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Silicon Dioxide Nanoparticles Boasted Gum Arabic as a Natural Polymer for Enhanced Heavy Oil Recovery

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Abstract

Heavy oil is defined as oil with an API gravity ranging from 10° to 22.3°. Heavy oil reservoirs are considered unconventional reservoirs and are more in the world than conventional reservoirs, and they should not be left unattended. Crude oil from the Niger Delta of API 19.03° and Gum Arabic natural polymer from Bauchi State were used for the flooding experiment to determine the incremental recovery after waterflooding. In this study, various concentrations of gum Arabic were used for coreflooding after waterflooding. The concentrations of Gum Arabic used were 1,000ppm, 3,000ppm, 5,000ppm and 10,000ppm. There was little incremental recovery (2%) when these four different concentrations were used for the brine coreflooding experiment. However, when 1,000ppm of Silicon Dioxide Nanoparticles were blended with 1,000ppm of Gum Arabic, an incremental recovery of 10.15% was observed. This incremental recovery using Silicon Dioxide Nanoparticles during the coreflooding with just a concentration of 1,000ppm has shown the potential synergy between Gum Arabic and Nanoparticles in sweeping Heavy Oil Reservoirs in Nigeria. This study goes ahead to state that companies with heavy oil reservoirs can collaborate with our research centre to carry out extensive studies on their heavy crude and production in a cost-effective and safe manner.

Keywords: *Gum Arabic; Heavy Oil; Nanotechnology; Polymer Flooding; Silicon Dioxide Nanoparticle.*

1. Introduction

1.1. Background

Heavy oil is defined as oil having an API of 10°-22.3° and a viscosity of 10–1,000 cP at reservoir conditions [1]. Heavy oils are classified as unconventional reservoirs since they are more widely distributed than conventional reservoirs and should not be ignored. Nigeria holds about 37 billion barrels of proven oil reserves as at 2016, ranking 10th in the world and accounting for about 2.25% of the world's total oil reserves of 1,650,585,140,000 barrels [2]. The Nigerian government currently derives the majority of its oil earnings from cheap/light oil derived from conventional reservoirs. Globally, these reservoirs are quickly depleting [3].

Nigeria has roughly 42 billion barrels of unconventional oil reserves in addition to its 37 billion barrels of proven reserves. This unconventional reservoir contains heavy oil. According to the numbers above, Nigeria's unconventional resources outnumber conventional resources. This is true for most places across the world. As a result, these unconventional reservoirs should not be ignored [4]. Heavy oil reserves are estimated to be 3,396,000 billion barrels on a worldwide scale. As previously stated, conventional oil is dwindling, and we must face the problem of developing heavy oil reservoirs to replace the dwindling light or conventional oil [5].

Waterflooding is seen as a low-cost intervention approach for recovering more oil after primary production. This is for obvious reasons, such as water compatibility, availability, and cost, especially in the offshore environment [6]. Waterflooding works better in lighter oils with lower viscosity and higher API° than in heavier oils with higher viscosity and lower API° [7].Viscous fingering is detected during waterflooding a heavy oil reservoir, which is the unstable displacement of a more viscous fluid by a less viscous fluid [8-9].

Heterogeneities in reservoir rocks cause uneven waterflooding in the reservoir. For zones with high permeabilities, they can receive so much water during waterflooding and this will cause early water breakthrough or thief zone in such reservoirs. As a result, the water bypasses the oil, leaving the unswept oil in the reservoir after the waterflooding [10]. The Water-Oil-Ratio (WOR) could reach up to 95% in some cases before becoming uneconomical. Because of pressure drawdown, the pressure in the injection well differs from the pressure in the production well. Infill drilling can be used to recover the unswept oil, but it is costly [6].

Chemical Enhanced Oil Recovery is utilized to address the challenges mentioned above. alkaline (A), surfactants (S), polymers (P), and even nanoparticles are employed separately or in combination as AS, AP, SP, or ASP to sweep and recover more residual oil. The polymers in the water enhance the viscosity of the water, lowering the mobility ratio. Polymer flooding can recover an additional 30% of the original oil in place. The total cost of adopting the polymer flooding approach is lower than that of water flooding due to reduced water production and increased oil production. As a result, money will be saved that would have been spent on dealing with excess produced water. The aim of polymer flooding is to lower the mobility ratio by raising the viscosity of the water and lowering the permeability of the formation [11].

For this research, gum Arabic, a natural polymer, and silicon dioxide (SiO_2) nanoparticles are used.

1.2. Gum Arabic (GA)

Gum arabic is the name given to natural gum exudates of hardened sap from Acacia Senegal (Senegalia Senegal) and Acacia Seyal (Vachellia), deciduous trees. Gum Arabic has other acceptable names like Acacia Gum, Arabic Gum, Gum Sudani, Gum Acacia, Acacia, Senegal Gum, Indian Gum, Gum Hashab, Gum Talha, etc. It is an important cash crop for most countries in sub-Saharan Africa, and Nigeria is not an exception. Sudan is the world's leading producer of gum Arabic, which has greatly benefited the country's economy [12-13]. Gum Arabic did not derive its name because it was produced in the Middle East; rather, Gum Arabic was transported to Europe from Arab countries via Arabic ports. As a result, the name Gum Arabic was chosen [14].

Gum Arabic is a complex mixture of polysaccharides and glycoproteins (GPs) and is soluble in water. It forms solutions over a wide range of liquids without turning very viscous. It is used in many industries, including food and beverages, with an E number of 414 (E414). Gum Arabic is primarily used as a natural emulsifier. It is also used in other industries like pharmaceuticals, ceramics, printing, textiles, inks, paper, adhesives, cosmetics, paint, glue, chewing gum, photosensitive chemicals, and pyrotechnics [13, 15-16].

As said, GA is a complex mixture of polysaccharides and glycoproteins (GP’s) with a pH ranging from near neutral to mild acidity. It exists as a blended calcium, magnesium, and potassium salt of a polysaccharide acid known as Arabic acid. The framework of GA is made up of 1,3-connected-d-galactopyranosyl units. The side chains are made up of two to five 1,3-connected-d-galactopyranosyl units, joined to the primary chain by 1,6-linkages. Both the fundamental and the side chains contain units of α-l-arabinofuranosyl, α-l-rhamnopyranosyl, β-d-glucopyranosyl, and 4-O-methyl-β-d-glucopyranosyl, the last two generally as end units. The chemical composition of GA can change with weather conditions, soil conditions, and the age of the tree and location of the tree [17-18].

Gashua *et al.* [12] reviewed several papers on GA and concluded that the characterization of gum Arabic using gel permeation chromatography (GPC), coupled to light scattering, refractive index, and UV detectors, has shown that the gum exudates obtained from both species of *A. senegal* and *A. seyal* consist of three main components. The components are arabinogalactan (AG), arabinogalactan-protein (AGP), and glycoprotein (GP), and they differ mostly in molecular size and protein concentration. The AG, AGP, and GP fractions each account for 90%, 10%, and 1% of the total gum, respectively. They have molar weights of 2,250 kg/mol, 1,200 kg/mol, and 200 kg/mol, respectively, and contain 1%, 10%, and 25-50 % proteinaceous material. The amino acid content/composition of the three components differs greatly, with the GP fraction having the least in common with the other two [12].

1.3. Nanotechnology

Nanotechnology is the application of nanoparticles characterized by a size ranging between 1 and 100 nm, and it has been used in the oil and gas industry. It is applicable to exploration, drilling, drilling and hydraulic fracture fluids, oilwell cementing, completion, corrosion & scale inhibition, formation evaluation, production, reservoir characterization & management, processing & refining, and enhanced oil recovery [19-20].

Nanotechnology has been around but was conceived as a new emerging technology in the 1980’s. Physicist Richard Feynman (1959) in a presentation tagged "There’s Plenty of Room at the Bottom" at an American Physical Society meeting at CalTech, presented the ideas and concepts of nanotechnology and nanoscience. Feynman suggested that processes could be more efficient if scientists could control and manipulate individual atoms and molecules. Professor Norio Taniguchi was the first person to use the word nanotechnology when he was exploring ultra precision machining, after over a decade since physicist Richard Feynman gave his talk. By 1981, individual atoms were visible through the use of Scanning Tunneling Microscope (STM), and modern nanotechnology started [21-22].

Nanotechnology is solving most of the challenges that are associated with CEOR, hence its applicability and synergy with CEOR has been harnessed. CEOR is applied to recover both the bypassed and residual oil trapped in the reservoir. Chemicals like polymers, surfactants, and alkaline are used to achieve this individually or in combination. Using nanoparticles is economical because only a small amount of the chemical is required to achieve the result. This is possible because nanoparticles have a large surface area [23].

Equally, nanotechnology has proven to be environmentally friendly and efficient. Other challenges in CEOR, such as in high temperature and high salinity reservoirs, degradation problems are taken care of using nanoparticles [24]. Apart from thermal and salinity resistance, nanoparticles can withstand mechanical degradation, high pressures and high shear rates in the reservoir and can be modified in any reservoir system. Nanoparticles have a high surface to volume ratio, which results in enhanced thermal properties [25-26].

Some authors have commended the applicability and usefulness of namomaterials in solving residual oil challenges in heavy and semi-heavy oil reservoirs over the last decade [27-28].

According to [23], aluminum oxide (Al_2O_3) and silicon oxide are good EOR agents, as experiments show. They showed that Aluminum Oxide nanoparticle is good for oil recovery when used with distilled water and brine as dispersing agents. From all their experiments also, they found out that the use of ethanol, Silane treated Silicon oxide gave the highest recovery, while hydrophobic silicon oxide in ethanol also gave good results. Their experiments confirmed that aluminum oxide nanoparticles reduced the oil viscosity, while silicon oxide nanoparticles changed the rock wettability and reduced the interfacial tension of water and oil in the presence of ethanol.

Ogolo *et al.*[29] investigated the ability of nanoparticles to trap migrating fines in a sandstone formation. This study used distilled water, brine, and ethanol as base fluids. They found out that two main fines trapping mechanisms in sands were found to be pH values of the surrounding fluids and electrostatic forces of adsorption and that Al_2O_3 had the most capacity to trap fines. Other trapping mechanisms include zeta potential, nanofluid point of zero charge, and surface charge density of nanoparticles.

Different researchers have used nanoparticles with different chemicals and have been able to solve most of the CEOR challenges [30].

The objective of this paper is to harness the usefulness of Silicon Dioxide nanoparticle in blending the abundant Gum Arabic, that was properly processed for effective flooding in a heavy oil reservoir in Niger Delta of Nigeria.

2. Materials and methods

2.1. Materials

Table 1 shows the list of materials used in this work and their respective descriptions.

Table 1**.** List of materials and description.

S/N	List of materials	Description
1.	Heavy crude oil of API° 19.03	Obtained from Niger Delta
2.	Core plug	Obtained from Niger Delta
3.	Gum arabic (GA)	Purchased from Bauchi State and processed
4.	Silicon dioxide (SiO_2) nanoparticle	Manufactured by Sigma Aldrich
5.	Toluene	Used for cleaning of Core Plug
6.	Sodium chloride (NaCl)	Monovalent Ion for Brine preparation
7.	Calcium chloride ($CaCl_2$)	Divalent Ion for Brine Preparation

2.2. Equipment/apparatus

Table 2 shows the list of equipment/apparatus used in this experiment and their various functionalities. The OFITE® RPT coreflooding schematics and the actual picture are shown.

Table 2 List of equipment and functionalities

S/N	List of equipment	Functionality
1.	OFITE® RPT	Permeability Measurement/Coreflooding
2.	Redwood viscometer	Determination of Heavy Oil Crude Viscosity
3.	Glass viscometer	Determination of Polymer Solution Viscosity
4.	Soxhlet extractor	Cleaning of Core Plug
5.	Desiccator	Drying of Core Plug
6.	Mud balance	Determination of Specific Gravity
7.	Hamilton beach mixer	Mixing of Polymer and Nanoparticle Solutions
8.	pH/ORP meter	Determination of temperature/pH of polymer solution
9.	Thermometer	Determination of Temperature
10.	Electronic weighing balance	To measure weight of sample
11.	Pycnometer of density bottle	Determination of Specific Gravity of Crude Oil
12.	Measuring cylinder	Measuring required quantity of deionized water
13.	B114 Elgastar deioniser	Preparation of deionized water
14.	Stop watch	For Time taking
15.	Spatula	Collection of polymer and nanoparticles samples

2.3. Procedures for the preparation of gum arabic powder

The gum Arabic was purchased from Bauchi State. The gum Arabic exudates were hand-picked to remove the impurities, and the clean exudates were pulverized with a sledge hammer in a clean, strong sack bag. The gum exudates were ground and sieved with a 250 m sieve initially and then with a 125 m sieve to obtain the desired gum Arabic powder.

2.4. Procedures for the preparation of gum arabic polymer and silicon dioxide nanoparticle solutions

The gum Arabic powder in various quantities was dissolved in deionized water to get various concentrations, ranging from 1,000ppm, 3,000ppm, 5,000ppm, and 10,000ppm. In percentage, these were 0.1%, 0.3%, 0.5% and 1.0% respectively. A plastic bottle was used in all the solution mixing. Deionized water was measured to 500 mL in each bottle. For the 0.1% or 1,000ppm, gum Arabic powder of 0.5g is measured and mixed into the 500ml deionized water, and 1.5g, 2.5g and 5.0g of gum Arabic powder into 500 mL deionized water representing 0.3% or 3,000ppm, 0.5% or 5,000ppm and 1.0% or 10,000ppm respectively. To determine the exact amount of gum Arabic powder, a spatula was used to scoop it into a filter paper, which was then placed on an electronic weighing balance. When making this measurement, all the fans are turned off so that the exact measurement can be used. When done, the solution is mixed vigorously using a Hamilton Beach Mixer. The solution is allowed for 24 hours to allow for complete hydration before it is used for polymer flooding. For the nanocomposite solution, 1,000 ppm only was prepared using the same procedures. The long period for hydration helps the flooding to be more effective and efficient and ultimately prevents plugging of the core plug representation of what will be done at the field scale

2.5. Procedure for determination of crude oil API°

To ascertain the gravity of the crude, a pycnometer or specific gravity bottle was used. weight of empty bottle (W_{eb}) = 32g; weight of bottle and crude oil (W_{bc}) = 79g; volume of empty bottle (V_c) = 50g

$$Specific\ Gravity(S.G) = \frac{W_{bc} - W_{eb}}{V_c} = \frac{79 - 32}{50} = \frac{47}{50} = 0.94$$

$$API = \frac{141.5}{S.G} - 131.5 = \frac{141.5}{0.94} - 131.5 = 150.53 - 131.5 = \mathbf{19.03}°$$

2.6. Procedure for coreflooding analysis setup

In this experiment, hydrocarbon recovery by using gum Arabic polymer as a tertiary means and its effectiveness in reservoirs in optimizing heavy oil production.

The experiments performed were conducted at room temperature and suitable differential pressures were selected with the assistance of the equipment used. A gradual rise in device pressure suggested one of two things, an empty accumulator and or a drop in core sample permeability.

Since brine was used to attain 100 % saturation of the cores, the primary recovery process was the first method employed. Once no more brine was produced, oil was injected into the core plugs at 1.5cc/min. This technique carried out the initial saturation of the water, S_{wi}.

Then next was to flood using water, in which water was pumped at 1.5cc/min into the core plugs until no more oil was generated. It would create saturation of the residual oil, Sor. As a tertiary phase polymer prepared was initiated. After the water flooding, they were inserted into the core plug to determine if they had any impact on oil recovery. The effect of the polymer can be ascertained to be positive if additional oil would be produced thereby increasing the recovery factor (RF).

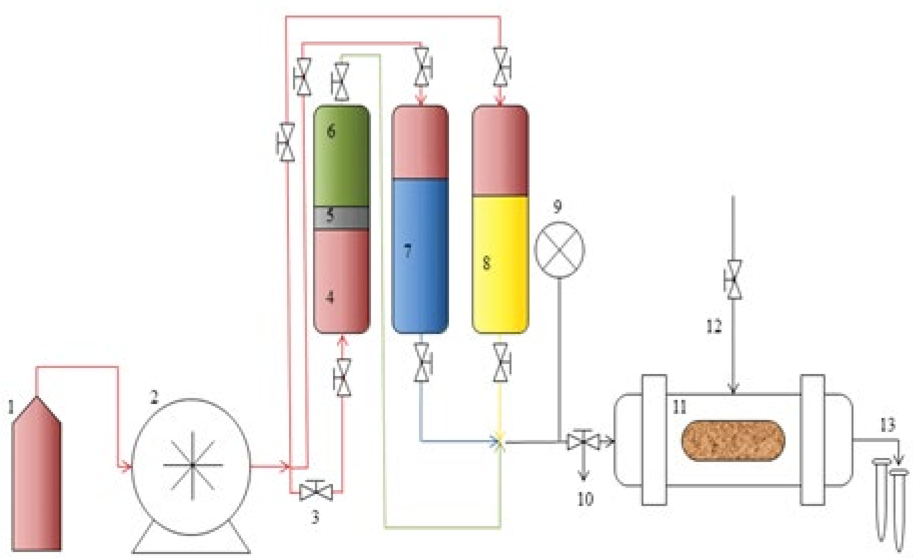

Figure 1. Core flood setup, 1) pump fluid, 2) pump, 3) valves, 4) displacing reservoir fluid, 5) piston to separate the oils, 6) crude oil, 7) NSB, 8) polymer 9) pressure gauge, 10) bypass valve, 11) hassler cell holder with core, 12) sleeve pressure , 13) effluent into test tubes [31]

Since no automatic means of calculating recovery, the experiment had to be consciously observed during the whole flood experiment. Effluent fluid samples were taken manually every 3 minutes at the core holder outlet. The samples were used to measure the quantity of oil and brine contained and were used to calculate saturation and recovery factor. Figure 1 above shows the schematic of a core flood setup

3. Results and discussion

From the experiment carried out as shown in the methodology, the specific gravity of the oil is 0.94, and using API° and specific gravity relationship, the API° of the crude oil is 19.03. The viscosity @ 27°C is 86 cP and the viscosity @ 50°C is 18 cP. Table 3 belows shows the property of the crude oil used in the experiment. Table 4 lists the properties of the core plug used in this experiment.

Table 3. Properties of crude oil

S/N	Property of crude	Value
1.	Specific Gravity	0.94
2.	API°	19.03
3.	Viscosity (cP) @ 27°C	86
4.	Viscosity (cP) @ 50°C	18

Table 4. Properties of core plug used

Polymer	L(cm)	D(cm)	BV	PV	ϴ	K(md)
GA	3.5	3.7	37.65	7.5	0.20	1994

Figure 2 is plotted in order to facilitate understanding on the oil recovery efficiency of waterflooding and gun Arabic polymer at four various concentrations of 1,000ppm, 3,000ppm, 5,000ppm and 10,000ppm, while Figure 3 is plotted in order to facilitate understanding on the oil recovery efficiency of waterflooding with gum arabic nanocomposite. From Figure 2, the waterflooding was able to recover 26.67% of OOIP. The plot is also evident that though four different concentrations of GA of 1,000ppm, 3,000ppm, 5,000ppm and 10,000pm were used for the flooding only additional 2% of oil recovery was recovered. The different concentrations are indicated with different colors on the plot. From Figure 3, when GA of 1,000ppm and SiO_2 of 1,000ppm were used for the flooding, an additional 10.15% of oil was recovered. The SiO_2 nanoparticles have enhanced the natural GA polymer by further altering the wettability of the core plug and reduced IFT.

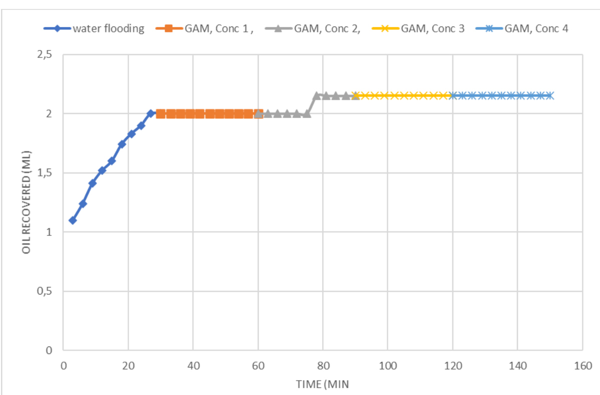

Figure 2. Waterflooding and gum arabic

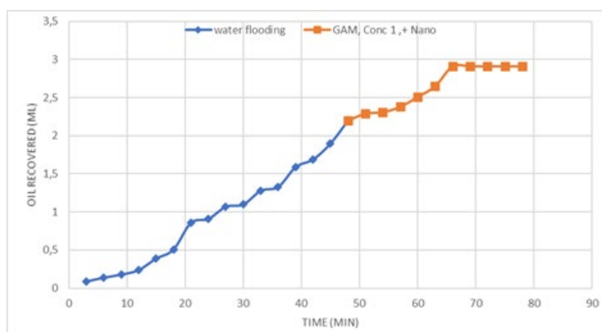

Figure 3. Recovery efficiency

4. Conclusion

In this polymer flooding study, it is concluded that nanoparticles blended with gum Arabic can enhance the heavy oil from the Niger Delta area of Nigeria. Based on the experimental analysis, the following are evident. Water flooding was able to recover the heavy oil reservoir up to 26.67%. GA natural polymer at four different concentrations was able to recover only 2.0% incremental recovery. GA+SiO_2 recovered an extra 10.15% of heavy oil. SiO_2 nanoparticles are capable of enhancing the abundant GA in Nigeria to recover heavy oil. SiO_2 has obviously improved the recovery above GA alone due to wettability alteration and reduction of IFT.

Symbols/Nomenclature

A	*Alkaline*
AG	*Arabinogalactan*
AGP	*Arabinogalactan protein*
AP	*Alkaline-Polymer*
API	*American Petroleum Institute*
AS	*Alkaline-Surfactant*
ASP	*Alkaline-Surfactant-Polymer*
BV	*Bulk Volume*
CalTech	*California Institute of Technology*
cP	*Centipoise*
cEOR	*Chemical Enhanced Oil Recovery*
D	*Diameter*
EOR	*Enhanced Oil Recovery*
GP	*Glycoprotein*
GPC	*Gel Permeation Chromatography*
IFT	*Interfacial Tension*
K	*Permeability*
Kg/mol	*Kilogram per Mole*
L	*Length*
OFITE® RPT	*OFITE® Reservoir Permeability Tester*
OOIP	*Original Oil in Place*
ϴ	*Porosity*
P	*Polymers*
pH	*potential of hydrogen*
PPM	*Parts Per Million*
PV	*Pore Volume*
s	*Recovery Factor*
S	*Surfactants*
SP	*Surfactant Polymer*
S_{oi}	*Initial Oil Saturation*
S_{or}	*Residual Oil Saturation*
STM	*Scanning Tunneling Microscope*
UNCTAD	*United Nations Conference on Trade and Development*
UV	*Ultraviolent*
V_c	*Volume of pycnometer*
W_{bc}	*Weight of pycnometer and crude*
W_{eb}	*Weight of empty pycnometer*

Declaration of competing interests

The authors have declared that no competing interests exist in this paper.

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