Petroleum and Coal

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Performance Study of Polymer-Assisted Low-Salinity Flooding for Enhanced Oil Recovery

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Received May 24, 2024; Accepted September 12, 2024

Abstract

Chemical Enhanced Oil Recovery (CEOR) using polymers have recorded high sweep efficiency and favorable recovery. Polymers can be grouped into natural and synthetic polymers. The polyacrylamide (PAM) and xanthan gum (XG) are the most commonly utilized in polymer CEOR but XG is preferred for CEOR due to its tolerance to temperature, mechanical shear and salinity. XG have been utilized for field-scale CEOR studies but is very expensive to the economy of developing the countries. These exorbitant cost have driven to the search for suitable local alternatives which if successful, can improve CEOR and be exported to the global market. In this work, performance study was conducted to determine the potentials of polymer-low salinity flood to improve oil recovery. *Terminalia mantaly* exudate (TME) and Okra (OK) were utilized as local polymer while Xanthan gum (XG) was utilized as conventional polymers. FTIR characterization, aqueous stability, viscosity and core-flooding study were carried out in this study. From the FIIR study TME and OK recorded similar hydrophilic and hydrophobic functional group with XG, and can be categorized as polysaccharides. From Aqueous Stability study, TME, OK and XG all formed colloidal phase with water at higher temperature. From viscosity test, OK and XG recorded low viscosity tolerance in saline environment while TME recorded high viscosity tolerance in saline environment. From polymer flooding OK yielded additional 20% recovery while XG an TME recorded 17.33% and 16.89% additional recoveries respectively. In polymer-low salinity flooding, the CEOR additional crude oil recovery of OK, XG and TME increased by 11.1%, 7.7% and 7.9% respectively. The polymer-low salinity hybrid solution, recorded better recovery and this is due to synergy between the polymer an low salinity solution.

Keywords: *Chemical Enhanced Oil Recovery; Polymers; Viscosity; Adsorption.*

1. Introduction

Conventional oil reservoir begins to produce crude oil using their natural energy as soon as they are perforated into. This natural energy are on the basis of their drive mechanism such as solution/dissolved gas, gas-cap, water drive, gravity drainage, combination drive [1]. Once these natural reservoir is depleted, secondary recovery approach is utilized. In secondary recovery, water and/or gas is injected into the reservoir for the purposes of pressure maintenance and sweep efficiency [2]. When the secondary recovery becomes ineffective due to the presence of viscous and capillary forces which traps the crude oil within the pores of the reservoir rock, enhanced oil recovery (EOR) approach is deployed [3]. EOR is an approach of recovery crude oil (liquid hydrocarbon) where the compression energy required to mobilize the oil to the wellbore is depleted with reduction in reservoir pressure [4]. The EOR approach are mainly classified into thermal and non-thermal EOR. Thermal EOR is not applied to thin pay-zones, huge depth or underlying aquifer reservoirs. This is due to the heat loss to the under-burden and overburden strata [5]. The environmental impact caused by greenhouse gas is another constraint [6] and this have resulted in the global preference of non-thermal EOR

methods. Chemical EOR, a non-thermal technique have shown potentials in improving oil recovery due to its high efficiency, experimental nature and less environmental concerns. Several chemicals such as polymer, nanoparticles, alkalis and surfactant have been utilized for CEOR [7]. These chemicals modify the rock-fluid and/or fluid-fluid interaction, enhances the sweep efficiency or causes higher pore-scale displacement of efficiency based on the type utilized [8]. CEOR using polymers have recorded global acceptance due to abundance & low cost of polymer chemicals, high sweep efficiency and favorable recovery. Polymers are high molecular weight chemicals comprising of repeated unit monomers bonded by a covalent bond [9], and are soluble in water. Their introduction enhances the viscosity of the injectant to yield better mobility control and conformance required to eliminate viscous fingering phenomena [10]. Polymers can be grouped into natural and synthetic polymers. The natural polymers are sourced from animals and plant source such as polyesters, polysaccharides and proteins, while the synthetic polymer are derived from petroleum oil and man-made source such as polyethylene. In polymer flooding, polyacrylamide (PAM) and xanthan-gum (XG) are they most commonly use [11]. PAM have higher viscoelastic behavior than XG solution in freshwater at same concentration but have lesser viscoelastic properties than the biopolymer in brine [12]. XG has high tolerance for temperature, mechanical shear and salinity, is been utilized as alternative to PAM for chemical EOR [13]. These conventional polymers are plagued with retention problems, cost and relative abundance [14], and this have necessitated studies for local alternatives which if successful can replace them for CEOR.

Several performance studies of polymer aimed at mobility control have been conducted by several authors. Ade *et al.* [15] compared the EOR performance of gum arabic, okra and ogbonno. From the result of their experimental evaluation okro yielded the best performance as it recorded 63.7% oil recovery while gum arabic and ogbonno recorded 53.01% and 47.3% oil recovery respectively. Ajabuego *et al.* [16] conducted a comparative CEOR performance study between archi, ogbonno and exudates gum. From their experimental evaluation, exudates gum performed better than the other polymers as it yielded 35.48% oil recovery while archi and ogbonno recorded 26.67% and 31.17% recovery respectively. Gbonhibor and Onyekonwu [17] carried out a CEOR performance investigation on aqueous beans. From their experimental study, the local polymer indicated a polymeric behavior as it recorded 44.6% additional oil recovery after waterflood. Abdulraheem *et al.*, [18] conducted a CEOR study between modified gum arabic, natural gum arabic, xanthan gum and hengfloc. From their experimental study, modified gum arabic yielded the best performance as it recorded 31.99% recovery while natural gum arabic, xanthan gum and hengfloc recorded 22.96%, 18.3% and 22.59% additional recovery. Obuebite *et al.* [19] compared the CEOR performance of ewedu, okro and editan in soft and hard brine. From their experimental evaluation in soft brine, okro yielded the best recovery as it recorded 26.3% additional oil recovery while ewedu and editan recorded 22.9% and 18.1% additional oil recovery. In hard brine, okro recorded 23.4% additional recovery while ewedu and editan recorded 18.4% and 14.1% additional oil recovery. Fadairo *et al.* [20] conducted a comparative CEOR study between gum arabic and starch extract from banana peel. From their experimental study, the extracts from banana peel performed better than gum arabic as it yielded 64.5% oil recovery while gum arabic yielded 62.6% oil recovery. Uzoho *et al.* [21] conducted a comparative EOR performance investigation between abelmoschusesculentus, brachysteiaeurycoma, irvingiagabonensis, mucunaflagellipes and detariummicrocarpiuum. From their experimental investigation abelmoschusesculentus yielded the best performance of the other polymers as it recorded incremental displacement efficiency of 5.2%. Uzoho and Onyekonwo [22] compared the CEOR performance of abelmoschusesculentus with polyacrylamide. From their experimental evaluation, abelmoschusesculentus performed better than polyacrylamide as it yielded 18.7% additional oil recovery while polyacrylamide yielded additional 12.73% oil recovery. Kerunwa *et al.* [23] conducted a comparative CEOR performance study between araucaria columnaris exudate (ACE), terminalia mantaly exudate (TME) and xanthan gum (XG). From the result of the experiment, ACE yielded the best performance as it recorded additional 15.91% oil recovery, while XG and TME recorded 14.09% and 13.18% additional crude oil recoveries respectively. However, the potentials of

these locally sourced polymer at prevailing condition needs to be comprehensively investigated to ascertain their ability to completely alternate conventional or foreign polymer reagents. In this study, *Terminalia mantaly* exudate (TME) and Okra (*Abelmoschus esculentus*) were utilized as local polymers while xanthan gum were utilized as conventional polymer. FTIR characterization, were conducted to ascertain the potentials of the aqueous stability, viscosity, adsorption and core-flooding local polymers in improving oil recovery.

2. Materials

The materials utilized for the evaluation include: 2 locally-sourced agro-polymer; *Terminalia mantaly* (TME) and Okra (OK), conventional polymer: Xanthan gum (XG), industrial salt (NaCl, KCl and $MgCl_2$), Buck 530 modelled IR-Spectrophotometer, measuring cylinder, co-reflood apparatus, weighing balance, beakers, syringe, lab oven, Ostwalds viscometer, density bottle, hot plate and crude oil. Crude Oil with dynamic viscosity of 4.87cP @ambient condition, API gravity of 34.97°API and specific gravity (SG) of 0.84, was sourced from well-X in a Niger-Delta Oilfield.

2.1. Preparation of polymers

TME was prepared using Michael *et al.* [24] approach. The gum was recovered from the incised section of the tree and dried for 5-days. 100g of the dried gum was purified with deionized water to remove impurities before been dried in a lab oven at temperature 50°C for 48hrs. The dried gum was hydrated in water-chloroform blend (95.5%:0.5%) for 5-days to soften and extract the mucilage. A thorough activity was conducted using white muslin material to further recover mucilage left in the gum. The gum was precipitate using absolute ethanol, and this precipitates were washed out using 100ml of dimethyl ether. The precipitated gum was dried in a lab oven at temperature of 50°C for 10hrs, before crushed into powder. The crushed gum were sieved uniform size gum, before being stored in an airtight container. OK was prepared using Obuebite and Okwonna [25] method. The natural polymer was washed 3-times with fresh water to remove impurities. The washed polymer was sliced into small piece and dried in a lab oven for 7days at 32°C temperature to reduce moisture content. The dried sample was pulverized and sieved to obtain uniform finer particles, which were packed and sealed in an airtight container to prevent contamination.

2.2. Preparation of brine

The low salinity brine solution was formulated with Kerunwa [3] method. Synthetic seawater with formulation depicted in Table 1 were prepared and diluted 8 times to yield the low salinity solution depicted in Table 2. The synthetic seawater density and viscosity were determined to be 1.0298g/cm^3 and 0.9321cP respectively, while LS-A density and viscosity is 1.0035g/cm^3 and 0.9038cP respectively.

Table 1. Synthetic seawater formulation.

S/N	Brine	NaCl	KCl	$MgCl_2$	TDS (x1000ppm)
1	Synthetic Seawater	29.69	0.89	5.76	36.34

Table 2. Low-salinity brine formulation.

S/N	Brine	NaCl	KCl	$MgCl_2$	TDS (x1000ppm)
1	LS-A	2.969	0.089	0.576	3.634

3. Methods

3.1. FTIR characterization

Fourier transform infrared spectroscopy (FTIR) evaluation was conducted on the polymers using Buck 530 modelled IR-spectrophotometer. 0.5g of the polymer agents were blended with 0.5g of potassium-bromide (KBr) powder. 1mL of Nujol (reagent utilized for preparation of 530 modelled IR-spectrophotometer) was injected to into the blend using syringe to yield a solution, before introduction to the instrument sample. At the instrument sample, the solution was allowed to scan at 600-4000 cm^{-1} wavelength to derive spectra height. The FTIR spectroscopy yielded plots in absorbance spectra form, showing the chemical bonds and molecular structures of the selected polymers. The spectral peak values were cross-matched with reference library (catalogue) of the equipment to identify their corresponding functional group present.

3.2. Aqueous stability test

To carry out fluid-fluid interaction evaluation, a phase stability experimental on the 4 polymers and brine solution were carried out to study non-homogeneity such as solution cloudiness, phase separation and precipitate presence in the aqueous phase. TME, OK and XG with concentration 0.25%wt were introduced into 400mL of brine formulation.

3.3. Polymer viscosity test

The density of the polymer solutions were determined using the density bottle before the fluid was introduced into an Ostwald's viscometer, were efflux time was determined. These efflux time was multiplied by viscometer constant to derive the kinematic viscosity. Absolute viscometer was derived by multiplying fluid's kinematic viscosity with its density.

3.4. EOR core flooding

Oil displacement was conducted to derive the EOR potentials of the selected polymer concentration 0,25% wt. The dry weight, length and diameter of the core samples were derived before their placement into the core saturator. Synthetic brine with concentration depicted in Table 1 was injected into the saturator and the system pressurized to 2500psi to achieve full saturation over 48hrs period. After 48hrs the cores were depressurized and reweighed before introduction into core-holder as shown in Figure 1 at confining pressure of 1000psi.

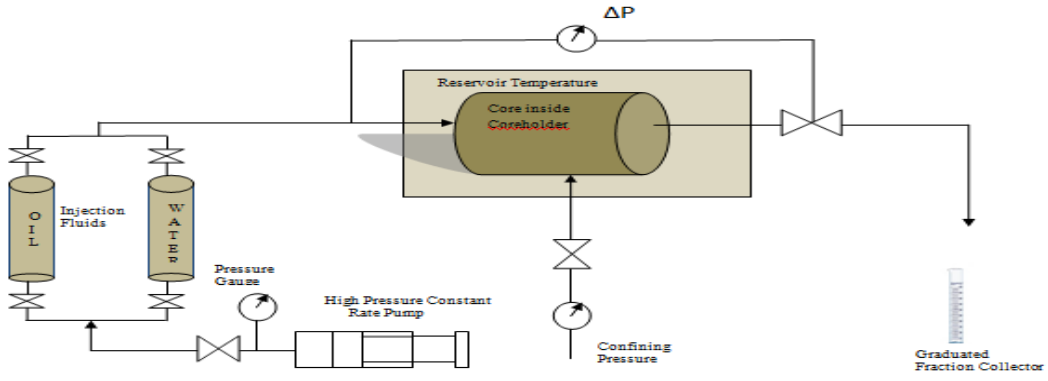

Fig. 1. Schematic of the experimental core-flood setup.

At 2cc/sec rate, the synthetic brine depicted in Table 1 was injected to ensure full removal of entrapped bubble and 100% saturation. Crude oil was introduced continuously into the core at 2cc/sec rate until Swi (initial water saturation) was attained. The crude oil was displaced by continuous brine injection at 2cc rate until Sor (residual oil saturation) was obtained with oil recovery during brine flooding recorded. After the determination of Sor, 3 method of CEOR was carried out. In the first scenario LS-A was utilized for low-salinity flooding, In the second

scenario polymer chemicals were utilized for polymer flooding while polymer-LS-A were utilized for polymer assisted low-salinity flooding. The core-flooding were carried out at ambient pressure and temperature condition. Figure 1, shows the typical experimental core-flood.

4. Results and discussion

4.1. FTIR characterization

Figures 2-4 depicted the FTIR spectra for XG, OK, ARF and TME. As shown in Figure 2, XG recorded wavelength of 3500cm^{-1}, 3100cm^{-1}, 2850cm^{-1} , 2600cm^{-1} , 2200cm^{-1} , 1900cm^{-1} , 1700cm^{-1} 1600cm^{-1} 1400cm^{-1} , 1320cm^{-1} , 1180cm^{-1} , 1000cm^{-1} 830cm^{-1} and 625cm^{-1} corresponding to hydroxyl stretch, C-H asymmetric stretch, methylene CH stretch, alkanes stretch, alkane stretch, carbonyl stretch, carbonyl stretch, symmetric COO stretch, asymmetric COO stretch, akyl ether C-O stretch, carboxylic acid CO stretch, ethers C-O stretch, chloro-compound C-CL stretch and chloro-compound stretch. As shown in Figure 3, OK recorded wavelength of 3791cm^{-1}, 3100cm^{-1}, 2900cm^{-1} , 2600cm^{-1} , 2050cm^{-1} , 1652cm^{-1} , 1496cm^{-1} 1398cm^{-1} 1059cm^{-1} , 851cm^{-1}, 789cm^{-1} and 538cm^{-1} which corresponds to secondary amine N-H stretch, C-H assymetric stretch, methylene CH stretch, alkanes symmetric stretch, alkanes symmetric stretch, carbonyl stretch, primary amine N-H stretch, C-H bending, C-H bending, akyl ester C-O stretch, chloro-compound C-CL stretch, chloro-compound C-CL and bromo-compound C-BR stretch respectively.

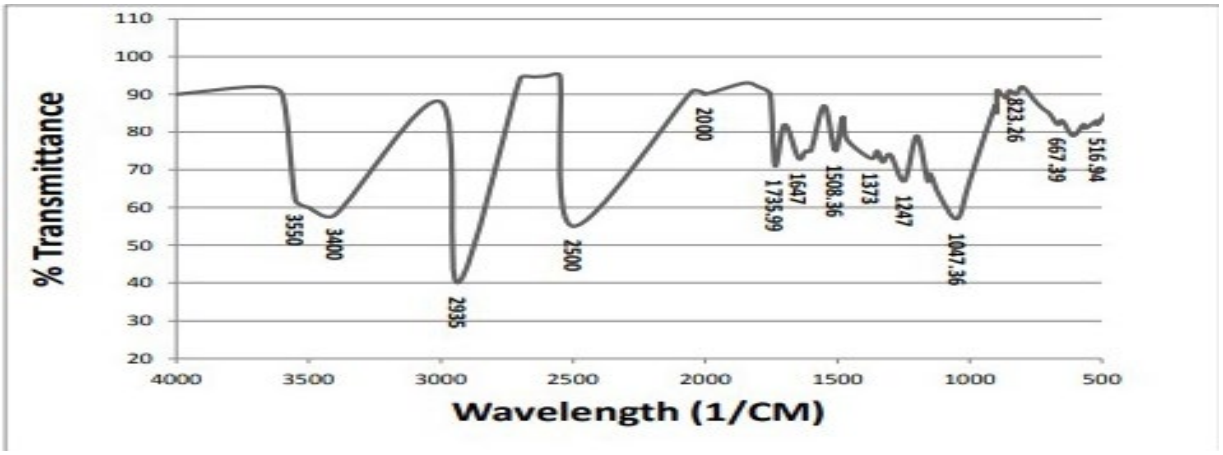

Fig. 2. FTIR spectra of XG.

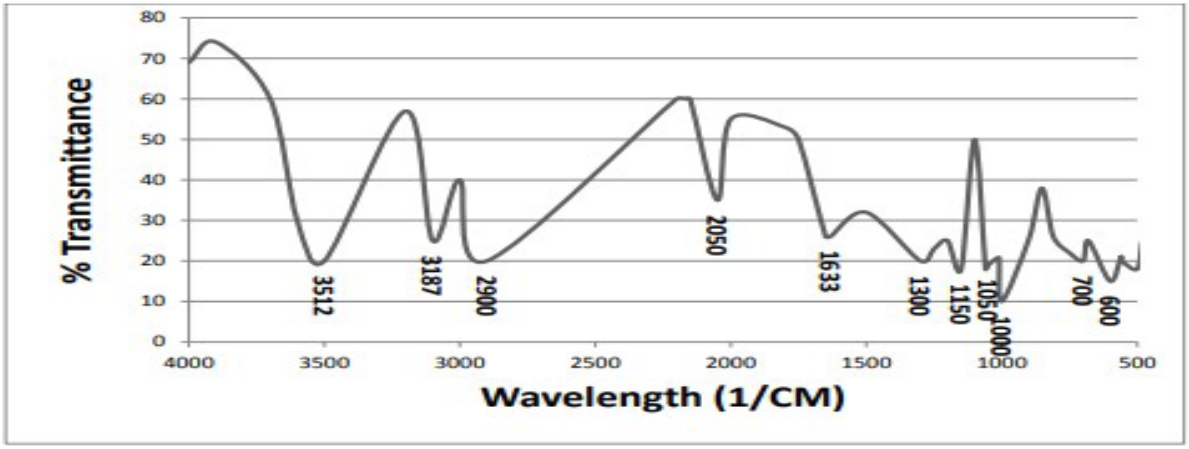

Fig. 3. FTIR spectra of OK.

As shown in Figure 4, ARF recorded wavelength of 3791cm^{-1}, 3187cm^{-1}, 2900cm^{-1} , 2050cm^{-1} , 1300cm^{-1} , 1150cm^{-1}, 1050cm^{-1} , 1000cm^{-1}, 700cm^{-1} and 600cm^{-1} which corresponds to secondary amine N-H stretch, hydroxyl, methylene, carbonyl stretch, Alkenes symmetric stretch, Ester C-O stretch, Ester C-O stretch, Amide stretch, Alkyl Ester, Chloro-Compound and Bromo-Compound respectively. As shown in Figure 4, TME recorded wavelength of 3500cm^{-1}, 3400cm^{-1}, 2925cm^{-1} , 2500cm^{-1} , 2000cm^{-1} , 1735.99cm^{-1} , 1647cm^{-1} 1508.36cm^{-1} 1373cm^{-1} , 1247cm^{-1}, 1047.36cm^{-1} ,823.26cm^{-1}, 667.39cm^{-1} and 516.94cm^{-1} corresponding to secondary amine N-H stretch, hydroxyl stretch, aliphatic alkanes, alkanes stretch, carbonyl stretch, aldehyde stretch, alkenes, amide, asymmetric carboxylic acid, primary amine, primary amine, chloro-compound, chloro-compound and bromo compound respectively. Commercial XG recorded presence of acetyl, carboxyl, hydroxyl and carbonyl functional group as reported in the works of Gilani *et al.* [26], and this functional group were observed to be present in the local polymers selected for the study indicating that they are polysaccharides.

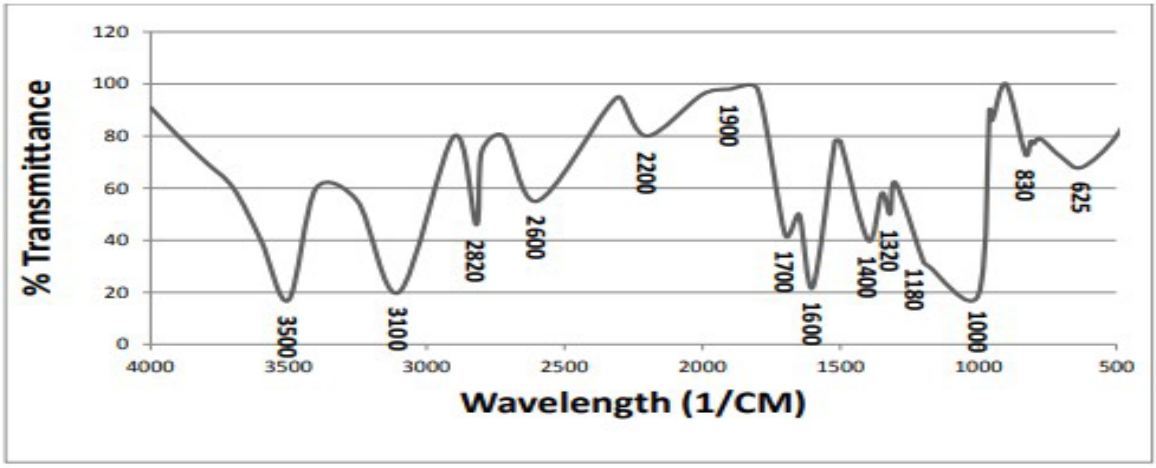

Fig. 4. FTIR spectra of (TME.

4.2. Aqueous stability

Table 3 depicts the phase behavior of the polymer. As shown in TME recorded clear solution at both ambient conditions and elevated temperature. OK recorded brown colored solution with particles setting at the top at ambient condition, while clear compatible solution were attained at elevated temperatures. XG recorded a clear solution at both ambient and elevated temperature. The phase behavior of polymer showed that the polymers are suitable for CEOR, as they are devoid of precipitates at reservoir temperature of 100°C

Table 4. Phase behavior of polymers.

Polymers	Concentration, (%)	Result @ 29°C	Result @ 100°C
XG	0.25	Clear solutions	Clear solutions
OK	0.25	Brown colored solution with particles at the top	Clear, compatible solution
TME	0.25	Clear solution	Clear solution

4.3. Polymer viscosity

Figure 5 depicts the absolute viscosity of the selected polymers in both fresh water and LS-A solution. As shown in Figure 5, XG recorded 0.9642cP and 0.954735 viscosities in fresh water and LS-A solutions respectively. TME recorded 0.8448cp and 0.847461cP viscosities in fresh water and LS-A solutions respectively, while OK recorded 0.990506cp and 0.976869cp viscosities in fresh water and LS-A solutions respectively. As observed from Figure 5, XG and OK recorded an obvious drop in viscosity with introduction of brine while TME recorded a slight increase. The drop can be attributed to the screening of the polymer chain and is in agreement

with Rellegadla *et al.* [27] which shows that polymer conformation can collapse due to charge screening. The increase in viscosity of TME is due to repulsive charge polyelectrolyte of the agro-based at increasing salinity [28].

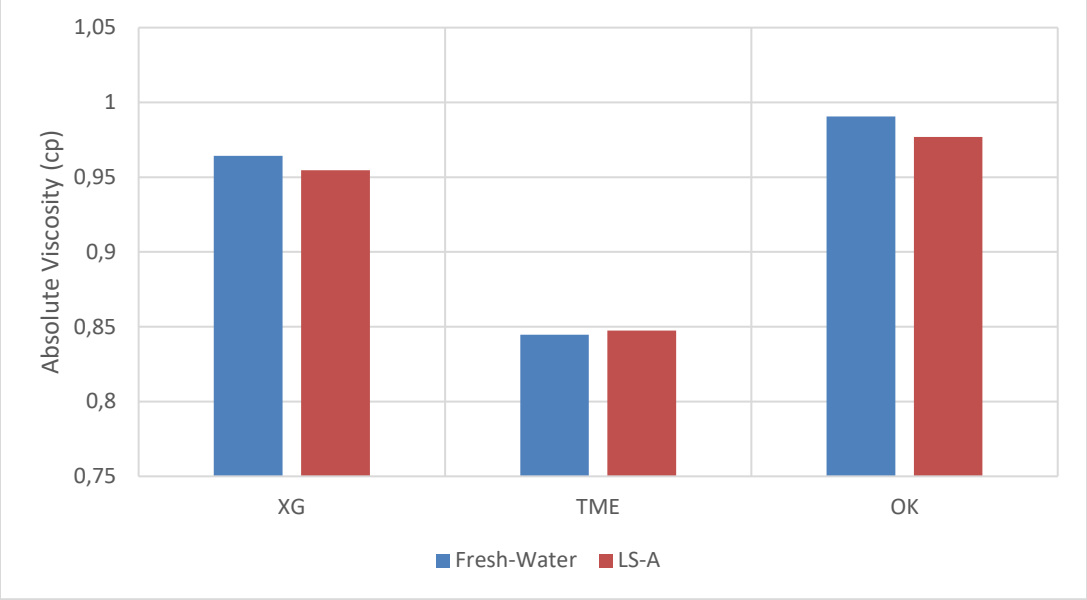

Figure 5. Absolute viscosity of polymer in freshwater and LS-A.

4.4. CoreFlood recovery

Figures 6-7 depicts the additional recovery of the selected polymers in polymer flooding and polymer-low salinity flooding.

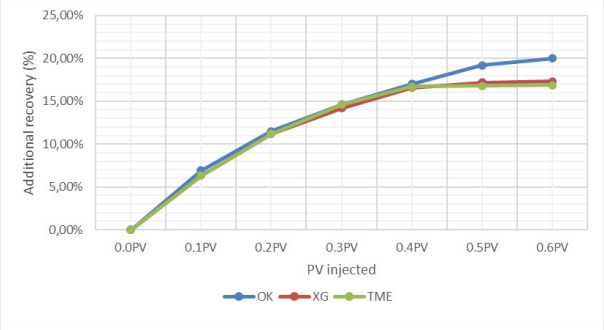

Figure 6. Additional recovery of polymer flooding.

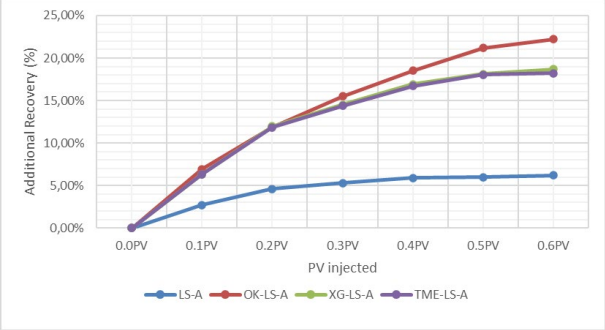

Figure 7. Additional recovery of low salinity and polymer-salinity solutions.

As shown in Figure 6, OK yielded the best CEOR performance with additional 20% crude oil recovery while XG and TME recorded 17.33% and 16.89% respectively. The performance of OK over attributed to its excellent mobility control and polymeric viscoelastic properties. As shown in Figure 7 OK-LS-A recorded best CEOR performance with additional 22.22% crude oil recovery while XG-LS-A and TME-LS-A recorded 18.67% and 18.22% additional crude oil recoveries. Comparing Figure 6 with Figure 7, the introduction of low salinity flooding to OK, XG and TME, improved their recoveries by 11.1%, 7.7% and 7.9% respectively. The CEOR performance of OK over XG and TME is attributed to better synergy between the polymer and low-salinity solution. Comparing Figures 6-7 with Figure 5, LS-A solution yielded the polymer to attain the right viscosity required for excellent mobility control and corresponding improved crude oil recovery.

5. Conclusion

The local polymer recorded similar functional groups with the conventional polymer and can be classified as polysaccharides. The local polymer formed colloidal phases with water can be utilized for CEOR without the risk of plugging-off pore channels in the reservoir. TME has high tolerance for saline environment while XG and OK has low tolerance for saline environment. OK yielded the best CEOR performance in polymer flooding with additional recovery of 20% while XG and TME recorded 17.33% and 16.89%. The introduction of LS-A to OK, XG and TME polymer solution improved their original oil recovery by 11.1%, 7.7% and 7.9% respectively.

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