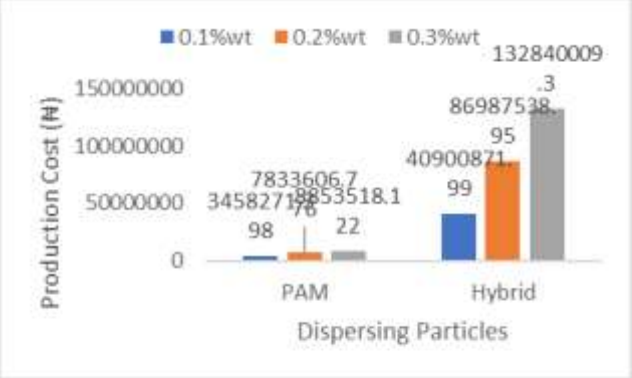

Fig. 4. Total Cost of Dispersing Fluid Production at 0.1 to 0.3%wt concentration.

Although the production cost of the hybrid solution is higher than that of the bare PAM, as indicated in table 7 and fig. 4, the potential benefits derived from improved performance and reduced dosage outweigh the increased production cost. This makes the hybrid solution more cost-effective in the long run, as demonstrated in table 8 and fig. 5 respectively.

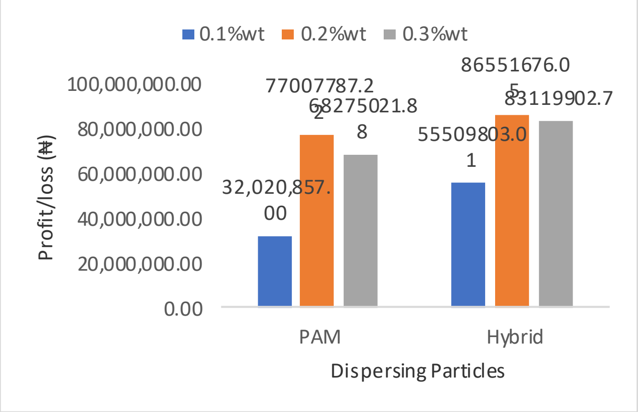

Fig. 5. Profit/loss Data with Dispersing Particles at 0.1%wt to 0.3%wt concentration.

## V. CONCLUSION

This research aimed to examine the potential of alumina nanoparticles ($Al_2O_3$ NPs) as an additive to improve the rheological and oil recovery properties of polyacrylamide (PAM) solutions. The study compared the effectiveness of PAM solutions and PAM/$Al_2O_3$ hybrid solutions. The findings indicated that the hybrid used in the chemical-enhanced oil recovery (CEOR) experiment displayed superior rheological properties compared to the pure PAM solution. Specifically, the hybrid solution prevented significant permeability alteration of 510.6 mD, while the pure PAM solution at a concentration of 0.3 wt% resulted in a significant permeability alteration of 939.3 mD. Furthermore, flooding with the

$PAM/Al_2O_3$ hybrid resulted in higher oil recovery efficiency compared to flooding with the pure PAM solution, particularly as the concentration increased. This improvement can be attributed to the inclusion of $Al_2O_3$ in the PAM solution, which is utilized to displace the oil.

To evaluate oil recovery, three concentrations of PAM polymer and $PAM/Al_2O_3$ hybrid ranging from 0.1 to 0.3 wt% were utilized. The $PAM/Al_2O_3$ hybrid demonstrated the best result at a concentration of 0.3 wt%, achieving an oil recovery efficiency of 83.81%. In comparison, the pure PAM solution achieved an oil recovery efficiency of 72.22% at the same concentration. However, it is important to note that while increasing the concentration of the hybrid enhances cumulative oil recovery, it also reduces the permeability of the formation and increases the cost of hybrid preparation. Nevertheless, the improved performance of the hybrid solution outweighs the higher production cost, making it a more cost-effective option in the long run.

To compare the efficiency of dispersing fluids such as PAM and hybrid solutions, a statistical model was utilized to establish the mutual correlation between permeability alteration, concentration, and oil recovery efficiency of the pure PAM and hybrid solutions.

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