



Experimental Assessment of Guar Gum and Silicon Oxide Nanoparticle Hybrid for Enhanced Oil Recovery

Mbachu Ijeoma Irene¹, Odorikpe Venus Ogechi²

^{1,2} Petroleum and Gas Engineering University of Port Harcourt, Rivers, Nigeria.

ABSTRACT: This study investigated the enhanced oil recovery (EOR) potential of hybrid formulations comprising guar gum polymer and silicon oxide (SiO₂) nanoparticles. The research aimed to address the limitations of using only polymer (Guar gum) as EOR agent, by exploring the synergistic effects of guar gum and SiO₂ nanoparticles in improving oil recovery efficiency. The study involved core flooding experiments using Niger-Delta sandstone samples with different concentrations of guar gum and SiO₂ nanoparticles in both low-salinity (30,000 ppm) and relatively high-salinity (60,000 ppm). The results showed that the guar gum-SiO₂ nanocomposite formulations significantly outperformed the individual components in terms of oil recovery. The rheological analysis indicated that the inclusion of SiO₂ nanoparticles improved the viscosity and viscoelastic properties of the hybrid fluids, enhancing their mobility control capabilities. Core flooding experiments demonstrated that the guar gum-SiO₂ nanocomposite formulations significantly outperformed the individual components, with the cumulative oil recovery rates reaching up to 83% in the low salinity condition of 30,000ppm and due to increase in salinity of 60,000ppm reduced recovery percentage of 79%. The study revealed that hybrid nanocomposites effectively mitigated permeability damage, a prevalent challenge associated with the use of polymers as enhanced oil recovery (EOR) agents. The incorporation of SiO₂ nanoparticles played a crucial role in preserving permeability by preventing the plugging of pore spaces, thereby enabling improved fluid flow and oil displacement.

KEYWORDS: Enhanced Oil Recovery, Guar Gum, Nanoparticle, Permeability damage, Rheology, Silicon Oxide.

1. INTRODUCTION

The world's energy needs continue to escalate, driven by factors such as population growth, industrialization, and urbanization. Despite the increasing prominence of renewable energy sources, the demand for oil remains high, particularly in sectors like transportation, petrochemicals, and various industrial processes [1]. This persistent reliance on oil underscores the critical need to maximize the extraction of this valuable resource from existing reservoirs. Conventional oil recovery methods, including primary recovery (driven by reservoir pressure) and secondary recovery (utilizing water or gas injection), typically leave a significant portion of the original oil in place [2] (Fig. 1). This untapped resource, known as residual oil, poses a substantial challenge to meeting global energy demands. Enhanced oil recovery (EOR) techniques have emerged as a vital tool for extracting this remaining oil, thereby extending the life of oil fields and increasing overall production [3].

EOR methods are categorized into three main types: thermal, chemical, and miscible (Fig 1). Thermal EOR methods, such as steam injection and in-situ combustion, utilize heat to reduce oil viscosity and improve its flow ability, primarily targeting heavy oil reservoirs [4]. Miscible EOR methods, like carbon dioxide (CO₂) flooding, involve injecting fluids that dissolve in the oil, reducing interfacial tension and enhancing displacement. Chemical EOR techniques, on the other hand, employ various chemicals to modify fluid properties and reservoir rock interactions, facilitating oil mobilization and recovery [5].

Chemical EOR encompasses a wide array of techniques, including polymer, surfactant, alkaline, and nanoparticle-enhanced flooding. Polymer flooding involves injecting water-soluble polymers to increase fluid viscosity and improve sweep efficiency [6]. Surfactants reduce interfacial tension between oil and water, while alkalis can react with acidic oil components to create surfactants in situ [3]. Nanoparticle-enhanced flooding utilizes nanomaterials to modify interfacial properties, wettability, and fluid flow behavior [7].

Recent research has highlighted the potential of combining different chemical EOR agents to create hybrid systems that offer synergistic benefits. These hybrid systems aim to overcome the limitations of individual components and achieve superior performance. In particular, the combination of polymers and nanoparticles has shown promise in improving oil recovery efficiency by enhancing rheological properties, interfacial tension reduction, and wettability alteration [8].

Guar gum, a natural polysaccharide, has garnered attention as a cost-effective and environmentally friendly polymer for EOR [9]. Its thickening and shear-thinning properties make it well-suited for improving sweep efficiency and mobility control [6]. Silicon oxide nanoparticles (SiO₂ NPs), known for their high surface area and tunable surface chemistry, have demonstrated the potential to enhance oil recovery through interfacial tension reduction, wettability alteration, and emulsion stabilization [10].

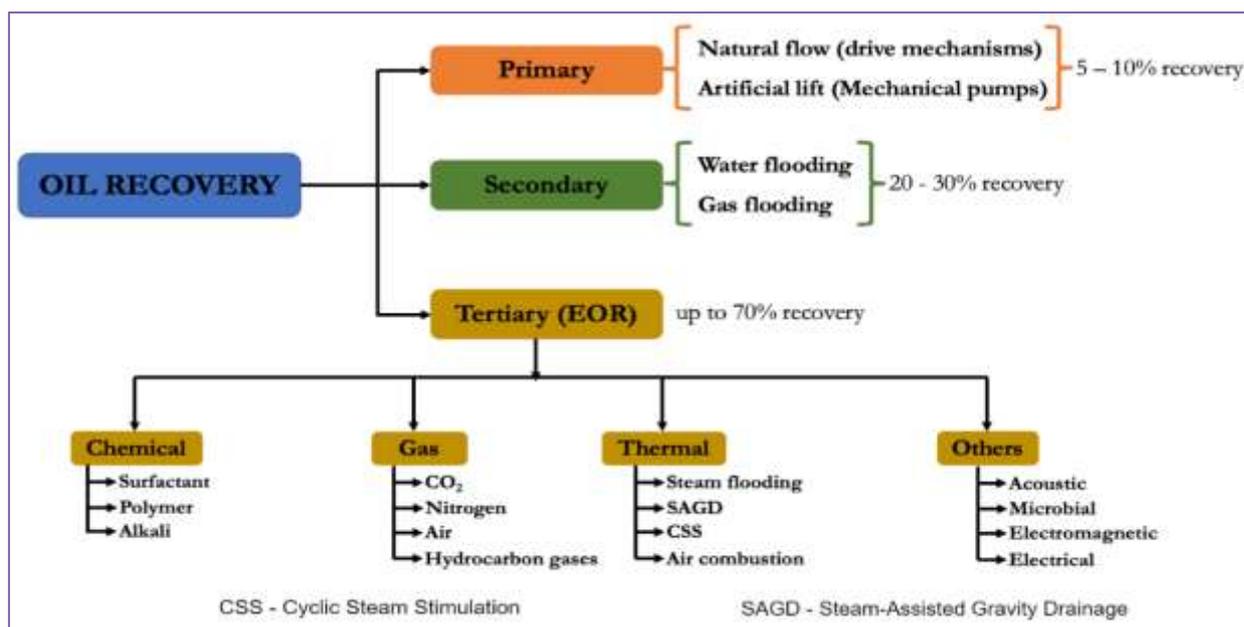


Fig. 1 Flowsheet of enhanced oil recovery methods [1]

A few studies have investigated the use of guar gum and synergistic effects of guar gum and SiO₂ NPs in EOR, demonstrating improved performance compared to individual components [11 - 14]. [13] reported that guar gum-SiO₂ NP hybrids effectively reduced interfacial tension and altered wettability in oil-wet carbonate rocks, leading to improved oil recovery in coreflood experiments. Similarly, [14] observed that guar gum-SiO₂ NP hybrids exhibited enhanced viscosity and shear stability compared to guar gum alone. The nanoparticles were found to adsorb onto the guar gum molecules, increasing their hydrodynamic size and enhancing their resistance to shear degradation.

Some studies have looked into the mechanisms through which guar gum-SiO₂ NP hybrids improve oil recovery. [15] suggested that SiO₂ NPs can act as bridges between guar gum molecules, forming a stronger network that enhances viscosity and elasticity. This network can better withstand shear forces and provide improved mobility control in porous media. Additionally, the adsorption of SiO₂ NPs onto rock surfaces can create a more water-wet environment, facilitating oil displacement and reducing residual oil saturation. This study aimed to investigate the effect of guar gum and silicon oxide (SiO₂) nanoparticles hybrid using sandstone from Niger Delta for Enhanced oil recovery (EOR). Through a series of core flooding experiments, rheological assessments, and permeability analyses were carried out in this study. The evaluation is achieved through the performance of the formulated hybrid solutions under varying salinity conditions as to determine the oil recovery efficiency, optimal concentrations of the components, and understand their rheological behavior.

2. GUAR GUM

Guar gum, a natural polysaccharide derived from guar beans, has gained prominence as a versatile and eco-friendly polymer for enhanced oil recovery (EOR). Its unique properties and cost-effectiveness make it a valuable tool in various EOR techniques. Guar gum's high molecular weight and long chain structure allow it to significantly increase the viscosity of injected water, improving sweep efficiency and reducing viscous fingering in the reservoir [16]. Its shear-thinning behavior enables easier injection and better flow through porous media. Additionally, guar gum's biodegradability makes it an environmentally friendly alternative to synthetic polymers [16].



Studies have demonstrated the effectiveness of guar gum flooding in improving oil recovery in both sandstone and carbonate reservoirs [17 - 18]. Its ability to increase viscosity and control mobility ratio has led to significant increases in oil recovery rates in field trials. It has also been successfully combined with other EOR agents, such as nanoparticles, surfactants, and alkalis, to create hybrid formulations that offer synergistic benefit. Guar gum-silica nanoparticle hybrids have shown promise in improving rheological properties, interfacial tension reduction, and wettability alteration. Modified guar gum derivatives with enhanced thermal and salinity stability have been developed to address the limitations of conventional guar gum in harsh reservoir conditions [18]. These modified polymers have shown promising results in laboratory and field tests, expanding the applicability of guar gum in challenging environments

3. METHODOLOGY

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, Sieve, Stirrer and flooding loop (displacement loop, flow meter, core holder, stem heads (2), Valve (2), accumulator and pressure gauge.

3.1.2 Materials

Preparation of Brine: Two laboratory brine solutions were formulated in this study. The brine solutions were prepared with 30g and 60g of sodium chloride (NaCl) in 1000ml of water. The density of the formulated brine using different 30000ppm and 60000ppm are 1.021g/dm^3 and 1.039g/dm^3 .

Preparation of Nanofluids: The silicon oxide nanoparticles used in this study was acquired from JoeChem Chemical Shop Port Harcourt, River's state, Nigeria. 0.1g and 0.3g of silicon oxide were dissolved in equal volume of 200ml of brine from the different concentrations of 30g/L and 60g/L. The formulated nanofluids with different 0.1g and 0.3g in 200ml of brine were added to equal concentrations of 200ml of formulated guar 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 °API gravity of 33.99 at the 29°C.

3.1.3 Experimental Procedure

Twelve core (plug) samples were prepared for the experiment with the grain sizes of 600µm, the length and diameter were measured, cleaned and were fully dried in an oven. The plug samples were well defined with samples identification number (A1 to A12) for easy identity. The EOR fluid prepared consist of metallic oxide nanoparticles (Silicon oxide) and polymer (Guar gum) having the concentration ranging from 0.1% and 0.3% in brine solution (S3₁ - S3₆ and S6₁ - S6₆ are fluid sample ID for 30000ppm and 60000ppm salinity respectively)

The weight, length and diameter of each prepared core was measured, and the result is presented in Table 1. The twelve core samples were fully saturated in a brine water of the different 30,000ppm and 60,000ppm concentrations as to measure the saturated weight of various core samples. The 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 60,000ppm using Equation 1 represented in Table 2. The porosity was determined 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 stated procedures. The water breakthrough time was recorded. The different concentrations of guar gum polymer, guar gum/SiO₂ hybrid and silicon nanofluid at different concentrations of 0.1wt% 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.

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



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

$$Porosity: Porosity, \phi = \frac{P.V}{B.V} \times 100\% \tag{2}$$

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

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

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 assessment of polymer guar gum and polymer-silicon oxide nanoparticle hybrid for enhanced oil recovery using different salinity concentrations of 30,000ppm and 60,000ppm are presented. The major discussion of this research findings includes petrophysical properties of the formation, fluid properties, oil recoveries and permeability damage.

4.1. Result for Petrophysical Properties for Various Core Samples

Bulk volume is the total sand volume used to form the core sample excluding the volume of the screen. Table 1 presents the result of bulk volume for twelve (12) encapsulated plugs with A1 to A12 sample ID. The grain size of the sieved formation used in preparing the encapsulated plug is 600 μ m. The results obtained from measurement of bulk volume for the plug samples ranges from 59.25 to 71.03cm³. The variations in bulk volume can be explained by differences in length and radius of the core samples.

Table 1. Bulk Volume of Encapsulated Plug

Plug samples. ID	Actual length of plug (cm)	Plug diameter (cm)	Plug radius (cm)	Bulk volume (cm ³) $\pi r^2 h$
A1	7.05	3.38	1.69	63.28
A2	6.75	3.40	1.70	61.31
A3	7.59	3.34	1.67	66.53
A4	7.71	3.36	1.68	68.39
A5	6.75	3.40	1.70	61.31
A6	6.76	3.34	1.67	59.25
A7	6.68	3.36	1.68	59.25
A8	7.81	3.38	1.69	70.11
A9	6.68	3.40	1.70	60.67
A10	6.68	3.38	1.69	59.96
A11	6.71	3.38	1.69	60.23
A12	7.82	3.40	1.70	71.03

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 24.09 to 28.63cm³ for plugs samples A7 and A12 having the lowest and highest porosity values respectively as shown in 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. It will be observed from the Table 2, despite variations in core size, the porosity values remain relatively stable across samples, indicating consistent pore structure across the core plugs.



Table 2. Pore Volume of the Plug Samples

Plug samples ID	Bulk volume (cm ³) $\pi r^2 h$	Wt. of screen + foil +dry plug (g)	Wt. of screen + foil+ saturated plug (g)	Wt. of saturation within the plug (g)	Density of sat. fluid +NaCl/KCl 1500 ppm(g/cm ³)	Pore volume cm ³	Porosity (%)
A1	63.28	132.13	158.00	28.03	1.021	25.35	40.06
A2	61.31	130.58	155.33	26.36	1.021	24.25	39.55
A3	66.53	149.46	176.33	29.19	1.021	26.33	39.58
A4	68.39	154.64	182.37	28.11	1.021	27.17	39.73
A5	61.31	129.75	155.34	27.57	1.021	25.08	40.91
A6	59.25	133.80	158.48	29.53	1.021	24.18	40.81
A7	59.25	131.13	155.71	27.6	1.021	24.09	40.66
A8	70.11	149.92	178.53	28.57	1.021	28.03	39.98
A9	60.67	133.59	159.88	27.21	1.021	25.76	42.46
A10	59.96	129.19	153.55	29.65	1.021	23.87	39.81
A11	60.23	133.59	158.81	27.18	1.021	24.71	41.03
A12	71.03	152.32	181.54	28.02	1.021	28.63	40.31

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 uniform flow rate of 0.9091 cm³/sec and the pressure difference was recorded for every experiment. The viscosity of the brine was 1.0224cp which was also uniform. 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 as shown in Table 3 as to measure the formation damage after the recovery.

Table 3. Permeability of the Formation Result

Sample plugs ID	Length (cm)	Radius (cm)	Visco. of brine (Cp)	Plug Area (cm ²)	Change in Pressure (psi) Before EOR	Change in Pressure (psi) After EOR	Permeability K(md) x 14700
A1	7.05	1.69	1.0224	92.8438	2.5	3.0	409.53
A2	6.75	1.70	1.0224	90.2943	2.5	3.0	403.17
A3	7.59	1.67	1.0224	97.2035	2.5	3.0	350.93
A4	7.71	1.68	1.0224	99.1583	2.5	3.0	349.45
A5	6.75	1.70	1.0224	90.2942	2.5	3.0	403.17
A6	6.76	1.67	1.0224	88.4909	2.5	3.0	412.00
A7	6.68	1.68	1.0224	88.2815	2.5	3.0	408.09
A8	7.81	1.69	1.0224	100.917	2.5	3.0	347.82
A9	6.68	1.70	1.0224	89.5462	2.5	3.0	402.32
A10	6.68	1.69	1.0224	88.9133	2.5	3.5	405.19
A11	6.71	1.69	1.0224	89.2319	2.5	3.0	405.55
A12	7.82	1.70	1.0224	101.727	2.5	3.5	345.49



4.2 Results of Fluid Properties (PH, Density, Viscosity. Shear rate and Gel strength)

The results for density, pH, viscosity, shear rate and gel strength of the formulated fluids of guar gum, guar gum-silicon oxide hybrid, and silicon oxide nanofluid for different concentrations of 30,000ppm and 60,000ppm brine of 0.1%wt, and 0.3%wt are presented in Table 4. The pH levels of the samples ranged from 5.1 to 7.8, with pure brine having a higher pH (7.8) compared to polymer and nanoparticle-containing samples (pH ~5.1 to 5.8). The decrease in pH upon adding guar gum or SiO₂ can be attributed to the slight acidic nature of these additives, which lowers the overall pH of the fluid.

Density is the mass of object per unit volume. It measures how dense a fluid can be. 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 newly formulated EOR fluids 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 60,000ppm. The fluids 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 SiO₂ 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.

Table 4. Density of Brine, Crude, and the EOR formulated solution

Sample fluids	Weight percent	Salinity (ppm)	Efflux time (sec)	Kinematic Viscosity. (cp)	Density (g/cm ³)	Dynamic viscosity. (cp)	PH
S31	0.1% SiO ₂	30,000	32.00	1.1653	1.0208	1.1896	5.10
S32	0.1% Guar gum		99.00	3.6053	1.0201	3.6778	5.30
S33	0.3 %SiO ₂		27.00	0.9833	1.0195	1.0025	5.20
S34	0.3% Guar gum		419.0	15.259	1.0205	15.571	5.30
S35	0.1% SiO ₂ /0.3% Guar gum		476.0	17.335	1.0159	17.61	5.70
S36	0.3% SiO ₂ /0.1% Guar gum		102.0	3.7145	1.0203	3.7899	5.80
S61	0.1% SiO ₂	60,000	38.00	1.3838	1.0394	1.4383	5.40
S62	0.1% Guar gum		74.00	2.6949	1.0397	2.8019	5.30
S63	0.3% SiO ₂		32.00	1.1653	1.0401	1.212	5.40
S64	0.3% Guar gum		503.0	18.317	1.0399	19.049	5.40
S65	0.1% SiO ₂ /0.3% Guar gum		490.0	17.844	1.0353	18.474	5.60
S66	0.3% SiO ₂ /0.1% Guar gum		120.0	4.370	1.0369	4.5312	5.50

Fig. 2 presents the shear rate and corresponding viscosity measurements of nanocomposite samples with varying concentrations of silicon oxide (SiO₂) and guar gum at two different salinities of 30,000 ppm and 60,000 ppm. The samples analyzed include 0.1% SiO₂/0.3% Guar Gum and 0.3% SiO₂/0.1% Guar Gum, both at low and high salinity levels. The viscosity of the samples decreases as the shear rate increases, a typical behavior of non-Newtonian fluids like those with guar gum and nanoparticle suspensions. Increasing the salinity from 30,000 ppm to 60,000 ppm generally resulted in higher viscosity values for the samples with 0.1% SiO₂/0.3% Guar Gum (S65). The viscosity at 600 rpm increased from 18 cP (S35) to 19 cP (S65), and the overall viscosity also increased slightly from 17.61 cP to 18.47 cP. This suggests that higher salinity enhances the thickening effect of the guar gum-nanoparticle hybrid, likely due to increased interaction between the nanoparticles and the guar gum, as well as ionic interactions in the fluid matrix.

The sample with a higher concentration of SiO₂ (0.3% SiO₂/0.1% Guar Gum) exhibited significantly lower viscosity compared to the sample with a higher guar gum content (0.1% SiO₂/0.3% Guar Gum). For instance, at 300 rpm, the viscosity for S3₆ (30,000 ppm) was 4 cP compared to 12 cP for S3₅ (30,000 ppm). This indicates that guar gum plays a more dominant role in increasing viscosity than SiO₂ nanoparticles. The polysaccharide structure of guar gum contributes more effectively to the thickening and viscoelastic properties of the fluid. All samples exhibited shear-thinning behavior, where viscosity decreases as the shear rate increases [19]. For example, S6₆ (0.3% SiO₂/0.1% Guar Gum at 60,000 ppm) showed a reduction in viscosity from 2 cP at low shear rates (3 rpm) to 7 cP at high shear rates (600 rpm). This shear-thinning property is advantageous for enhanced oil recovery (EOR) as it allows the fluid to have lower viscosity during injection (high shear rates), making it easier to pump, while increasing viscosity in the reservoir (low shear rates) to enhance oil displacement. The viscosity reduction is due to uncoiling and alignment of guar polymer chains when exposed to shear flow [20-21]. The results generally suggest that optimizing the ratio of SiO₂ nanoparticles and guar gum can tailor the fluid properties for specific reservoir conditions, maximizing recovery efficiency.

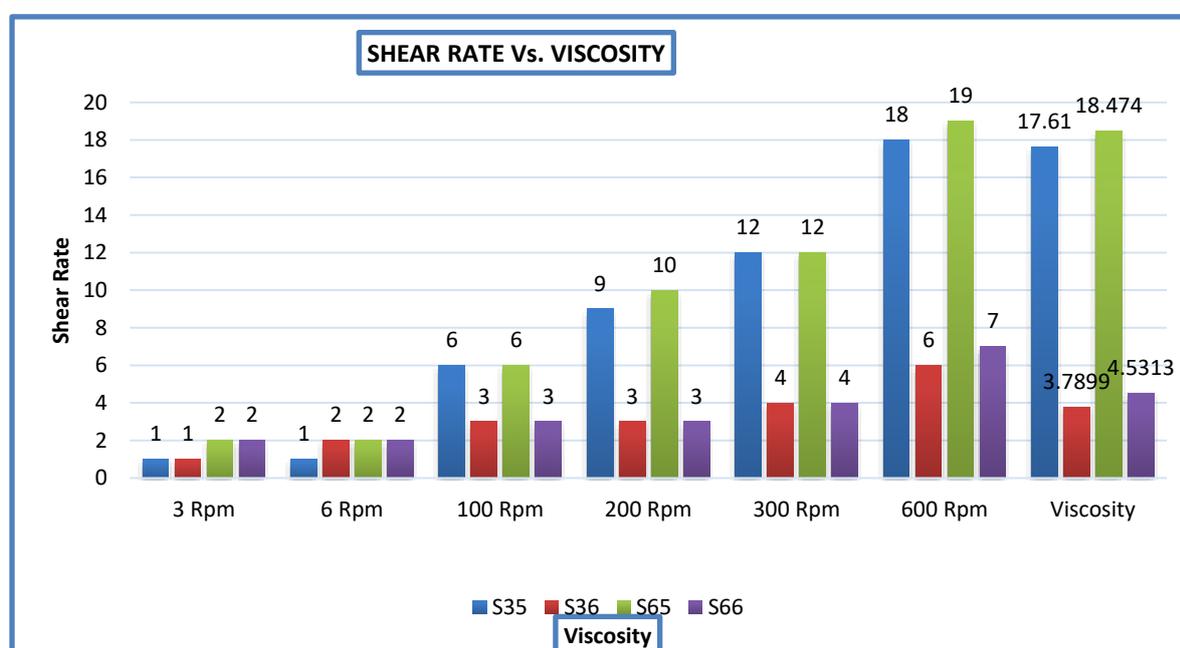


Fig. 2 Shear rate against Viscosity of the formulated Fluid

Fig. 3 provides the gel strength measurements of various hybrid fluid samples over time. Gel strength is a critical rheological property in the context of enhanced oil recovery (EOR) because it indicates the ability of a fluid to form a stable gel structure. This property helps in blocking high-permeability zones and improving the sweep efficiency during flooding operations. At the initial 10-second mark, (Sample 35, 0.1% SiO₂/0.3% Guar Gum) and Sample 36 (0.3% SiO₂/0.1% Guar Gum) both exhibited a gel strength of 1. This indicates that the hybrid solutions had just started forming a gel structure and displayed minimal resistance to deformation. In contrast, Sample 65 (0.1% SiO₂/0.3% Guar Gum with 60,000 ppm salinity) and Sample 66 (0.3% SiO₂/0.1% Guar Gum with 60,000 ppm salinity) showed a gel strength of 2. The higher salinity in these samples likely contributed to faster gelation, as the increased ionic concentration enhances the crosslinking of polymer chains and nanoparticles, forming a more robust network. After 10 minutes, the gel strength of (Sample 36, 0.3% SiO₂/0.1% Guar Gum) increased from 1 to 2, indicating a continued gel formation process. This suggests that the formulation with a higher SiO₂ concentration (Sample 36, 0.3% SiO₂/0.1% Guar Gum) experienced delayed gelation but achieved similar final strength as other samples over time. The increased salinity in (Samples 65 and 66, 60,000 ppm) accelerated the gelation process compared to lower salinity samples (Samples 35 and 36 with 30,000 ppm). The higher ionic strength in saline conditions likely promoted stronger interactions between guar gum chains and silicon oxide nanoparticles, leading to a faster and more robust gel network formation.

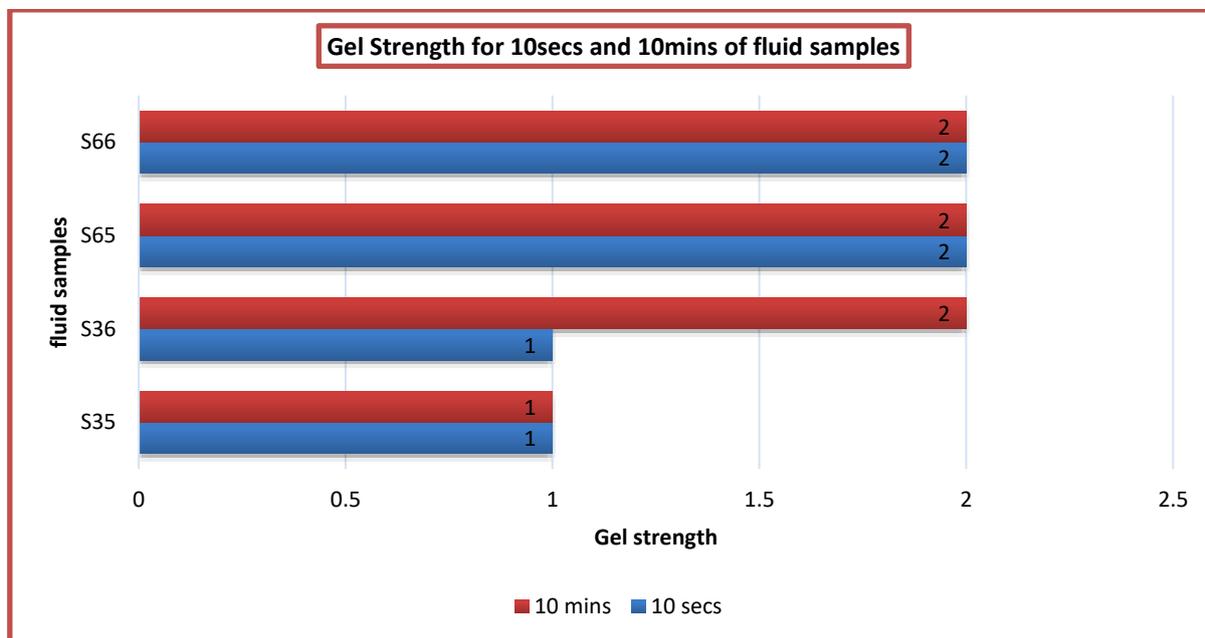


Fig. 3 Fluid Sample against Gel Strength

4.2 Recovery of Crude Oil by Water and Tertiary Methods

Fig. 4 presents an in-depth analysis of oil recovery performance using various fluid samples, including SiO₂ nanoparticles solution, Guar gum solution, and their hybrid nanocomposites, using two different salinities of 30,000 ppm and 60,000 ppm. The cumulative oil recovery (%), which indicates the efficiency of each EOR fluid in displacing the original oil in place (OIP), is a crucial parameter. The highest recovery was achieved with hybrid nanofluids (SiO₂/Guar gum combinations), particularly at 30,000 ppm salinity, showing superior performance compared to individual components.

Silicon oxide Nanoparticles Solution: At 0.1% SiO₂ concentration (S31 and S61), the oil recovery at 30,000 ppm was 72.92%, while at 60,000 ppm, it dropped to 68.8%. At 0.3% SiO₂ concentration (S32 and S62), the recovery improved slightly at 30,000 ppm (70.83%) but decreased at 60,000 ppm (67.4%). This shows that while SiO₂ nanoparticles enhance oil recovery, their efficiency reduces at higher salinity levels.

Guar Gum Solution: At 0.1% concentration (S33 and S63), the oil recovery was 73.91% at 30,000 ppm and 71.74% at 60,000 ppm, indicating better performance than 0.1% SiO₂. At 0.3% concentration (S34 and S64), the cumulative oil recovery increased to 73.08% at 30,000 ppm but declined to 72.59% at 60,000 ppm, showcasing that Guar gum is more effective at higher concentrations and moderate salinity levels.

Hybrid Nanofluids Performance: The combination of SiO₂ nanoparticles and Guar gum (S35, S36, S65, and S66) provided the highest oil recovery percentages, indicating a synergistic effect that enhanced EOR performance. S35 (0.1% SiO₂/0.3% Guar gum at 30,000 ppm) achieved the highest recovery at 83.33%, showing the most effective EOR fluid, particularly in lower salinity conditions. S36 (0.3% SiO₂/0.1% Guar gum at 30,000 ppm) also performed well, with an 79.55% recovery. S65 (0.1% SiO₂/0.3% Guar gum at 60,000 ppm) achieved 76.09.8%, slightly lower than at 30,000 ppm but still significantly higher than using individual SiO₂ or Guar gum alone. S66 (0.3% SiO₂/0.1% Guar gum at 60,000 ppm) reached 75.47%, confirming the hybrid fluid's consistent performance across different salinities. From this experimental study, it can be found that the synergy effect of guar gum and silicon oxide as a hybrid both in 30,000ppm and 60,000ppm increase oil recovery better than standalone polymer guar gum and silicon nanofluids. (Fig.4). These results match with findings of [18] who showed that additional oil recovery can be obtained with a high concentration of polymer solutions but reduces at a very high concentration due to polymer adsorption on the rock surface. In the case of (guar gum/SiO₂) decreasing of recovery factor at slug concentration increases above 0.3wt% resort to an accumulation of SiO₂ nanoparticles at higher concentrations, which in turn cause clogging of the pore throat and permeability reduction. These results



are highly compatible with many polymer-nanofluids findings that proved that increasing hydrophilic nanoparticles concentration adversely affects the oil recovery owing to impairment of the reservoir rock permeability.

Breakthrough Time and Oil Recovery: The breakthrough time, which indicates the time it takes for the injected fluid to break through the oil front, was generally longer for samples with higher viscosities and better recovery performance. The hybrid nanofluids, especially S35 and S65, demonstrated delayed breakthrough times (39 sec for S35 and 35 sec for S36), which allowed for more efficient oil displacement, resulting in higher cumulative oil recoveries.

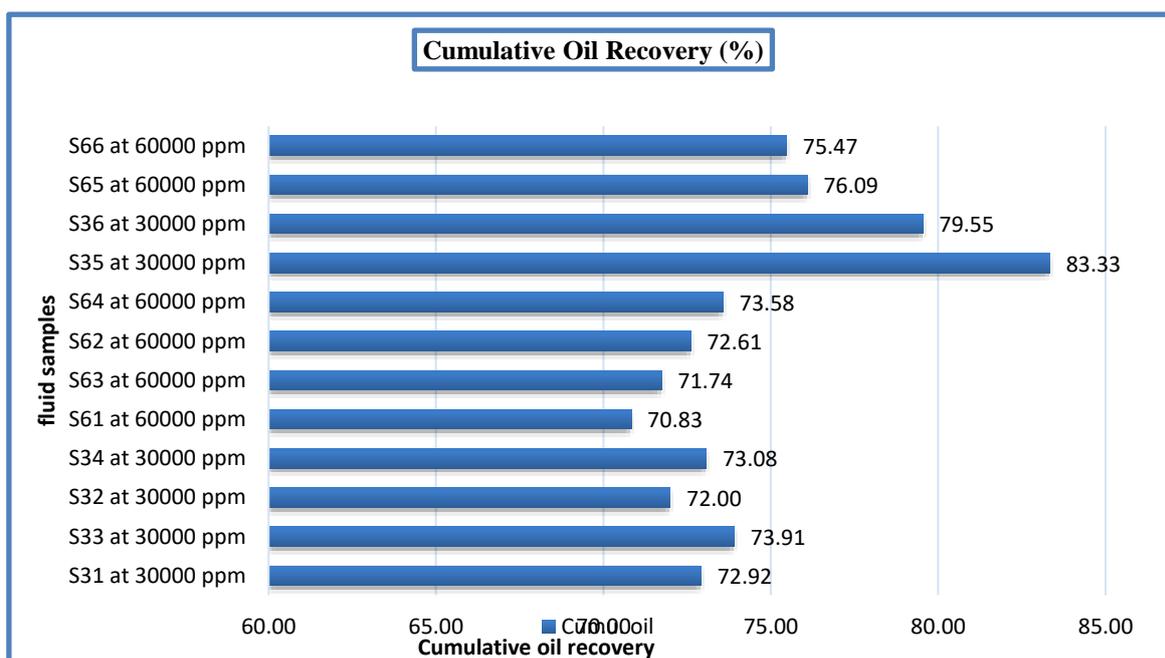


Fig. 4 Cumulative Oil Recovery against Fluid Samples

4.3 Permeability Change Result

Fig. 5 presents the results of permeability alteration using various fluid samples with silicon oxide (SiO₂), guar gum, and their hybrid nanocomposites at two salinity levels (30,000 ppm and 60,000 ppm). The aim is to analyze how different EOR fluid formulations impact permeability and correlate this with oil recovery performance. Here, we evaluate the permeability damage (reduction in permeability) based on the alteration values (K₁–K₂). K₁ is the initial permeability before flooding and K₂ is the final permeability after flooding. The alteration value (K₁–K₂) indicates the degree of permeability reduction. Lower permeability damage (smaller alteration value) typically correlates with improved oil recovery since it implies better fluid mobility and flow resistance. The plug samples with the lowest permeability damage (Samples A9 and A11) are those treated with 0.1% SiO₂ / 0.3% guar gum, and these correspond to high oil recovery rates, as seen in core flooding results (S35 and S65). Conversely, plug samples with higher permeability damage (A10 and A12), using 0.3% SiO₂ / 0.1% guar gum, correlate with lower oil recovery due to increased flow resistance caused by severe plugging.

Hybrid nanocomposites of 0.1% SiO₂ / 0.3% guar gum (Samples A9 and A11) exhibit the lowest permeability damage, aligning with the highest oil recovery in core flooding experiments. This suggests that this formulation effectively enhances fluid flow while preventing significant pore blockage. The formulation of 0.3% SiO₂ / 0.1% guar gum (Samples A10 and A12) shows the highest permeability alteration, which could hinder oil recovery due to increased flow resistance. This indicates that excessive nanoparticle concentration may lead to plugging issues, reducing the efficiency of the EOR process. The data demonstrate that careful optimization of SiO₂ and guar gum concentrations is crucial to achieving the best balance between minimizing permeability damage and maximizing oil recovery which agreed with [22] conclusion. Overall, these findings support the conclusion that hybrid EOR fluids with a higher proportion of guar gum (as in A9 and A11) are more effective in enhancing oil recovery by preserving permeability and reducing flow resistance.

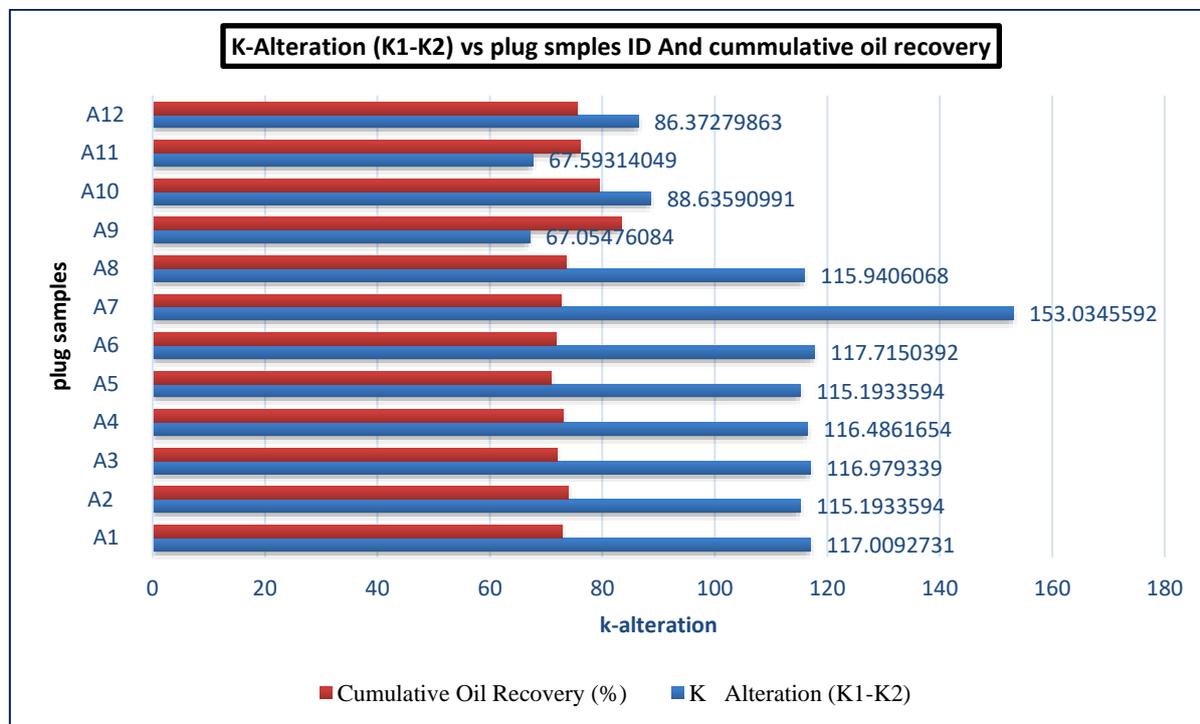


Fig. 5. Permeability Alteration for different concentration of EOR agents

5. CONCLUSION

The results from the experimental tests have proved the effectiveness of the synergy of the silica oxide (SiO₂) nanoparticles and guar gum polymer in improving oil recovery in both 30,000ppm and 60,000ppm brine concentrations. The presence of silicon oxide in guar gum improved the viscosity of polymer solution, which reduced the mobility ratio between the injected fluids and the oil in the reservoir. Secondly, this synergized polymer-nano-silica solution reduced the permeability damage of the formation. Among the hybrid compositions studied, the least altered permeability values were observed in S35 (67.05md), S36 (88.63md), S65 (67.59md), and S66 (86.37md). These compositions which when compared to those with the highest permeability alteration values such as samples S63 (117.72md) gave the best recovery percentage. Generally, the guar gum/ silicon oxide hybrid in both 30,000ppm and 60,000ppm 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 60,000ppm based on viscosity, rheological, permeability change, and oil recovery.

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