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Research Article

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Effect of Silicon Oxide Nanoparticles in Xanthan Gum Solution Using Different Salinity for Enhanced Oil Recovery

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Abstract Enhanced oil recovery (EOR) techniques are important for increasing oil production as to meet global energy demands. Polymer flooding is a commonly used EOR method, but it has issues with polymer retention and vulnerability to degradation both at high temperature and salinity. The study compares the effect of stand-alone xanthan gum polymer solution, xanthan gum/silicon oxide hybrid and silicon oxide nanofluid on viscosity, salinity ranges of 30,000ppm and 50,000ppm, permeability change and oil recovery. The efficiency of the formulated fluids was tested using different fourteen core samples of Niger - Delta sand. The results indicate that the polymer-nanoparticle hybrid solution enhanced the viscosity, gave better permeability change and higher oil recovery for both 30,000ppm and 50,000ppm salinity change examined. 0.2wt% Xanthan gum/S_iO_2 hybrid gave the highest cumulative oil recovery of 89.01% for 30,000ppm brine concentration as to compare to stand alone xanthan gum that gave the cumulative oil recovery 74.94% at the same fluid and salinity concentration. Xanthan gum/S_iO_2 hybrid at 0.2wt% and 50,000ppm concentration recovered more oil than the standalone xanthan gum and silicon oxide nanofluid at the same fluid and salinity concentration. Xanthan gum/S_iO_2 hybrid with 0.2wt% concentration gave lower permeability change of 53.12md than every other concentration investigated. The combination of Silicon oxide nanoparticle and xanthan gum polymer enhances polymer properties as to improve displacement efficiency, reduce polymer adsorption and permeability damage.

Keywords Brine, Enhanced Oil Recovery, Silicon Oxide Nanoparticle, Xanthan Gum, Viscosity, Silicon Oxide

1. Introduction

After the application of primary and secondary recovery, the literature shows that huge volumes of oil remain in a reservoir leading to decline in oil production ([1], [2]). There are several factors contributing to the declining of the oil production which include [3].

Bypassed or residual oil trapped in the reservoir after primary and secondary recovery due to unfavorable mobility ratio of the injectant which prone to viscous fingering and resistance of oil to flow.

The oil is trapped because of the high capillary forces across the interface between water and oil or pressure declining the reservoir.

The heterogeneities present in the reservoir.

The remaining oil-in-place otherwise known as residual or immobile oil is the target of enhanced oil recovery (EOR) [4]. EOR processes is divided into chemical, thermal, gas and microbial. Polymer flooding is one of the chemicals enhanced oil recovery (EOR) methods and has been proved to be suitable for EOR application globally. There are extensive studies regarding the usage of nanoparticle materials in tertiary oil recovery methods even in chemical flooding, which helps the conventional methods to increase the oil production ([5, 6]). Nanoparticles are small with the range of 1 – 100 nm. Their small size provides them with the ability to access pore spaces where the conventional recovery methods cannot enter [7]. The nanofluid floodings are concluded to have mechanisms of recovery by wettability alteration, interfacial tension reduction, pickering emulsion formation and stability, structural disjoining pressure and oil viscosity reduction [5]. [8] presented types of nanoparticles which includes organic, inorganic, metal oxides and non-silica nanoparticles (Fig. 1.) Organic nanoparticles are carbon nanoparticles and carbon nanotube (CNT) nanoparticles. However, inorganic nanoparticles can be silica oxide (S_iO_2), while the metal oxides nanoparticles are aluminum oxide (Al_2O_3), titanium oxide (T_iO_2) and iron oxide (Fe_2O_3/Fe_3O_4). Polymer nanoparticles and polymer-coated nanoparticles are examples for non-silica nanoparticles.

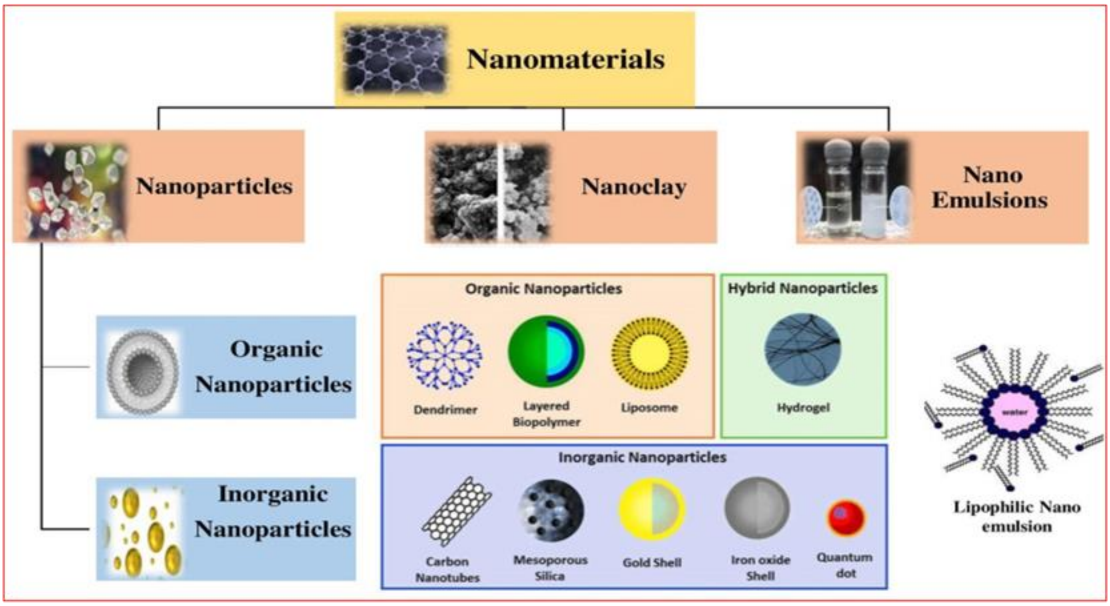

Figure 1: Nanomaterials division breakdown [8]

Xanthan gum is widely used in the industry, including food, clothes and the oil and gas industry. According to [9] xanthan gum is an extracellular polysaccharide formed by the xanthomonas campestris. Its primary structure comprises the backbone of glucose monomers or cellulose-like chain and trisaccharide side chain (Fig. 2). Silica nanoparticles, for instance, are cheap and easy to control their chemical behaviour by using surface modification technique [10]. Moreover, these nanoparticles are also environmentally friendly, which is another advantage of using this type of nanoparticles in EOR apart from their ability to improve production. [11] stated that xanthan gum is a high molecular anionic polysaccharide that is formed by bacterium Xanthomonas campestris during the process of cellulosic backbone fermentation. This water-soluble polymer has been commonly used in EOR proving that it is able to improve sweep efficiency by controlling the mobility of water, lowering the permeability of water in the swept zones as well as contacting unswept zones.

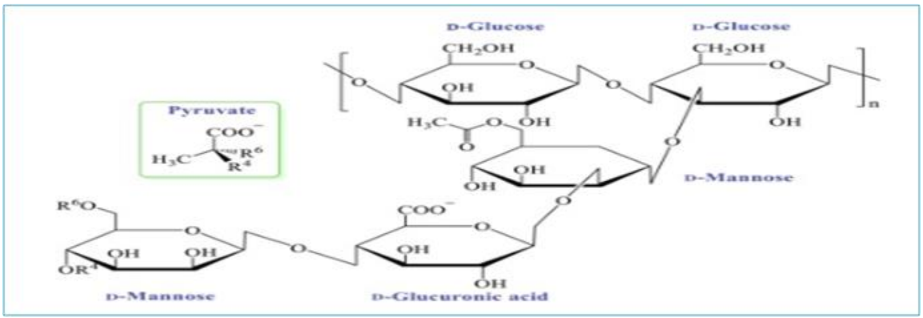

Figure 2: Structure of Xanthan Gum [12]

Recently, some authors like [13], [14]. [15], [16], [17], [18] and [19] have showed that the use of nanoparticles in polymer improves oil recovery. The use of xanthan gum as a polymer is ongoing research with lots of interests and improvement. Nanoparticles like Silicon oxide, Aluminum oxide and iron oxide has been fused together with the polymer to improve recovery. The study of [13] focused on using the hybrid of polymer and nanoparticle for oil recovery. The study was done through evaluating their efficiency in core flooding. The experiment used xanthan gum as polymer with brine (NaCl) as base with silicon oxide nanoparticle. The impact of viscosity was observed to be little instantaneously and remarkable over time. The authors reported using this hybrid for the core flooding was observed to yield twice as more in recovery as compared to the bare polymer (Xanthan gum alone). The study of [14] was centered on using xanthan gum and xanthan-g-silica derivatives as both chemical flooding agents and rock wettability modifiers. The study was carried out by performing core flooding on ten sandstone reservoir samples with different porosity and permeability values. The different fluids were evaluated based on their impact on the reservoir parameters by observing their shearing rate, ionic strength, and thermal stability. The wettability alterations calculation process was conducted at different water saturation and accessed through permeability curves. The results of this experiment however showed that the polymer nano fluid was a better option for recovery as compared to the polymer.

[15] did a study on polymer-nano fluids using nanoparticles of Fe_3O_4, SiO_2 and Xanthan gum polymer from the extract of Alocasia macrorrhiza plant supporting a green alternative for EOR fluids formulation. Aside experimenting with the formulated fluid for oil recovery, an investigation on their impact on interfacial tension (IFT) reduction and wettability alteration was carried out. The experimental findings showcase a substantial reduction in interfacial tension (IFT) and a consequential alteration in wettability. Such alterations are transformative, suggesting a shift from strong oil-wet to strong water-wet systems. This transformative effect on wettability is a critical facet, influencing the mobility of fluids in porous media and paving the way for more effective oil recovery strategies. This experiment was conducted under limited temperatures and salinities.

[16] researched on chemical displacement using xanthan gum, xanthan/S_iO_2 and xanthan grafted with vinylsilane derivatives. The chemical characterization was done using traditional spectroscopic methods. Investigation of fluids response to reservoir environment assessed through rheological performance relative to shearing rate, ionic strength, and thermal stability. A sequence of flooding runs generated on 10 sandstone outcrops with different porosity and permeabilities. Core wetness assessed through relative permeability curves at different water saturation. The flooding tests indicated that grafting of the silica derivative overcome the shortage of xanthan gum solution in flooding operations relative to the reservoir conditions. The ability of the flooding solutions to alter rock wettability explored through relative permeability curves at different water saturation. The results reveal that the synthesized composite was a promised. agent for enhancing oil recovery and profile conformance. [17] in their study, they synthesized α-Fe_2O_3 nanoparticles and blended it with xanthan gum by Sono-chemical method through an ex-situ process. The α-Fe_2O_3-xanthan gum nanocomposite X-ray diffraction (XRD) shows that there are no additional peaks. Only the α-Fe_2O_3 and the xanthan gum peaks are detected with the crystallite size of around 16-20 nm. The particle size of α-Fe_2O_3-xanthan gum (1:1) nanocomposite as measured by Particle Size Analyzer (PSA) was 228.43 nm with the type of polydisperse. The functional group of the nanocomposite is a combination of the α-Fe_2O_3 and xanthan gum functional groups which shows there are no other compounds detected in IR spectra. The EOR test showed that xanthan gum had a significant effect on increasing the viscosity of the α-Fe_2O_3-xanthan gum nanofluid to 1.964 cP at a 1:2 composition. Based on these results, α-Fe_2O_3-xanthan gum nanofluid is the potential material used in the chemical flooding process in the reservoir.

[18] conducted research as to compare the impact of a bare polyacrylamide (PAM) polymer solution and a polyacrylamide-alumina nanoparticle (PAM/Al_2O_3 NP) hybrid in terms of viscosity, pH, efflux time, and oil recovery. The authors indicated from their experimental study; the hybrid solution showed higher oil recovery efficiency (83.81%) compared to the bare PAM solution (72.22%) at a concentration of 0.3wt%. The hybrid solution also exhibited higher viscosity, efflux time, and pH (57.15cP, 1543sec, and 7.9, respectively) compared to the bare PAM solution (49.68cP, 1342sec, and 6.1, respectively) at the same concentration. Mpakaboari and Mbachu stated that the addition of Al_2O_3 NP to the PAM solution modifies its properties, reduces PAM adsorption, preserves polymer chains, and maintains entanglement. [19] synthesized Amide- and alkyl-modified nano-silicas (AANPs) and it was introduced into xanthan gum (XG) solution, aiming to improve the temperature/salt tolerance and oil recovery. The rheological behaviours of XG/AANP hybrid dispersions were systematically studied at different concentrations, temperatures, and inorganic salts. At high temperature of 75ºC and high salinity of 10,000mgL^{-1} AANPs increase the apparent viscosity and dynamic modulus of the XG solution, and XG/AANP hybrid dispersion exhibits elastic-dominant properties. The most effective concentrations of XG and AANP interacting with each other are 1750 mg. $L^{-1}$and 0.74 wt.%, respectively. The temperature tolerance of XG solution is not satisfactory, and high temperature further weakens the salt tolerance of XG. Yong and his team reported that the AANPs significantly enhance the viscoelasticity of the XG solution

through hydrogen bonds and hydrophobic effect. Under reservoir conditions, XG/AANP hybrid recovers approximately 18.5% more of original oil in place than AANP and 11.3% more OOIP than XG. The enhanced oil recovery mechanism of the XG/AANP hybrid is mainly increasing the sweep coefficient, the contribution from the reduction of oil-water interfacial tension is less. Having gone through the literature, is a need to improve and to increase oil production, hence this study aimed at using a synergy effect of xanthan gum polymer and silicon oxide nanoparticle to improve oil recovery mainly at high salinity concentration.

2. Chemical Enhanced Oil Recovery Method

The target of tertiary recovery is the residual oil left behind after the secondary recovery process has become uneconomical. An EOR process may involve injection of miscible gases, chemicals, and thermal energy into the reservoir to displace additional oil. Three main classes of enhanced oil recovery currently being applied in the oil and gas industry are thermal, chemical, and microbial methods. Chemical process is enhanced oil recovery of interest in this study. Fig. 3 gives the broad classification, challenges, and mechanism of enhanced oil recovery.

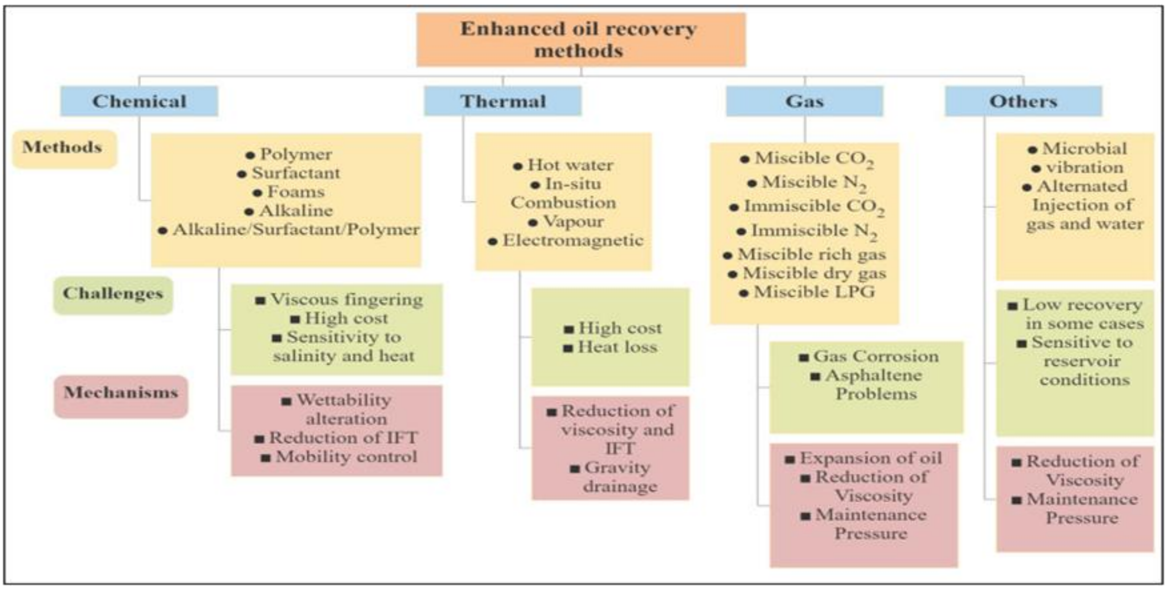

Figure 3: Enhanced Oil Recovery methods [20]

2.1. Polymer flooding

Polymers are used to reduce the mobility ratio of water – oil by increasing the water viscosity which improves the volumetric sweep efficiency during EOR processes. There are two main groups of polymers in conventional polymer flooding: synthetic and biopolymer. Partially hydrolyzed polyacrylamide (HPAM) is the most widely used synthetic polymer for polymer flooding and is a linear water-soluble polymer. The implementation of HPAM is relatively easy and can significantly improve oil recovery rate under standard reservoir conditions. Natural and biopolymers are gaining significant interest for their application in chemical EOR because of their eco-friendly nature [21]. A few of the recently used biopolymers are xanthan gum, gum Arabic, guar gum. Advance in research is leading to combining polymers with nanoparticles mainly xanthan gum and partially hydrolyzed polyacrylamide for better performance due to their synergy effect.

2.2 Alkaline flooding:

It is a type of chemical enhanced oil recovery method where synthetic chemicals such as sodium hydroxide, sodium orthosilicate or sodium carbonate are injected into a reservoir to enhance oil recovery. The injected alkaline reacts with the naturally occurring organic acids in the oil and forms surfactants inside the reservoir. The surfactants eventually play a big role by reducing interfacial tension between oil and water which contributes to increase oil recovery [21]. Alkaline flooding agent has an advantage over surfactant flooding agent because of its cost effectiveness.

3. Materials and Methods

3.1 Equipment and Materials

3.1.1 Equipment

Encapsulated plug sample (unconsolidated Sand-packs), Venire caliper, Density bottle, PH meter, Hydrometer, Thermometer, Canon U-tube Viscometer, Electronic Weighing balance, Stopwatch, Retort Stand, Pump, Flooding Pump Setup, Core-holder, Sieve and Stirrer.

3.1.2 Materials

The materials utilized in this research work are xanthan gum (Polymer), silicon oxide nanoparticle, brine (mixture of industrial salt and water), encapsulated cores, crude oil.

Brine Preparation: Two laboratory brine solutions were formulated in this study. The brine solutions were prepared with 30g and 50g of sodium chloride (NaCl) in 1000ml of water. The density of the formulated brine using different 30000ppm and 50000pm formulated brine are 1.0191g/dm^3 and 1.0321g/ dm^3.

Nanofluids Preparation: The silicon oxide nanoparticles used in this study was acquired from JoeChem Chemical Shop Port Harcourt, River's state, Nigeria. 0.1g, 0.2g and 0.3g of silicon oxide were dissolved in equal volume of 100ml of brine from the different concentration of 30g/L and 50g/L.

Polymer-Nanofluids Hybrid Preparation: The polymer used in this study is xanthan gum. 100ml equal volume of Xanthan gum was mixed with 0.1wt%, 0.2wt% and 0.3wt% of Silicon (ii) oxide formulated solution. The formulated nanofluids with different 0.1g, 0.2g and 0.3g in 100ml of brine were added with equal concentrations of 100ml of formulated xanthan gum.

Crude Oil Properties: The crude oil sample was obtained from a field from Niger Delta of Nigeria and has the following properties: specific gravity of 0.860, density of 0.8958g/cm^3, viscosity of 43.022cP and ^{o}API gravity of 33.99 at the 29^{o}C.

3.2 Experimental Procedure

- The fourteen unconsolidated Niger - Delta core (plug) samples were prepared, cleaned, and fully dried in an oven.
- The weight, length and diameter of each prepared core was measured, and the result is presented in Table 1.
- The fourteen core samples were fully saturated in a brine water of the different 30,000ppm and 50,000ppm concentrations as to measure the saturated weight of various core samples.
- Pore volume of each core sample was estimated by removing the saturated weight from dry weight and the outcome was divided by the density of the different brine solution of 30,000ppm and 50,000ppm. (Equation 1 and Table 2).
- Porosity determination was done by using the bulk volume result (Table 1) and pore volume result (Table 2) using Equation 2.
- The flooding experiment started by injecting crude oil into the core to displace the brine solution. It should be noted that not all the brine solution was displaced, and the remaining water is known as connate water.
- The same quantity of oil that entered the unconsolidated core is equivalent to brine solution displaced from the core samples at constant flow rate of 0.9091cc/sec.
- The brine was injected (secondary recovery) into the core to displace crude oil and the amount of oil recovered was measured and recorded. The laboratory brine water injection was a control experiment.
- Other laboratory experiments were carried out following the above procedures. The water breakthrough time was recorded.
- The different concentrations of xanthan gum polymer, xanthan gum/SiO2 hybrid and silicon nanofluid at different concentrations of 0.1wt%, 0.2wt% and 0.3wt% (Table 4) were injected into the core until no oil could be recovered at the residual oil saturation.
- Finally, the unconsolidated core was removed from the core-holder and re-weighted, the recovered oil was measured and change in permeability was determined using Equation 3.

Pore Volume Equation: $$PV = \frac{W_{sat.plug} - Weight_{dry\ plug}}{P_{NaCl}} \qquad (1)$$

Where; $W_{sat.plug}$ = weight of saturated plug, $Weight_{dry\ plug}$ = weight of dry sample, P_{NaCl} = density of Brine

Porosity: $Porosity, \emptyset = \frac{P.V}{B.V} \times 100\%$ (2)

Where, P.V = pore volume, B.V = bulk volume

Permeability: $K = \frac{Q\mu_{NaCl/KCl}L_{plug}14700}{A_{plug}\Delta P}$ (3)

Where, Q = flow rate, μ_{NaCl} = viscosity of NaCl/KCl (Brine), L_{plug} = length of plug, A_{plug} = cross section area of plug, ΔP = differential pressure and K = permeability

4. Results and Discussion

The results of the experimental study on the effect of polymer (Xanthan Gum) and polymer-Nanoparticle hybrid (Xanthan Gum/Silicon Oxide) for enhanced oil recovery using different salinity concentration are presented in this section. The polymer and polymer-nanoparticle used are xanthan gum (XG) and silicon oxide (S_iO_2) with different brine concentrations of 30,000ppm and 50,000ppm.

4.1 Petrophysical Properties of the Formation

The result of bulk volume for each core sample are represented in Table 1. The plug samples with identity of P31, P32, P33, P34, P35, P36 and P3S are saturated with 30,000ppm brine while those with P51, P52, P53, P54, P55, P56 and P5S identities are saturated with 50,000ppm as indicated in (Table 1). Bulk volume is the total sand volume used to form the core sample excluding the volume of the screen. The grain size of the sieved formation used in preparing the encapsulated plug is between 425µm-625µm. The results obtained from measurement of bulk volume for the plug samples of 30,000ppm brine concentration ranges from 57.46 to 62.68cm^3 and 56.54 to 62.78 cm^3 for 50,000ppm brine concentration are (Table 1).

Table 1: Bulk Volume of Encapsulated Plug

Sample Plug ID	Saline Concentration	Total Length of Plug Length (cm)	Plug Diameter (cm)	Plug Radius (cm)	Bulk Volume (cm^3) $\pi r^2 h$
P31		7.05	3.3	1.65	60.3
P32		6.8	3.28	1.64	57.46
P33		7.24	3.32	1.66	62.68
P34	30,000ppm	7.07	3.3	1.65	60.47
P35		6.78	3.3	1.65	57.99
P36		7.3	3.28	1.64	61.68
P3S		6.89	3.28	1.64	58.22
P51		6.98	3.32	1.66	60.43
P52		6.79	3.28	1.64	57.29
P53		7.34	3.3	1.65	62.78
P54	50,000ppm	6.82	3.28	1.64	57.63
P55		6.95	3.32	1.66	60.17
P56		6.61	3.3	1.65	56.54
P5S		7.31	3.32	1.65	62.52

The pore volume is the total volume of small openings/spaces in the bed of the adsorbent particle. It's an indication of the volume of fluid that can be occupied by the pore space. The higher the pore volume /porosity the higher the volume of fluid that can be contained in the core and the better the reservoir formation. The results of the calculated pore volume of the core samples varies from 25.86 to 28.97cm^3 for 30,000ppm brine concentration and 26.36 to 28.73 cm^3 for 50,000ppm brine concentrations (Table 2). The porosity of the porous medium (Sand pack) was calculated from the bulk Volume (Table 1) and pore volume of the samples using Equation 2. The porosity result is shown in Table 2.

Table 2: Pore Volume and Porosity of the Plug Samples

Sample Plug ID	Saline Concentration	Wt of Dried plug + screen + foil	Wt of Sat. plug + screen + foil	Wt of fluid within the pores	Density of Sat. Fluid (g/cm^3)	Pore Volume	Bulk Volume(cm^3) $\pi r^2 h$	Porosity (%)
P31		136.67	164.7	28.03	1.0191	27.51	60.3	45.62
P32		133.75	160.11	26.36	1.0191	25.86	57.46	45.01
P33		137.43	166.62	29.19	1.0191	28.64	62.68	45.69
P34	30,000pm	135.64	163.75	28.11	1.0191	27.58	60.47	45.61
P35		136	163.54	27.57	1.0191	27.02	57.99	46.59
P36		138.48	168.01	29.53	1.0191	28.97	61.68	46.97
P3s		133.23	160.82	27.6	1.0191	27.08	58.22	46.51
P51		134.84	163.41	28.57	1.0321	27.68	60.43	45.81
P52		133.92	161.13	27.21	1.0321	26.36	57.29	46.01
P53		136.81	166.46	29.65	1.0321	28.73	62.78	45.76
P54	50,000pm	134.57	161.75	27.18	1.0321	26.33	57.63	45.69
P55		134.8	162.82	28.02	1.0321	27.15	60.17	45.12
P56		132.57	159.82	27.25	1.0321	26.4	56.54	46.69
P5s		134.07	163.59	29.52	1.0321	28.6	62.52	45.75

Permeability is the ability of the core sample to allow fluid to flow through it. It was measured by injecting water into core at a flow rate 0.9091 cm^3/sec and the pressure difference was recorded for every experiment. The permeability(K) of the sand packed was estimated using Darcy's law equation as shown in Equation 3. Permeability of the core samples were measured before and after flooding with different EOR dispersing agents as shown in Table 3.

Table 3: Result for Permeability of the Plug Sample

Fluid ID	Fluid Concentration		K_i (mD)	K_f (mD)	ΔK (mD)	Percentage Recovery (%)
F31	XG-0.1wt%		342.55	256.91	85.64	73.89
F32	XG-0.2wt%		341.78	256.33	85.45	74.94
F33	XG-0.3wt%		340.71	250.39	90.32	72.13
F34	XG/S_iO_2-0.1wt%		380.12	325.82	54.3	85.89
F35	XG/S_iO_2-0.2wt%	30,000ppm	376.34	322.58	53.76	89.01
F36	XG/S_iO_2-0.3wt%		343.28	277.72	65.56	84.55
F3S	S_iO_2/brine 0.2wt%		344.27	258.2	86.07	70.78
F51	XG-0.1wt%		376.94	282.7	94.22	71.25
F52	XG-0.2wt%		348.05	261.04	87.01	73.29
F53	XG-0.3wt%		345.48	250.47	95.01	72.01
F54	XG/S_iO_2-0.1wt%		454.43	378.69	75.74	81.08
F55	XG/S_iO_2-0.2wt%	50,000ppm	453.63	378.03	75.6	82.64
F56	XG/S_iO_2-0.3wt%		450.1	371.15	78.95	79.12
F5S	S_iO_2/brine 0.2wt%		282.38	286.79	95.41	68.92

4.2 Results of Oil Recovery Using Tertiary and Secondary Methods

Density is the mass of object per unit volume. It measures how dense a fluid can be. The results for both density and viscosity using formulated EOR agents of xanthan gum, xanthan-silicon oxide hybrid, and silicon oxide nanofluid for different concentrations of 30.000ppm and 50,000pm brine of 0.1%wt, 0.2%wt and 0.3%wt are presented in Table 4. The density measurement is important because it will be used to determine the fluid kinematic viscosity. Kinematic viscosity is a ratio of dynamic viscosity to density and dynamic viscosity is the measure of fluid's internal resistance to flow. The higher the fluid's viscosity the more it's resistance to flow. One of the characteristics of a good EOR agent is one that can increase the viscosity of the brine. The results of kinematic and dynamic viscosities of the polymer, polymer – nanoparticles hybrid, nanofluids are presented in Table 4. It can be observed that the viscosity of polymer-nanofluids slug using 30,000ppm brine concentration is higher than those formulated with 50,000ppm. The fluids samples of F3S and F5S, which are samples formulated with silicon oxide nanoparticle and brine for both brine concentrations has the lowest viscosity. The polymer solutions' viscosity improvement is due to the adsorption of the polymer on the S_iO_2 particle surface driven by a hydrogen-bonding based interaction. Second reason can also be attributed to the interaction between polymer and nanoparticles through electrostatic, van der Waals and hydrophobic interaction. There was a decrease in viscosity of EOR agents of xanthan gum than those xanthan gum/silicon oxide hybrids. Viscosity reduction and degradation of xanthan gum by incremental salt addition is because of dipole ionic interaction among the formation water cations (C_a^{+2}, N_a^{+}) and oxygen (COO_) of ester in xanthan polymer chains [22].

Table 4: Result for Density /Viscosity of the Flooding Sample and Crude

Fluid ID	Fluid Concentration	Brine Concentrations	Efflux time	Viscometer constant150/60lb	Density of fluid	Kinematic viscosity	Dynamic viscosity (cp)
F31	XG-0.1wt%		24.88	0.036415	1.0159	0.9060	0.9204
F32	XG-0.2wt%		27.38	0.036415	1.0171	0.9970	1.0141
F33	XG-0.3wt%		28.28	0.036415	1.0164	1.0298	1.0467
F34	XG/S_iO_2-0.1wt%	30,000ppm	29.91	0.036415	1.0148	1.0892	1.1053
F35	XG/S_iO_2-0.2wt%		30.28	0.036415	1.0153	1.1026	1.1195
F36	XG/S_iO_2-0.3wt%		31.74	0.036415	1.0157	1.1558	1.1740
F3S	S_iO_2/brine 0.2wt%		28.06	0.036415	1.0153	1.0218	1.0374
F51	XG-0.1wt%		26.47	0.036415	1.0273	0.9639	0.9902
F52	XG-0.2wt%		28.58	0.036415	1.0281	1.0407	1.0670
F53	XG-0.3wt%		30.76	0.036415	1.0288	1.1020	1.1324
F54	XG/S_iO_2-0.1wt%	50,000ppm	27.43	0.036415	1.0268	0.9989	1.0256
F55	XG/S_iO_2-0.2wt%		28.23	0.036415	1.0272	1.0280	1.0560
F56	XG/S_iO_2-0.3wt%		32.34	0.036415	1.0281	1.1193	1.1508
F5S	S_iO_2/brine- 0.2wt%		29.19	0.036415	1.0263	1.0630	1.0909

4.3 Recovery of Crude Oil by Water and Tertiary Methods

Chemical-enhanced oil recovery (CEOR) was conducted using a xanthan gum solution and a xanthan gum/S_iO_2 hybrid using fourteen (14) core plugs of Niger Delta sand pack at a temperature of 29°C. The results of the hybrid flooding experiment were compared to those of the xanthan gum solution alone and silicon oxide nanofluids after a waterflooding process. The solutions of xanthan gum, xanthan/S_iO_2 hybrid and Silicon oxide nanofluid were separately examined as enhanced oil recovery agents using different concentrations of 0.1wt%, 0.2wt% and 0.3wt% in this study. 0.2wt% concentration of silicon oxide nanofluid was also used as part of evaluation. The bare Xanthan gum solution, Xanthan gum/S_iO_2 hybrid and silicon oxide nanofluid increased oil recovery after the waterflooding process in both brine concentrations of 30,000 ppm and 50,000ppm. The concentrations of the polymer/nanoparticle hybrid with 30,000ppm gave the highest cumulative oil recovery ranging from 84.55% to 89.01% than the polymer stand alone and silicon oxide nanofluids (Table 5). The Xanthan gum/S_iO_2 hybrid demonstrated a better cumulative oil recovery even in higher brine concentration of 50,000ppm with recovery range of 79.12% to 82.64% as to compare to bare Xanthan gum that recovered OOIP in the range of 71.25% to 74.94% (Table 5).

It can also be discovered, as the concentration of xanthan gum increases from 0.1wt% to 02. wt.% there was also an increase in cumulative oil recovery for the bare polymer, but at 0.3wt% the recovery dropped due to the adsorption of polymer on the formation leading to the plugging of pore formations. For the xanthan gum/S_iO_2 hybrid, the cumulative recovery also increases with an increase in concentrations but there was a slight reduction of oil recovered at the concentration of 0.3wt% as depicted in Fig. 4. Table 5 and Fig. 4 illustrates that the xanthan gum/S_iO_2 hybrid outperformed the bare Xanthan gum solution and silicon oxide nanofluids in terms of oil recovered, particularly at the concentration of 30,000 ppm. This is attributed to the synergy effect of xanthan gum/S_iO_2 hybrid, which improves viscosity, stability, and mobility control, thereby increasing oil efficient mobilization particularly at 0.2wt% fluid concentration. It is known that generally polymer degrade in higher salinity, but it is observed from this research study that the presence of nanoparticle in xanthan gum also enhanced the performance of the polymer even at higher brine concentration of 50,000ppm. The result agrees with the findings of [23] and [24] that the synergy of polymer and silicon performed better than bare polymer.

Table 5: Summary of the Oil Recoveries from Samples

Fluid ID	Fluid Concentration	Salinity Concentration (ppm)	Oil initially in Place	Breakthrough Time @Drainage	Secondary Recovery (ml)	Tertiary recovery (ml)	Cumulative recovery (ml)	Percentage Recovery (%)
F31	XG-0.1wt%		21.0	56.51	12.6	2.92	15.52	73.89
F32	XG-0.2wt%		24.0	63.82	14.4	3.59	17.99	74.94
F33	XG-0.1wt%	30,000ppm	23.0	61.14	13.8	2.79	16.59	72.13
F34	XG/S_iO_2-0.1wt%		22.0	57.92	13.2	5.7	18.9	85.89
F35	XG/S_iO_2-0.2wt%		24.0	63.81	14.4	6.96	21.36	89.01
F36	XG/S_iO_2 0.3wt%		23.0	60.45	13.8	5.65	19.45	84.55
F3S	S_iO_2/brine 0.2wt%		22.0	58.14	13.2	2.37	15.57	70.78
F51	XG-0.1wt%		23.0	60.75	13.8	2.59	16.39	71.25
F52	XG-0.2wt%		24.5	64.51	14.7	3.25	17.95	73.29
F53	XG-0.3wt%	50,000ppm	21.0	55.94	12.6	2.52	15.12	72.01
F54	XG/S_iO_2-0.1wt%		23.0	59.5	13.8	4.85	18.65	81.08
F55	XG/S_iO_2-0.2wt%		22.0	55	13.2	4.98	18.18	82.64
F56	XG/S_iO_2-0.3wt%		22.0	57	13.2	4.21	17.41	79.12
F5S	S_iO_2/brine 0.2wt%		24.0	64.18	14.4	2.14	16.54	68.92

From this experimental study, it can be found that the synergy effect of xanthan gum and silicon oxide as a hybrid both in 30,000ppm and 50,000ppm increase oil recovery better than standalone polymer and silicon nanofluids. (Fig.4). These results match with findings of [25] who showed that additional oil recovery can be obtained with a high concentration of polymer solutions but reduces at a very high concentration due polymer adsorption on the rock surface. In the case of (XG/S_iO_2) decreasing of recovery factor at slug concentration increases above 0.3wt% resort to an accumulation of S_iO_2 nanoparticles at higher concentrations, which in turn cause clogging of the pore throat and permeability reduction. These results are highly compatible with [26] who stated that increasing hydrophilic nanoparticles concentration adversely affects the oil recovery owing to impairment of the reservoir rock permeability.

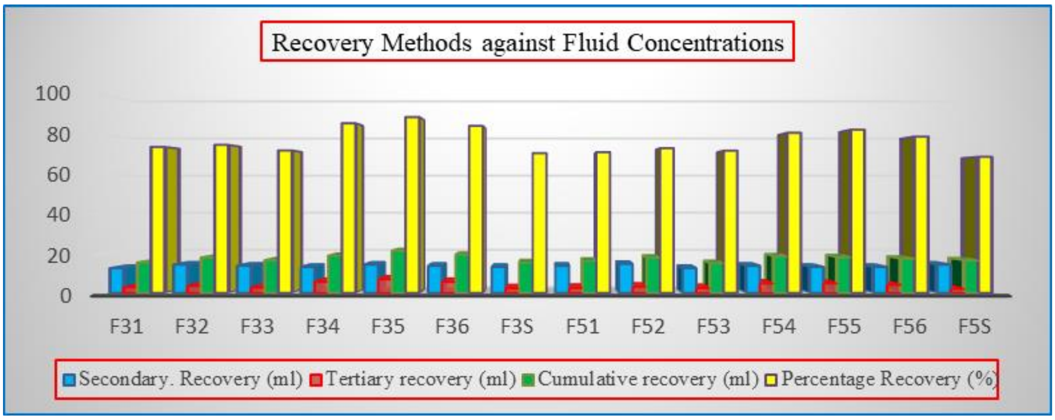

Figure 4: Secondary, Tertiary, Cumulative recovery against Fluid concentrations

4.4 Result for Permeability Change

After the secondary and tertiary flooding, the core's permeability was measured as to evaluate the extent of formation damage caused by various EOR agents for the different brine concentration of 30,000ppm and 50,000ppm. There is a decrease in permeability of the reservoir formation after the tertiary flooding most especially with polymer fluids and the fluids that contains higher concentration of nanoparticle. From Table 3 and Fig. 5, permeability alteration for all the polymer concentrations evaluated ranges from 85.45 md to 94.22 md for both 30,000 and 50,000ppm brine concentrations and 53.76 md to 78.95 for polymer/nanoparticle hybrid. The lowest value of 54. md permeability change was gotten from fluid concentration of 0.2wt% of xanthan gum/S_iO_2 hybrid as to compare to 85.45 md and 65.56 md of 0.2wt% in bare xanthan gum and silicon oxide nanofluid for 30,000ppm brine. The presence of nanoparticle in polymer reduced formation damage and increased oil recovery as also reported by [27].

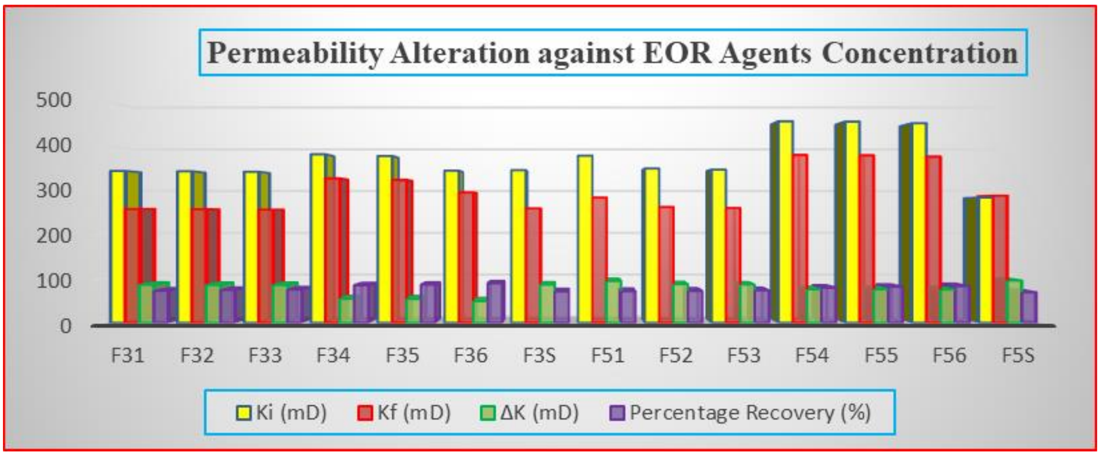

Figure 5: Permeability Alteration for different concentration of EOR agents

5. Conclusion

The results from the experimental tests have proved the effectiveness of the synergy of the silica oxide (S_iO_2) nanoparticles and Xanthan Gum polymer in improving oil recovery in both 30,000ppm and 50,000ppm brine concentrations. The presence of silicon oxide in xanthan gum has improved the viscosity of polymer solution, which reduced the mobility ratio between the injected fluids and the oil in the reservoir. Secondly, this synergised polymer-nano-silica solution reduced the permeability damage of the formation from 94.22 md to 53.76 md. which led to good oil recovery but can block formation pores at higher concentration. Generally, the xanthan gum/ silicon oxide hybrid in both 30,000ppm and 50,000ppm gave higher oil recovery than standalone polymer and silica nanofluids for the different brine concentrations examined. All the concentrations that are based on 30,000ppm brine performed better than 50,000ppm based on viscosity, permeability change, and oil recovery. Thus, the recovery of the oil is increased by 85.89% by using 0.1wt% polymer-silica nanofluid flooding and increased up to 89.01% when injecting 0.2wt% polymer-silica nanofluid solution with a slight drop 84.55% in 0.3wt%. This study recommends the use of polymer-nanoparticle for high salinity reservoir.

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