

Enhancing Oil Recovery through Alkaline Flooding: Investigating Surfactant Formation and Interfacial Tension Reduction

Damilare Stephen Adepehin^{1*}, Ayodeji Bodunde Babinisi², Akintayo Ikusika³, Matthew Inalegwu Amanyi⁴, Eghwubare Akpoguma⁵, Ndianaobong Ikpe Noah⁶, Abimbola Isaac Odudu⁷, Pauline Oluwatoyin Ijila⁸

^{1*,4}Department of Physics, Federal University of Health Sciences, Otuipo, Benue State, Nigeria

²Department of Physical Sciences, Olusegun Agagu University of Science and Technology, Okitipupa, Ondo State, Nigeria

^{3,7,8}Department of Physics, Adeyemi Federal University of Education, Ondo, Ondo State, Nigeria

⁵Nuclear Technology Center, Nigeria Atomic Energy, Federal Capital Territory, Nigeria

⁶Department of General Studies, Federal College of Lands Resource Technology, Kuru, Plateau State, Nigeria

*Correspondence: damilare.adepehin@fuhso.edu.ng, Orcid number: <https://orcid.org/0000-0002-7149-4947>

ABSTRACT Alkaline flooding induces a neutralization reaction between the carboxylic acid in crude oil and the injected alkali, leading to soap formation (saponification). This process reduces water-oil interfacial tension and alters petrophysical properties, enhancing oil recovery. In this paper, the interaction between alkaline flooding chemicals and the carboxylic function of the crude oil was examined by accounting for both physical and chemical properties of the resulting neutralization reactions. Fourier Transform Infrared (FTIR) employed to examine the spectrum of the reservoir crude oil shows the presence of Carboxylic (COOH) and Carbonyl (C=O) functional groups which are responsible for the in situ surfactants formation responsible for lowering of the interfacial tension (IFT) of water and oil. This study evaluates the effect of alkaline flooding on oil recovery using sand-pack experiments. Fourier Transform Infrared (FTIR) spectroscopy was employed to analyze crude oil composition, and interfacial tension (IFT) was measured under varying NaOH concentrations. Results indicate a 6.1% increase in oil recovery compared to conventional water flooding.

KEYWORDS: Carboxylic, Alkaline, Tension, Saponification, Sand-pack

I. INTRODUCTION

Among the recent methods of enhancing the recovery of oil, alkaline flooding seems to be one of the most effective as it involves increasing the pH of the flooding water with alkaline chemicals such as the carbonate, the hydroxide and the orthosilicate of sodium (Na_2CO_3 , NaOH and NaSiO_4) [1],[2],[3],[4],[5],[6],[7],[8] and [9]. The reaction of these alkalis with crude oil reduces the tension at the interface of water and oil, separates oil into droplets on the water surface, alters the wettability of rocks and makes interfacial oil film soluble. These effects help to facilitate EOR process as they are to the benefits of improved recovery of oil. [10],[11],[12],[13],[14] and [15]. Although alkaline flooding is a widely used enhanced oil recovery (EOR) technique, its effectiveness depends on reservoir conditions, crude oil

composition, and precise laboratory validation. Alkaline flooding has been investigated by many researchers in geosciences. (Khlaifat *et al.* [16], Hornof *et al.* [17], Li *et al.* [18], Guo *et al.* [19], Bortolotti1 *et al.* [20] and Bortolotti2 *et al.* [21]) stressed that the interfacial tension (IFT) between oil and water will reduce regardless of the concentration of the alkali used and that the effectiveness of the alkaline chemical flooding of reservoirs depends largely on the reservoir rocks mineral constituents, the crude oil and the attributes of the injection fluids. They further established that concentrated alkalis, when used have the tendency of generating loss in production capacity. The formation of surfactant resulting in-situ, from the neutralization reaction between the crude oil and the alkali lowers the P^H of the flooding water. [16]. Phukan *et al.* [22] studied the effects of flooding with alkaline surfactant as against an alternate gas flooding. He concluded that the alkaline flooding lowered the IFT of the oil and water and produced an additional recovery of 14.26% of the original oil in place (OOIP) whereas the alternative gas (CO_2) flooding produced an additional recovery of 12.03% of the OOIP which is less than the percentage recovered during alkaline flooding. Sun *et al.* [23] reported the relationship between the viscosity of the injection fluid and the IFT under a particular oilfield and geological attributes of the reservoir. It was discovered that both injection viscosity and the IFT are approximately equal when a particular oilfield condition was considered. This was regardless of whether a strong alkaline surfactant polymer (SASP) or a weak alkaline surfactant polymer (WASP) was utilized for the flooding process. Considering the geological attributes, the WASP gives better and reasonable values that support better oil recovery enhancement when compared to the SASP. Sun *et al.* [23] however concluded that despite the existence of some certain irregularities in the process, the WASP is better than the SASP and can be leveraged on as the basis for oil recovery in other oilfields. Ragab and Mansour [24] worked on chemical EOR. This was with a view to enhancing the displacement of oil, improving the efficiency of the volumetric sweep and reducing the viscosity of oil/or by lowering oil-water IFT. Employing alkaline flooding, the low oil-water IFT paved way for improved oil recovery when compared to the ordinary water flooding. Arnold [25] investigated the IFT of various oil type and water of varying chemical components when alkaline flooding was carried out. Two oil samples which were detected to contain carboxylic acid group of varying concentrations were considered and in order to accurately mimic the reservoir water, an alkaline flooding agent, sodium carbonate (Na_2CO_3) was added to varying concentrations of clean (distilled) water and brine. The IFT was accurately measured by considering the pendant and spinning drops. It was discovered that the spinning reduction is applicable to all available range of studied IFT, while the pendant reduction did not work at a value below 1 mN/m. Experimental results obtained by him revealed that the distilled solution of water used produced a significant fall in the IFT and considerable emulsification while that of brine showed neither a significant fall in the IFT nor a considerable emulsification as witnessed with distilled water even when both the spinning and pendant drops were considered. A further investigation of the IFT showed that this behavior can be attributed to temperature dependencies. Akpoturi and Ofesi [26] compared the effect of local alkali to other usual laboratory alkaline flooding agents such as Sodium hydroxide (NaOH), Potassium hydroxide (KOH) and Sodium carbonate (Na_2CO_3). As against the 40% recovery of the (OOIP) that was obtained through the primary recovery process, the secondary recovery process produced 55% of the original oil in place (OOIP). Investigating the usual aforementioned alkalis and the local one, the tertiary approach recovered 66% of the (OOIP), 74% of the (OOIP), 59% of the (OOIP) and 64% of the (OOIP) when NaOH, KOH, Na_2CO_3 and local alkali were respectively used as flooding agents. Each of the alkaline solution was able to lower the IFT and produced additional recovery when compared to the only 40% obtained by the usual reservoir pressure. Adepehin *et al.* [27] estimated the important petrophysical parameters, such as the (Shale volume, V_{sh} , Permeability, K , Water saturation, S_w and the Hydrocarbon saturation, S_h) before and after enhancing the recovery of hydrocarbon in a Niger Delta field of Nigeria. Sodium hydroxide, (NaOH), Potassium hydroxide, (KOH), Ammonium hydroxide, (NH_4OH) and Lithium hydroxide, (LiOH) were used as alkaline flooding agents for recovery enhancement. In line with many works carried out in petrophysics, the shale volume and water saturation were found to have reduced after EOR while the permeability and the hydrocarbon saturation were found to have increased. Based on the work done by Adepehin *et al.* [27], 60% of the original oil in place (OOIP) was left trapped in the reservoir but the use of the aforementioned

chemicals assists in reducing the oil-water IFT and the viscosity of the crude oil. Reduction of the IFT and the viscosity gives rise to higher recoveries of hydrocarbon from the studied reservoirs. Flooding the reservoirs with Sodium hydroxide, Potassium hydroxide, Ammonium hydroxide and Lithium hydroxide, recoveries of 59.4, 64.5, 69.5 and 78.5% of the OOIP were respectively obtained which were respectively 19.4, 24.5, 29.5 and 38.5% more than the initial primary recovery of only 40% of the OOIP. Hincapie *et al.* [28] examined the effect of three different flooding agents. A combination of regular Alkaline flooding with Nanoparticles and Polymer flooding showed a drastic reduction of the water-oil IFT. The flooding agents were separately used to discover their effectiveness. It was discovered that the use of alkalis and nanoparticles facilitates an in-situ saponification which is responsible for lowering the interfacial tension (IFT) and also affects wettability to a reasonable extent. Experiment done with polymers as flooding agent showed a rapid displacement of oil, improved mobility of oil and a better oil recovery ratio (ORR). The use of all the three flooding agents was able to enhance oil recovery when compared to an ordinary primary approach which depends solely on the reservoir pressure.

Owing to the variability of the reservoir rocks and crude oil composition which are anchored on the peculiarity of oil field, alkali effect on acidic crude oil and the rocks composition is quite complex and requires a careful study. It is important to further design a proper flooding chemical slug bearing in mind the concentration and the volume of the slug. Thus, a whole lot of works are required to better understand the technology and to forestall a robust economic execution of the technology on real time oil fields. As a result of the inefficiency of conventional oil recovery methods, particularly their inability to maximize recovery from acidic crude oils, which leaves significant amounts of oil trapped in reservoirs. This research seeks to explore the novel use of alkaline flooding as a method to enhance oil recovery through the formation of in-situ surfactants that lower interfacial tension between oil and water. Examining varying concentrations of the alkaline chemicals slugs, comparison and discussion of results obtained were done following the available possibilities in the mechanisms of crude oil mobility. By investigating the interaction between alkaline agents and acidic crude oil, this work not only contributes to a deeper understanding of the mechanisms involved but also demonstrates a marked increase in oil recovery specifically, a 6.1% improvement compared to traditional methods highlighting the potential for more effective extraction techniques within the oil industry.

II. MATERIALS AND METHODS

Graded Sodium hydroxide of purity about ninety-five percent (95%) obtained from a Fine Chemical Company was used as alkaline flooding agent. The crude oil employed to experiment flooding was obtained from an oil field in the Niger Delta (Nigeria). After a thorough examination for acidic strength, the crude oil was found to have a total acid number (TAN) of 0.035 mg of KOH/g, specific gravity of 36.34° API and viscosity of about 121 mPa at a temperature of 32 °C. Sodium chloride obtained from the Fine Chemical Company was used as brine. The alkaline flooding chemical slug was prepared through the use of advance technology employed to get rid of most of the contaminants from the used water by pressurizing it through a selective-permeable membrane. Surface tension was measured using a force tensiometer (model K6, tear-off technique ring) at atmospheric pressure and 25°C, ensuring consistent experimental conditions. Each of the measurements is first preceded by a thorough cleaning and sun-drying of the tensiometer ring. The core of the tensiometer is made up of a torsion wire attached to the ring and the surface tension was measured by immersing the ring in the sample (liquid) after which it was slowly withdrawn by reducing the level of the liquid. The surface tension in the liquid caused twisting of the torsion wire and the deflection was revealed on a calibration showed by a drag pointer. The pointer migrated to the point of the maximum force and ceased after turning off the lamella so that the surface tension (γ) can be determined in Newton per metre (N/m). To be sure that the tensiometer glassware was well cleaned, it was calibrated by measuring the surface tension of distilled water at 20° C (293 K). The measurements were repeated five times and none of the values deviated from the firstly obtained value by more than ± 0.05 m N/m. The digital pH-meter (model HQ-40D) with about ± 0.05 uncertainties was used to determine the pH of the alkaline chemicals. 25° C was maintained for every measurement done in order to maintain uniformity of conditions

leading to the obtainment of the results. The crude oil was examined to determine the infrared (IR) spectra between 500 and 4000 cm^{-1} using pellets of Potassium Bromide (KBr) on a (model-300-UV/VIS) spectrophotometer. Interpretation of the (IR) spectra was done using established facts from literature. The flooding experiment was done with apparatus which include holder containing sand-pack, crude oil, two cylindrical compartments for holding crude oil and alkali slug, (model-D60) pump for displacing oil and laboratory measuring cylinder for holding chemical samples. The procedural details of the used apparatus are captured in Figure 1. The displacement section for oil is a set of Millipasca Exxol syringe pressure pump. The measuring and control system is made up of transducers at varying pressure in Millipasca and a computer. The physical set-up has a length, L of 40 cm and a radius, r of 4.0 cm with a sand-packing homogenous system having a vertical rhythm. The sand to be loaded into the sand-packing system was firstly cleaned, dried and then successively loaded into the system with at least 1% of brine. This was with a view to ensuring that each of the tested sand has uniform wettability. The sand-pack which was partially saturated with brine was thereafter wholly saturated with the solution and the absolute (K-Permeability) was detected by passing the solution at a uniform pressure of 22Mpa. After this, the sand-pack was flooded with the reservoir oil injected at a pressure of 765 Mpa for initial S_h and S_{wirr} . The sand system was allowed to rest for two days after which it was flooded with water at a pressure of 170 Mpa. This continued until the water limit assumed a percentage of about ninety- six (96%). The reservoir generated little amount of oil after the flooding experiment was carried out. The rest of the oil that was trapped in the reservoir was recovered by injecting alkaline chemicals at varying concentration and pressure of about 170 Mpa, followed by ordinary water (H_2O) flooding at similar pressure. The fractionating column was repeatedly switched on to collect the recovered additional oil at consistent intervals. The permeability and saturation as related to both water and oil were obtained using empirical formulas from Darcy's algorithm. All the flooding experiments were carried out at a uniform temperature of 25 ° C. A flowchart revealing the systematic steps of the flooding experiment is shown in Figure 2.

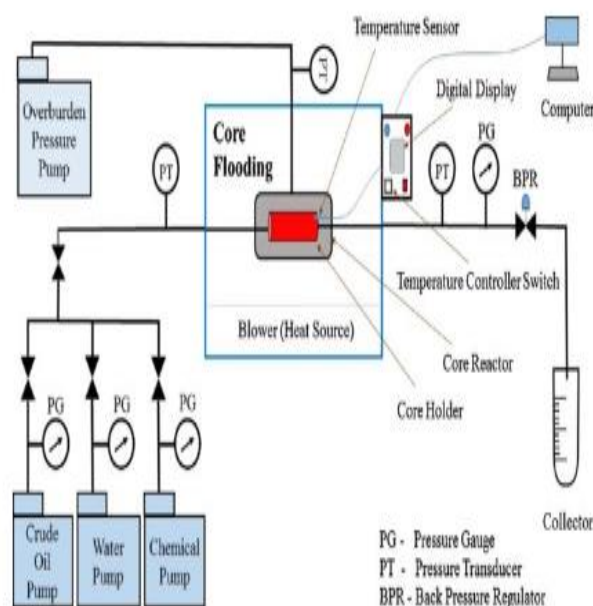


Figure 1: Procedural Details of the Experimental Set Up

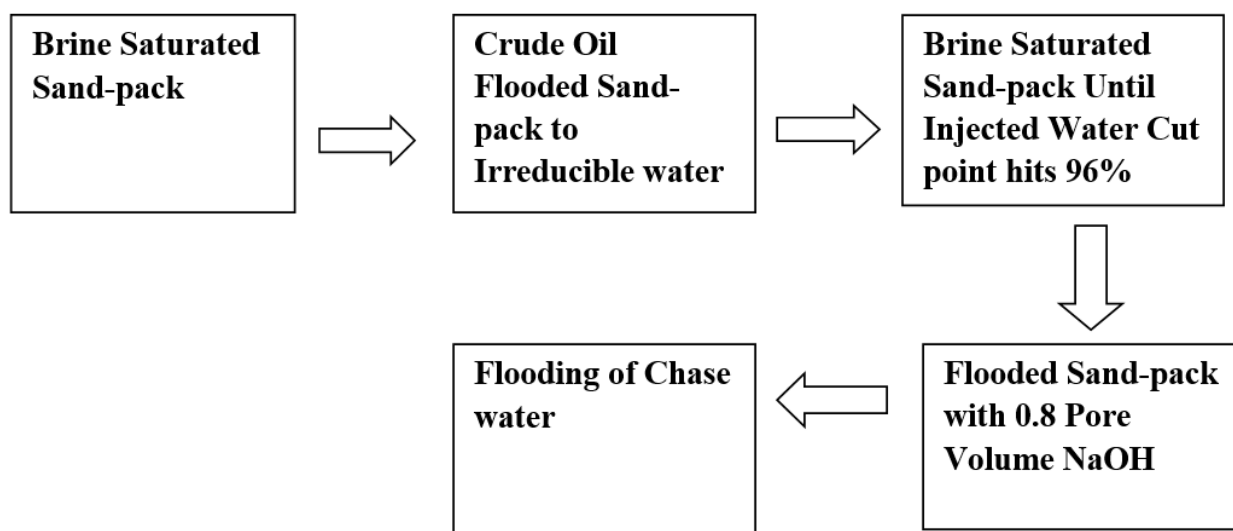


Figure 2: Flowchart Showing the Alkaline Chemical Flooding

A. ETHICAL CONSIDERATIONS

Ethical considerations are foundational to the study of alkaline flooding in enhanced oil recovery. A thorough examination of the environmental impacts, chemical disposal concerns, and compliance with research authority protocols is necessary to ensure that the research is conducted responsibly. The application of alkaline flooding in oil recovery necessitates an environmental impact assessment (EIA) to identify and mitigate any risks to local ecosystems. This method has the potential to alter habitat characteristics by changing the geochemical composition of groundwater and surface water. Introducing alkaline agents, particularly sodium hydroxide (NaOH), into the subsurface environment can lead to increased soil pH, potentially affecting the health and diversity of local flora and fauna. Table 1 demonstrates the concentrations of sodium hydroxide monitored in groundwater samples before and after flooding experiments, highlighting the importance of careful monitoring to prevent harm to aquatic life. As such, the study must incorporate environmental safeguards, including the establishment of buffer zones and regular environmental monitoring, to protect biodiversity and assess the long-term impacts of these operations.

Table 1: Sodium Hydroxide Concentrations in Groundwater Post-Alkaline Flooding

Sample Point	NaOH Concentration (mg/L)	
	Before	After
A	5.0	50.0
B	6.0	45.0
C	4.5	52.0

Additionally, the disposal of unreacted chemical agents and waste products from the alkaline flooding processes raises significant concerns that must be addressed through strict waste management protocols. Improper disposal can result in soil and water contamination, posing serious health risks to local communities. In response to this concern, the study will develop a comprehensive chemical waste management plan. This plan will include the proper storage of hazardous materials in designated containment areas, ensuring that waste is treated in accordance with guidelines set by local regulatory agencies to prevent the release of residual chemicals into the environment. Whenever feasible, strategies for recycling alkaline agents will be implemented to minimize overall chemical usage and reduce disposal requirements. The chemical waste storage and management plan will involve a detailed site assessment to evaluate the accessibility, safety, and regulatory compliance of the designated storage area. This area will be equipped with

appropriate containment systems and situated away from high-traffic zones and sensitive ecosystems. Standard procedures for storage will ensure that all chemical containers are clearly labeled with their contents, hazard symbols, and handling instructions. Secondary containment systems will be employed to catch spills, and access to hazardous materials will be restricted to authorized personnel, who will be trained in safe handling and storage protocols. Inventory tracking is crucial for ensuring compliance with local regulations, and it will be necessary to maintain a comprehensive inventory list of all chemical waste generated, including details about quantities and locations. Regular updates will be conducted to ensure the inventory reflects any changes in waste management. Routine inspections of the storage area will be performed to identify any leaks, spills, or anomalies, with all findings documented for accountability. The conditions for chemical storage, including temperature and ventilation, will be monitored to ensure compliance with safety guidelines. The stages of chemical waste disposal will also be approached systematically, starting with the identification and classification of generated waste. All containers will be labeled and dated upon generation, and temporary storage will involve placing chemical waste in designated, compatible containers that are secure and leak-proof. Documentation efforts will include completing waste tracking forms to indicate the type and quantity of waste generated, as well as preparing manifest forms to facilitate transportation and disposal. Transportation will adhere to safety regulations to ensure that hazardous waste reaches licensed disposal facilities equipped to handle such materials properly. Ethical research practices also mandate obtaining approval from the relevant regulatory bodies before conducting experiments involving hazardous materials. In this study, the storage and management of chemical wastes will align with the protocols stipulated by the National Environmental Standards and Regulations Enforcement Agency (NESREA) and the Institutional Review Board at the Federal University of Health Sciences, Otuokpo. A research compliance timeline will be established to outline key milestones and actions taken throughout the study to ensure adherence to ethical and regulatory protocols. This timeline will detail critical phases including project proposal submission for review, obtaining ethics approval, completing preliminary site assessments, finalizing the chemical waste management plan, and conducting training sessions for personnel on safety and regulatory compliance. Additionally, the data collection period will include rigorous monitoring of environmental impacts, followed by a post-experiment assessment to evaluate any observed changes. The study will culminate in the submission of a final report containing research outcomes, compliance documentation, and records of waste disposal. In conclusion, the incorporation of these ethical considerations underscores the responsibility of the research team to mitigate environmental risks associated with this study, ensure the safe handling of hazardous materials, and comply with relevant regulatory standards. This commitment is vital for fostering trust among stakeholders and promoting sustainability in enhanced oil recovery practices.

III. RESULTS AND DISCUSSION

A. DISCUSSION ON THE SURFACE TENSION

One of the ways of enhancing the recovery of oil is reducing the surface tension. This was achieved through the addition of sodium hydroxide (NaOH) solution. It was observed that the surface tension reduced when the concentration of the sodium hydroxide (NaOH) was increased, although it became unchanged after a certain value of concentration was exceeded. The crude oil was extracted alongside aqueous NaOH at varying concentration after which the measurement of the surface tension of the NaOH in aqueous state

was done. A careful comparison of the concentrations of both the extracted and the normal aqueous NaOH showed that the extracted solution has a lower concentration. It is clear from the results that the formation of surfactants in-situ takes place only when acidic crude oil is recovered alongside the alkaline flooding agent. The surfactant formed in-situ assisted the emulsification of oil at the water and oil interface. The emulsified droplets of oil are trapped in smaller sizes contracted pores. This helped to reduce the mobility of flooding water, enhanced the mobility oil, lowered the IFT and altered the wettability so that more of the oil within the contracted pores can be recovered. Our results support Samanta *et al.* [29] who compared the surface tension at the water and oil interface was to the varying concentration of the alkali and discovered the surface tension did not really fall with the change in concentration but gradually became reduced with a regular change in time. However, unlike Samanta *et al.* [29], our study observed the surface tension at concentration range of (0.8 – 2.4)% each at a 48 hours interval and discovered a fall in the surface tension as the concentration increases. Table 2 shows the NaOH concentrations and the corresponding surface tension after 48, 96 and 144 hours while Table 2 shows the initial and final pH at the aforementioned additional hours. Figures 1 and 2 respectively show the variation of the surface tension and the pH with the concentration of the alkali.

Table 1: NaOH Concentration and the Surface Tension

Concentration in (M)	Initial γ (N/m)	γ after 48 hrs (N/m)	γ after 96 hrs (N/m)	γ after 144 hrs (N/m)
0.10	66.0	51.0	45.8	40.1
0.20	63.0	50.9	45.0	40.0
0.30	60.0	50.5	44.3	39.9
0.40	57.2	48.2	40.1	38.5
0.50	55.1	47.3	39.2	38.2
2.00	54.9	45.1	38.2	36.0
3.00	54.0	41.0	35.1	35.7
4.00	53.9	39.2	34.8	33.3
6.00	53.2	34.0	35.9	34.3
8.00	52.0	39.2	34.2	32.5
9.00	50.0	38.0	36.1	34.6
9.80	51.0	39.1	37.5	35.2
12.0	52.0	39.2	38.0	37.4
16.0	51.2	40.0	39.1	38.0
18.0	51.0	41.2	38.2	36.5
20.0	50.0	41.4	39.2	38.7

B. CONCENTRATION OF THE ALKALINE FLOODING AGENT

As a result of the high concentration of the alkaline water, its injection into the reservoir facilitates a lower IFT and additional recovery of oil. The acidic nature of the crude oil and the basic nature of the alkali give rise to a neutralization reaction between the carboxylic acid of the crude oil and the alkali. This neutralization reaction leads to the formation of emulsified droplets of oil and surfactants which reduced the pressure in the capillary between octadec-9-enoic and the aqueous phases, hence the IFT between water and oil decreased. Surfactant formed does not necessarily result from the concentration of the alkali but rather on the variation of the TAN of different crude oil. A mixture of water and alkali has a pH in the range of 10 – 14 which is very high, hence formation of hydroxide ion results due to the dissociation of aqueous flooding alkali. The used alkali, NaOH reacts with the carboxylic acid of the crude oil to reduce tension at

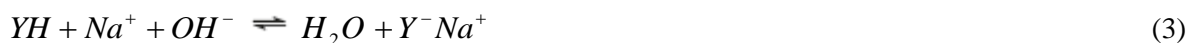
the water-oil interface and also form surfactant. The reaction between the aqueous NaOH and organic acid results into soap formation which is shown in the equation below:



Where, HX stands for the acidic crude and X^- stands for the surfactant. The equilibrium constant, K can be expressed as

$$K = \frac{C_X}{C_{HX} C_{OH^-}}. \quad (2)$$

The alkaline mixture has the characteristics of a buffer. Therefore, C_{OH^-} is considered to be a constant. It was noticed that the surface tension decreased with an increase in the concentration of the alkali extracted alongside the crude oil and then increased. Further investigation of the behavior of the surface tension showed that it firstly reduced as a result of the fall in the concentration of the acids ionized at the water-oil interface. The surface tension decreased owing to the decrease in the concentration of the un-ionized parts of the acid at the water-oil interface. It is worthy to emphasize that, at the interface between the alkaline flooding water agent and the oil, the pH decreased with time, although it became stable at a point because the alkali ceased to be used up as the acidic part of the crude oil has reacted with it to form surfactant. The reaction of the alkali and the rocks in the reservoir depends on its mineralogy. These reactions can be any of dissolution, hydrolysis and formation of non-polar salts with hardness dissociated ions in the reservoir fluid and the ones formed at the surface. The interaction between the flooding alkali/NaOH and the rock necessitated the reversible reaction shown below.



Y^- represents the location of the exchange ion.

Similar research carried out by Yin *et al.* [30] showed the integration of Sodium carbonate, polymer and surfactant and the effect of the combination on EOR. The six flooding experimental processes carried out showed a super low IFT and high emulsification of oil. Yin *et al.* [30] concluded that the highest oil recovery was obtained when 0.3%, 0.6% and 2000 mg per litre of respectively surfactant, sodium carbonate and polymer was used. The method is however suggested for effective process of EOR as a high concentration of alkali is not necessarily required for a high recovery because a small increase in concentration records a very significant sensitivity enough to enhance the recovery of oil.

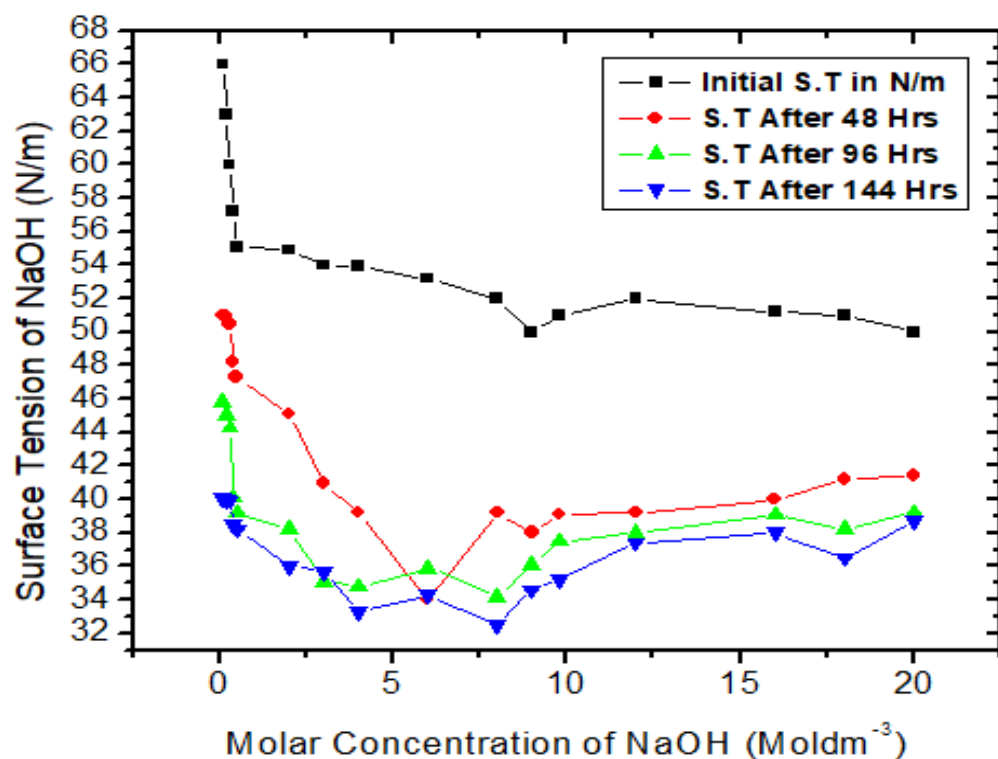


Figure 3: Variation of Concentration with the Surface Tension

Table 3: Initial and Final pH

Concentration in (M)	Initial pH	pH after 48 hrs	pH after 96 hrs	pH after 144 hrs
0.10	11.2	10.2	9.3	8.7
0.20	11.3	10.4	9.5	8.9
0.30	11.5	10.7	9.7	8.9
0.40	11.7	10.9	9.8	9.2
0.50	11.9	11.0	9.9	9.3
2.00	12.1	11.3	10.2	9.5
3.00	12.4	11.5	10.3	9.7
4.00	12.6	11.7	10.5	9.9
6.00	12.9	11.9	10.7	10.2
8.00	13.0	12.0	10.9	10.4
9.00	13.3	12.2	11.1	10.5
9.80	13.5	12.4	11.3	10.8
12.0	13.7	12.5	11.3	11.0
16.0	13.9	12.7	11.5	11.2
18.0	14.0	12.9	11.7	11.4
20.0	14.3	13.0	11.9	11.5

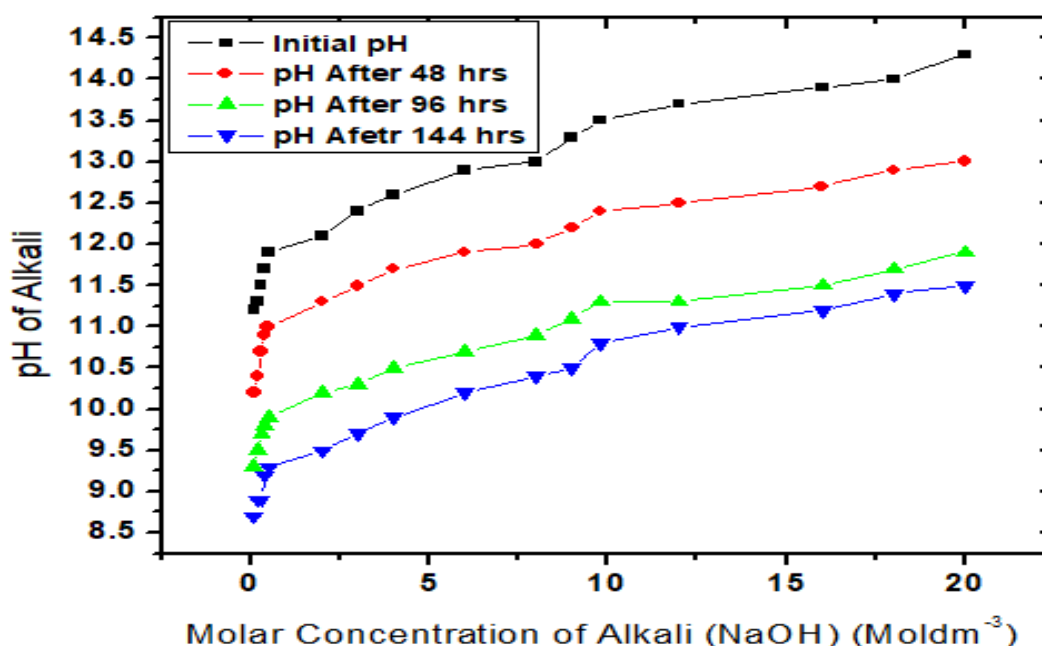


Figure 4: Variation of Concentration with pH

C. EFFECT OF ALKALINE FLOODING AGENT ON OIL RECOVERY (OR)

To appropriately test for the effects of alkaline flooding, the displacement reactions that are necessary before oil recovery have to occur under a uniform condition of permeability and porosity. There is a need to be sure of the fresh preparation of the used chemical solution because a long-prepared solution may be subjected to open-air exposure and this may not give the true picture of what it would have been when it was fresh. Table 3 shows a summary of all the reactions that took place during the flooding experiment. To ascertain the impact of the alkali, three different sets of experiments were performed on the used sand-pack. The Lowering of the pH and the IFT of the water and oil can be related to the flooding alkaline chemical. Based on how alkaline chemicals react with acidic crude oil, the concentration of the alkali injected into the reservoir was made to occur at a range of (0.8 – 2.4) %. A very small range of percentage was maintained because of the high sensitivity of the used alkali when reacted with the crude oil. Using the sand-pack in this research work, the usual water flooding experiment was able to recover only 50% of the OOIP because of its high permeability and its porosity. The usual water flooding revealed that water started to have significant effect after a sudden drop when the volume of its injection reached about 0.2 PV after which its cut point suddenly springs up to more than 95% for all the experiments. The alkaline chemical slug injection done immediately after the water (H₂O) flooding showed a gradual decrease of the water cut and a later increase to hit a 100% mark after the completion of the flooding experiment. This process facilitated the formation of surfactant that helped to change the physical and chemical properties of the petrophysical factors and hence the trickling of oil downstream. When compared to the usual and original EOR approach, the alkaline flooding was able to assist the recovery of an additional 5.85, 5.9 and 6.5% which means 55.85, 55.9 and 56.5% of the OOIP when 0.8, 1.6 and 2.4% of the alkaline chemical slug were respectively injected. The alkaline flooding experiment demonstrated a 6.1% increase in oil recovery (56.1% total recovery) compared to conventional water flooding (50%). This improvement is attributed to in-situ surfactant formation, which lowered IFT and enhanced crude oil mobility. Tables 4, 5 and 6 show the

percentage of NaOH at varying concentrations and the recoveries from both water and alkali injection experiments. Figures 5, 6 and 7 show the actual values of the recoveries in percentage while Figure 8 shows the variation of the percentage oil recovered with the injected pore volume at varying concentrations of 0.8, 1.6 and 2.4% of NaOH. Our results further affirm the discovery from the work of (Wei *et al.* [31] who utilized a combination of alkali surfactant polymer to flood a hydrocarbon reservoir and found that a higher percentage recovery at a high water cut point which helps to reduce the viscosity and IFT of the water and oil and consequently resulting to high sweeping efficiency from the flooding process which facilitated the recovery of more oil from the reservoir. However, our work compared the P^H of NaOH from 11.2 to 14.3 to the concentration and discovered a decrease as the P^H increases.

Table 4: Injection Water Cut Point and Percentage recovery from of 0.8% NaOH at Varying Concentration

Injected Pore Volume	% Recovery	Injected Water Cut Point
0.00	7.00	0.00
0.20	15.00	0.10
0.21	25.00	35.00
0.40	35.00	75.00
0.45	38.00	90.00
0.50	41.00	88.00
0.60	42.00	88.10
0.70	43.00	88.20
0.80	44.00	88.30
1.00	46.00	88.40
1.50	48.00	88.30
1.51	48.30	88.20
1.52	48.40	88.10
1.53	48.50	96.00
1.54	48.60	95.00
1.56	49.00	95.00
1.57	49.40	90.00
2.00	50.00	40.00
2.20	52.10	30.00
2.30	55.00	9.00
2.32	55.30	96.00
2.50	56.00	96.00
3.00	56.00	97.00
3.20	56.20	98.00
3.30	60.30	99.00
4.20	60.35	100.00
4.45	60.40	100.00

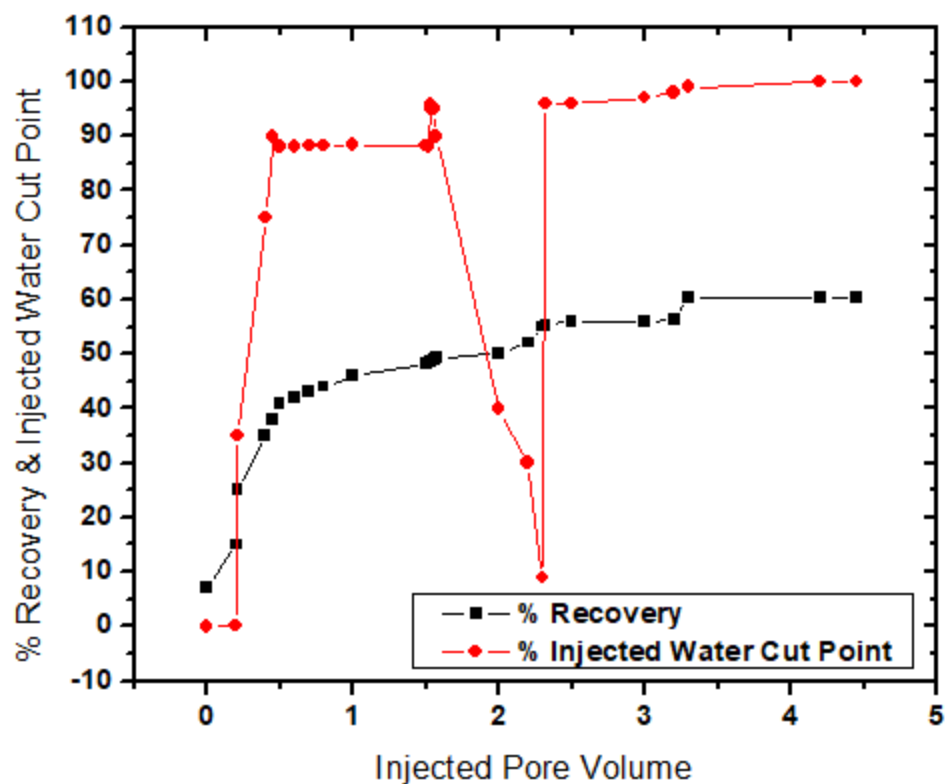


Figure 5: Variation of the Injected Pore Volume with the % Oil Recovery and the Injected Water Cut Point (Using 0.8% of NaOH)

Table 5: Injection Water Cut Point and Percentage recovery from 1.6% NaOH at Varying Concentration

Injected Pore Volume	% Recovery	Injected Water Cut Point
0.00	7.20	0.00
0.20	15.30	0.20
0.21	25.10	34.00
0.40	35.40	76.00
0.45	38.20	91.00
0.50	41.10	89.00
0.60	42.20	89.20
0.70	43.00	89.30
0.80	44.20	88.40
1.00	46.10	88.50
1.50	49.00	88.20
1.51	49.20	88.10
1.52	49.30	88.05
1.53	49.40	95.00
1.54	49.44	96.00
1.56	49.00	96.00
1.57	49.40	90.00
2.00	50.20	40.00
2.20	51.10	35.00
2.30	54.00	12.00
2.32	54.20	96.20

2.50	55.00	96.20
3.00	55.00	97.50
3.20	55.30	99.50
3.30	58.30	99.00
4.20	61.55	99.80
4.45	62.10	100.00

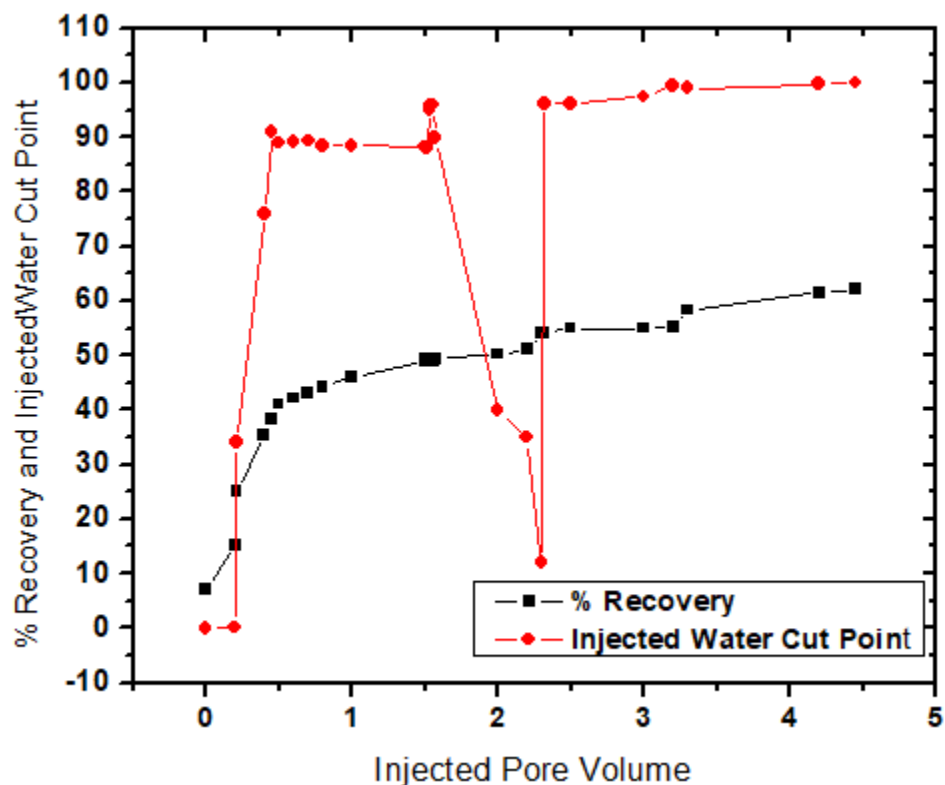


Figure 6: Variation of the Injected Pore Volume with the % Oil Recovery and the Injected Water Cut Point (Using 1.6% of NaOH)

Table 6: Injection Water Cut Point and Percentage recovery from of 2.4% NaOH at Varying Concentration

Injected Pore Volume	% Recovery	Injected Water Cut Point
0.00	8.00	0.00
0.20	17.00	0.30
0.21	25.00	35.00
0.40	37.00	75.00
0.45	39.50	89.00
0.50	39.00	87.00
0.60	41.20	88.15
0.70	42.10	88.20
0.80	43.00	88.30
1.00	50.00	88.20
1.50	50.00	88.50
1.51	50.30	87.20
1.52	51.40	86.30

1.53	48.50	96.20
1.54	48.60	95.20
1.56	49.00	94.00
1.57	49.40	92.00
2.00	50.00	40.00
2.20	52.10	35.00
2.30	54.30	8.00
2.32	55.50	96.00
2.50	56.00	96.00
3.00	56.00	97.00
3.20	56.20	97.00
3.30	62.30	97.00
4.20	61.35	100.00
4.45	63.60	100.00

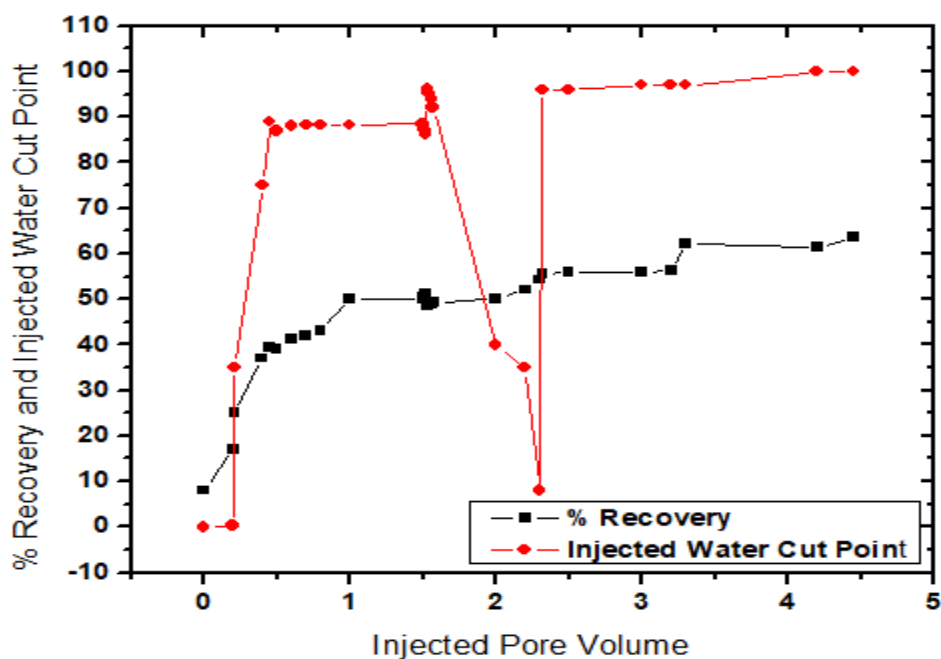


Figure 7: Variation of the Injected Pore Volume with the % Oil Recovery and the Injected Water Cut Point (Using 2.4% of NaOH)

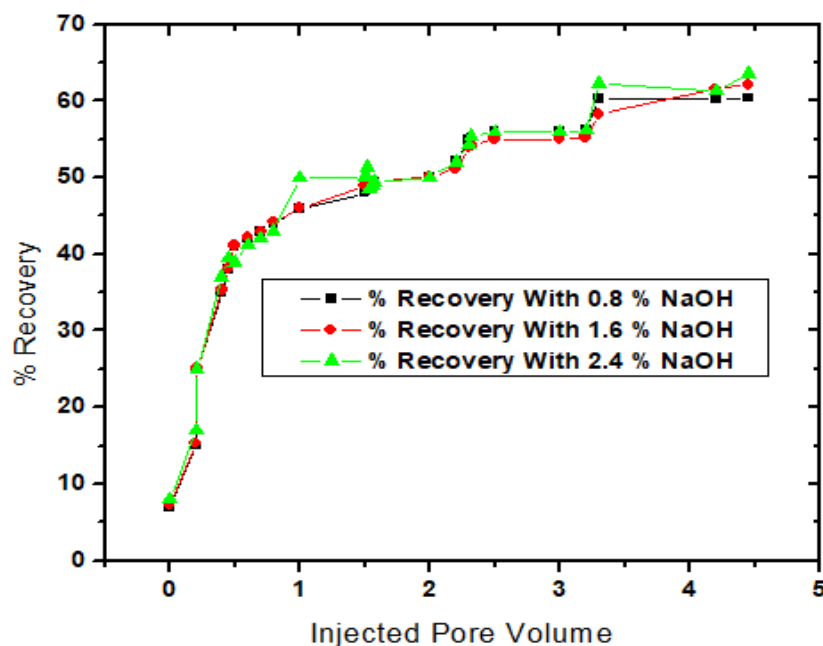


Figure 8: Variation of the percentage oil recovered with the injected pore volume at varying concentrations of 0.8, 1.6 and 2.4% of NaOH.

D. INFRARED SPECTRA OF THE RESERVOIR CRUDE OIL

The infrared spectra employed for this research were made to fall between 500 and 4000 cm^{-1} , so as to accommodate wide range of wave numbers. Similar members of chemically structured bonds are characterized by more or less, similar frequency bands irrespective of molecular structures of the remaining parts. The reservoir crude is characterized by absorption type of bands of hydrocarbon bonds. Some of the bonds originated from aromatic, aliphatic, nitrogen, sulphur and oxygen. There exists a saturate stretch between (2842.43 and 2994.02 cm^{-1}), saturate deformation at (1465 cm^{-1}) and symmetric saturate deformation at (1388 cm^{-1}). The alkyl group, (both long and branched chains, CH_2) n where, $n > 4$) are indicated by the peak (720 cm^{-1}). The carboxylic acid group is the indicated by a range of (1900 – 1750 cm^{-1}). The existence of the wave number absorption at a range of 3600 – 3200 cm^{-1} indicates the presence of phenolic group. The weak bands that occur between 1600 - 1500 cm^{-1} has also helped in suggesting the presence of carbon – carbon double bond which strongly confirms the presence of carboxylic acid group and this may be responsible for the in-situ formation of surfactants after alkaline flooding. The vertical axis of Figure 9 (Transmittance, T) was estimated using the relation, $T = 10^{-A}$. The letter “A” in the formula stands for the absorbance. Table 6 shows the functional group inherent in the reservoir crude oil.

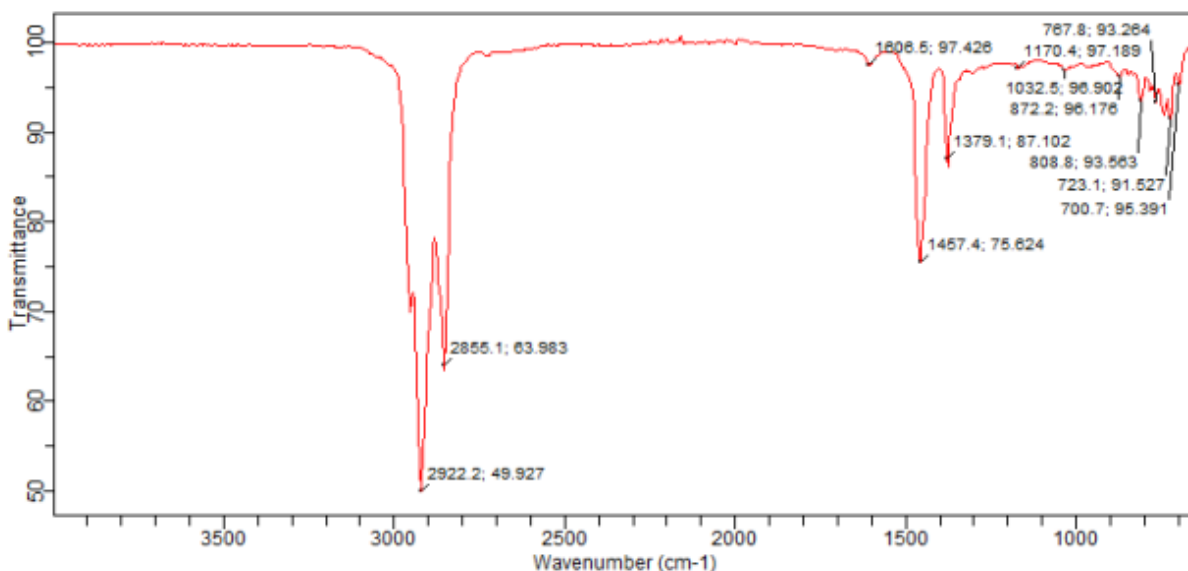


Figure 9: Infrared Spectrum of the Reservoir Crude After Reaction with 2.4% NaOH

Table 7: Functional Group in the Reservoir Crude Oil

Inherent Functional Group	Absorption Location (cm ⁻¹)	Intensity of Absorption
-CH ₂ and CH ₃	2841 – 2995	Medium to Strong stretch of saturate C – H
-CH ₂ and CH ₃	1465	Medium to Strong stretch of saturate C – H deformation
-CH ₂	1388	Medium to Strong stretch of symmetric saturate C – H deformation
-C-H	720	Medium to Strong stretch of benzene substituted C – H
C=C	1464 – 1585	Medium to Strong of stretched ring, aromatic -C=C
O – H	3600 – 3200	Strong stretch of Phenolic groups with (-OH)
C=O	1600 – 1790	Strong stretch of Carboxylic groups (-C=O)

IV. CONCLUSION

In this research work, the relationship between alkaline flooding and the reservoir crude oil as it affects OR was studied. Analysis of the crude oil spectrum reveals the presence of carbonyl and Carboxylic acid groups in the reservoir crude oil which after reaction with the used alkali (NaOH) was discovered to be responsible for the in-situ formation of surfactants which aided in reducing the tension at the interface of water and oil. The surfactants formation was evident in the variation of the surface tension with time. The alkaline chemical slug was maintained at (0.8 - 2.4) % NaOH, as a small addition of it recorded a very high sensitivity to the IFT of the water and oil. The sensitivity of the alkali was ascertained by performing three different sets of alkaline chemical flooding tests on the sand pack. Alkaline flooding using NaOH improved

oil recovery by 6.1% compared to water flooding. This was attributed to interfacial tension reduction and surfactant formation. This was made possible through the wettability change, emulsification and reduction of the IFT at the water-oil interface. Future research should explore alternative alkalis and optimize flooding conditions for different reservoir types.

ACKNOWLEDGEMENT

We would like to express our gratitude to the Department of Physics at the Federal University of Health Sciences, Otuokpo, for providing the departmental laboratory for the analysis conducted in this research.

REFERENCES

- [1] P. Druetta, P. Tesi and C. De Persis, "Methods in Oil Recovery Processes and Reservoirs Simulation", *Advances in Chemical Engineering and Science*, Vol. 1, No. 1, pp. 399- 435, 2016.
- [2] F. G. McCaffery, "Interfacial tensions and aging behaviors of crude oils against caustic solutions", *Canadian Petroleum Geology Bulletin*, Vol. 15, No. 1, pp. 71-80, 1976.
- [3] J. J. Sheng, "Enhanced Oil Recovery Field Case Studies (Alkaline Flooding)", Elsevier, Vol. 10, No. 1, pp. 143 – 160, 2013.
- [4] A. Rezaei and S. Bagherpour, "Formation damage during chemical flooding", Elsevier, Vol. 1, No. 1, pp. 461-478, 2022.
- [5] A. Rahimi, M. Jami, H. Divandari and M. Safari, "Alkaline Flooding", Elsevier, Vol. 10, No. 1, pp. 141- 220, 2022.
- [6] M. A. Ahmadi, "Fundamentals of Enhanced Oil and Gas Recovery from Conventional and Unconventional Reservoirs (Chemical Flooding)", Elsevier, Vol. 1, No. 1, pp. 187-522, 2018.
- [7] A. A. Soliman, M. A. Elshahaa, S. M. Elsaied, E. G. Zaki and A. M. Attia, "Sulfonamide Derivatives as Novel Surfactant/Alkaline Flooding Processes for Improving Oil Recovery", *Journal of Chemical Engineering*, Vol. 8, No. 1, pp. 29401-29413, 2023.
- [8] G. R. Seetharaman, R. M. Jadhav and J. S. Sangwai, "Effect of Monovalent and Divalent Alkali (NaOH and Ca(OH)₂) on the Interfacial Tension of Pure Hydrocarbon-Water Systems Relevant for Enhanced Oil Recovery", *Journal of Petroleum Science and Engineering*, Vol. 197, No. 1, pp. 107-892, 2021.
- [9] A. Mehdizadeh and H. H. Handy, "Further Investigation of High Temperature Alkaline Floods", *SPE Reservoirs Engineering*, Vol. 4, No. 1, pp. 171-177, 1989.
- [10] E. Yonguep, K. F. Kapiamba, K. J. Kabamba and M. Chowdhury, "Formation, stabilization and chemical demulsification of crude oil-in-water emulsion", *Journal of Petroleum Research*, Vol. 10, No. 1, pp. 459-472, 2022.
- [11] I. Nowrouzi, A. H. Mohammadi and A. K. Manshad, "Water-oil interfacial tension (IFT) reduction and wettability alteration in surfactant flooding process using extracted saponin from *Anabasis Setifera* plant", *Journal of Petroleum Science and Engineering*, Vol. 189, No. 1, pp. 106-901, 2020.
- [12] A. Miadonye, D. J. G. Irwin and M. Amadu, "Effect of Polar Hydrocarbon Contents on Oil–Water Interfacial Tension and Implications for Recent Observations in Smart Water Flooding Oil Recovery Schemes", *American Chemical Society*, Vol. 10, No. 1, pp. 9086-9100, 2023.
- [13] N. K. Abbood, N. A. Dahham, M. A. Dezfouli and S. Hosseini, "Effect of sodium hydroxide, sodium dodecyl benzenesulfonate, and resin on the interfacial tension of asphaltenic synthetic oil extracted from acidic crude oil under low salinity condition", *Journal of Petroleum Exploration and Production Technology*, Vol. 13, No. 1, pp. 2457-2474, 2023.
- [14] T. M. Janssen, P. L. Zitha and R. M. Pilus, "Oil Recovery by Alkaline/Surfactant/Foam Flooding: Effect of Drive-Foam Quality on Oil-Bank Propagation", *SPE Journal*, Vol. 24, No. 1, pp. 27-58, 2019.
- [15] H. Li, S. C. Mahavadi, A. Anton and S. I. Andersen, "Estimating Reservoir Fluid Interfacial Tension: An Insight into the Role of Polar Species of Crude Oil", *Journal of Dispersion Science and Technology*, Vol. 1, No. 1, pp. 1825-1840, 2021.
- [16] A. I. Khlaifat, D. Dakhallallah and F. Sufyan, "A Critical Review of Alkaline Flooding: Mechanism, Hybrid Flooding Methods, Laboratory Work, Pilot Projects, and Field Applications", *Energies*, Vol. 15, No. 1, pp. 3820-3848, 2022.
- [17] V. Hornof, G. H. Neale and A. Yu, "Effect of flooding sequence on the displacement of acidic oil by alkaline solutions", *Journal of Petroleum Science and Engineering*, Vol. 10, No. 1, pp. 291-297, 1994.
- [18] M. Y. Li, M. Q. Lin, Z. L. Wu and A. A. Christy, "The influence of NaOH on the stability of paraffinic crude oil emulsion", *Fuel*, Vol. 84, No. 1, pp. 183-187, 2004.

- [19] J. X. Guo, Q. Liu, M. Y. Li and A. A. Christy, "The effect of alkali on crude-oil/water interfacial properties and the stability of crude oil emulsions", *Colloids and Surfaces*, Vol. 273, No. 1, pp. 213-237, 2006.
- [20] V. Bortolotti, G. Gottardi, P. Manchi and F. Srisuriyachai, "Intermittent alkali flooding in vertical carbonate reservoir", *Society of Petroleum Engineers Proceedings*, Vol. 10, No. 1, pp. 241-259, 2009.
- [21] V. Bortolotti, P. Manchi and F. Srisuriyachai, "Laboratory evaluation of alkali and alkali-surfactant-polymer combined with intermittent flow in carbonate rocks", *Society of Petroleum Engineers Proceedings*, Vol. 1, No. 1, pp. 10-21, 2009.
- [22] R. Phukan, S. B. Gogoi and P. Tiwari, "Enhanced oil recovery by alkaline-surfactant-alternated-gas/CO₂ flooding", *Journal of Petroleum Exploration and Production Technology*, Vol. 9, No. 1, pp. 247-260, 2019.
- [23] C. Sun, H. Guo, Y. Li, G. Jiang and R. Ma, "Alkali Effect on Alkali-Surfactant-Polymer (ASP) Flooding Enhanced Oil Recovery Performance: Two Large-Scale Field Tests' Evidence", *Journal of Chemistry*, Vol. 2, No. 1, pp. 1-22, 2020.
- [24] A. Ragab and E. M. Mansour, "Chemical Flooding. Geophysical and Ocean Waves Studies", *Intechopen*, Vol. 10, No. 1, pp. 1-13, 2021.
- [25] P. Arnold, "Experimental investigation of interfacial tension for alkaline flooding", *Master's Thesis, Australia University of Technology*, Vol. 1, No. 1, pp. 1-74, 2018.
- [26] P. Akpoturi and S. F. Ofesi, "Enhanced Oil Recovery using Local Alkaline", *Nigerian Journal of Technology*, Vol. 36, No. 1, pp. 515-522, 2017.
- [27] D. S. Adepehin, A. I. Odudu, A. O. Adelayi, S. O. Adikwu, M. S. Ahmad and D. O. Alfred, "Estimating Geophysical Parameters Using Petrophysical Algorithm to Enhance Hydrocarbon Recovery in Lokaka Field, Niger Delta, Nigeria", *UMYU Scientifica*, Vol. 1, No. 1, pp. 15-29, 2022.
- [28] R. E. Hincapie, A. Borovina, E. Neubauer, M. Tahir, S. Saleh, V. Arekhov, M. Biernat and T. Clemens, "Recovery Observations from Alkali, Nanoparticles and Polymer Flooding as Combined Processes", *National Library of Medicine, National Center for Biotechnology Information, Pubmed Central*, Vol. 14, No. 1, pp. 603-625, 2022.
- [29] A. Samanta, K. Ojha and A. Mandal, "Interactions between Acidic Crude Oil and Alkali and Their Effects on Enhanced Oil Recovery", *Energy and Fuels*, Vol. 25, No. 1, pp. 1642-1649, 2011.
- [30] D. Yin, D. Zhao, J. Gao and J. Gai, "Experimental Study of Enhancing Oil Recovery with Weak-Base Alkaline/Surfactant/Polymer", *International Journal of Polymer Science*, Vol. 2017, No. 3523, pp. 1-13, 2017.
- [31] J. Wei, J. Li, X. Shi and R. Zhou, "Combination of alkali-surfactant-polymer flooding and horizontal wells to maximize the oil recovery for high water cut oil reservoir", *Elsevier*, Vol. 7, No. 1, pp. 1123-1136, 2021.