

Enhanced Oil Recovery Performance of SiO₂-PAM and Al₂O₃-PAM Hybrid Nanofluids in Sandstone Reservoirs

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-----ABSTRACT-----

The growing global energy demand necessitates improved hydrocarbon recovery from mature sandstone reservoirs, where conventional enhanced oil recovery (EOR) methods often leave substantial oil trapped due to unfavorable mobility ratios and capillary forces. This study investigates the synergistic effects of silica (SiO₂) and alumina (Al₂O₃) nanoparticles combined with polyacrylamide (PAM) polymer on oil recovery performance in sandstone cores. Nano-polymer hybrid fluids were formulated in 30,000 ppm NaCl brine at nanoparticle concentrations of 0.1% and 0.3% with 0.2% PAM. Rheological characterization revealed significant viscosity enhancement, with the 0.3% SiO₂-PAM hybrid achieving the highest viscosity (14.61 cP) compared to PAM-only (10.74 cP). X-ray diffraction confirmed quartz-dominated mineralogy (57.8%), while Fourier transform infrared spectroscopy confirmed interactions between the nanoparticles and PAM polymer matrix. Core flooding experiments using encapsulated sandstone plugs demonstrated that the 0.3% SiO₂-PAM hybrid achieved the highest oil recovery (81.82%), surpassing PAM-only (77.27%) and individual nanoparticle systems (71.74-76.19%). However, permeability reduction was more pronounced in hybrid systems (up to 287.92 mD for 0.3% Al₂O₃-PAM) compared to individual nanoparticles (100.90-140.45 mD), revealing a critical optimization trade-off between recovery enhancement and formation damage. The optimal nanoparticle concentration of 0.3% with 0.2% PAM provided the best balance between improved sweep efficiency and acceptable permeability impairment. This study demonstrates that silica-PAM hybrids offer superior performance compared to alumina-PAM hybrids under identical conditions, with the optimized formulation providing a promising approach for maximizing oil recovery in sandstone reservoirs while maintaining acceptable formation integrity.

KEYWORDS;- Enhanced Oil Recovery, Nanoparticles, Polyacrylamide, SiO₂, Al₂O₃, Hybrid Nanofluids, Sandstone Reservoir, Permeability Damage, Core Flooding

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I. INTRODUCTION

The global energy landscape continues to rely heavily on hydrocarbon resources, with sandstone reservoirs constituting a significant portion of the world's oil-bearing formations [1]. Primary and secondary recovery processes often leave 40-70% of the original oil in place, trapped inside the pores of the reservoir [2]. Therefore, enhanced oil recovery (EOR) techniques are essential to meet the ever-increasing energy demand. Different EOR methods including chemical flooding (notably polymer flooding) have been quite successful in enhancing sweep efficiency through mobility control [3].

Polyacrylamide (PAM) and its derivatives have been widely employed in polymer flooding due to their ability to increase injected water viscosity, thereby improving the mobility ratio and sweep efficiency [4]. However, conventional polymer flooding faces significant challenges in high-salinity and high-temperature reservoirs, including polymer degradation, viscosity loss, and excessive adsorption onto rock surfaces [5]. These limitations necessitate innovative approaches to enhance polymer performance under challenging reservoir conditions.

Nanotechnology has emerged as a transformative solution in petroleum engineering, offering nanoparticles (1-100 nm) with unique properties including high surface area-to-volume ratios, tunable surface chemistry, and the ability to modify fluid-rock and fluid-fluid interactions [6]. Silicon oxide (SiO₂) and aluminum oxide (Al₂O₃) nanoparticles have attracted particular attention for EOR applications due to their abundance, stability, and compatibility with reservoir environments [7, 8]. These nanoparticles can reduce

interfacial tension, alter wettability toward water-wet conditions, and improve oil displacement efficiency through structural disjoining pressure mechanisms [9].

Recent studies have demonstrated that combining nanoparticles with polymers can produce synergistic effects, enhancing the rheological properties and thermal stability of polymer solutions while mitigating some limitations of individual EOR agents [10, 11]. Gbadamosi et al. [5] reported that nanoparticle-polymer hybrids exhibit improved viscosity retention and reduced polymer adsorption in high-salinity environments. Similarly, Al-Anssari et al. [12] showed that ZrO₂ nanoparticles enhanced the viscosity of PAM solutions under saline conditions. However, systematic comparative studies evaluating SiO₂-PAM and Al₂O₃-PAM hybrids under identical experimental conditions remain limited, particularly regarding the optimization of nanoparticle concentration to balance oil recovery enhancement against formation damage.

The novelty of this study lies in three key aspects: (1) direct comparison of SiO₂-PAM and Al₂O₃-PAM hybrid nanofluids under identical flooding conditions; (2) systematic analysis of the relationship between nanoparticle concentration, rheological properties, oil recovery, and permeability damage; and (3) identification of optimal nanoparticle concentrations for maximizing recovery while maintaining acceptable formation integrity.

This study aims to: (i) formulate and characterize SiO₂-PAM and Al₂O₃-PAM hybrid nanofluids; (ii) evaluate their rheological performance; (iii) conduct core flooding experiments to assess oil recovery efficiency; and (iv) analyze the impact of these hybrids on permeability alteration. The findings provide valuable insights for designing effective nano-polymer EOR formulations for sandstone reservoirs.

II. LITERATURE REVIEW

Nanoparticles in Enhanced Oil Recovery

Nanoparticles have demonstrated remarkable potential in EOR applications through multiple mechanisms including interfacial tension reduction, wettability alteration, and mobility control [13]. Hydrophilic silica nanoparticles can adsorb onto rock surfaces, creating a water-wet film that facilitates oil detachment and mobilization [7]. Alumina nanoparticles, with their high surface reactivity, have shown effectiveness in reducing interfacial tension and improving displacement efficiency [8].

Hendraningrat et al. [9] demonstrated that nanoparticle size significantly affects wettability alteration, with smaller particles producing greater changes in contact angle due to enhanced electrostatic repulsion forces. Ogolo et al. [14] evaluated various nanoparticles for EOR and found that aluminum oxide in brine reduced oil viscosity, while silicon oxide effectively altered wettability. However, studies on combined nanoparticle-polymer systems under controlled conditions are relatively scarce.

Polymer Flooding and Its Limitations

Polymer flooding enhances oil recovery primarily through mobility control, increasing the viscosity of injected water to improve sweep efficiency [3]. However, polymer degradation due to mechanical shear, thermal effects, and chemical interactions in high-salinity environments remains a significant challenge [4]. The adsorption of polymer molecules onto rock surfaces can also reduce injectivity and impair formation permeability [5].

Nano-Polymer Hybrid Systems

The integration of nanoparticles with polymers has emerged as a promising strategy to overcome the limitations of conventional polymer flooding. Nanoparticles can enhance polymer viscosity through electrostatic and hydrogen bonding interactions, improve thermal stability, and reduce polymer adsorption onto rock surfaces [10, 11]. Sowunmi et al. [15] reported that xanthan gum-alumina nanocomposites achieved 72.8% oil recovery, demonstrating the potential of such hybrids.

Despite these advances, systematic studies comparing different nanoparticle-polymer combinations and optimizing concentrations to balance recovery enhancement versus formation damage remain insufficient. This study addresses this gap by evaluating SiO₂-PAM and Al₂O₃-PAM hybrids under identical conditions, providing a comprehensive comparative analysis.

III. MATERIALS AND METHOD

The materials utilized in this study were sourced from commercial suppliers and prepared in the laboratory. Silicon oxide (SiO₂) nanoparticles with an average particle size of 20-30 nm and purity exceeding 99% were employed, alongside aluminum oxide (Al₂O₃) nanoparticles with an average particle size of 20-40 nm

and similar purity. Polyacrylamide (PAM) polymer with a molecular weight of approximately 8×10^6 g/mol and a degree of hydrolysis of about 20% was selected as the base polymer. Sodium chloride (NaCl) of analytical grade was used for brine preparation. The crude oil sample, characterized by an API gravity of 33°, a viscosity of 13.03 cP at 28°C, and a density of 0.87 g/cm³, was obtained from a Niger Delta field. Brine solution was prepared at a salinity of 30,000 ppm NaCl. Encapsulated sandstone core plugs, prepared from unconsolidated Niger Delta formation material with a grain size of 600 μm, served as the porous medium for flooding experiments. All chemicals were used as received without further purification.

Nanofluid Preparation

The brine solution was prepared by dissolving 30 g of sodium chloride in 1 L of distilled water to achieve a salinity of 30,000 ppm. Nanoparticle suspensions were then formulated at concentrations of 0.1% and 0.3% (w/v) in the prepared brine, with PAM added at a constant concentration of 0.2% (w/v). The fluid preparation procedure involved several sequential steps. First, the required quantities of PAM and nanoparticles were accurately weighed using a precision balance. These materials were subsequently dissolved in the brine solution under continuous magnetic stirring at 500 rpm for 30 minutes to ensure initial dispersion. To enhance nanoparticle dispersion and prevent agglomeration, the suspensions were subjected to ultrasonication at 40 kHz for 15 minutes. Finally, the formulated fluids were aged for 12 hours to allow the system to reach a homogeneous phase before use in subsequent experiments. This aging period was essential for achieving stable fluid properties and consistent performance during rheological and core flooding measurements. The fluid formulations are summarized in Table 1.

Table 1: formation of Fluid Compositions

Fluid ID	Composition
F1	Brine only
F2	Brine + 0.1% Al ₂ O ₃
F3	Brine + 0.3% Al ₂ O ₃
F4	Brine + 0.1% SiO ₂
F5	Brine + 0.3% SiO ₂
F6	Brine + 0.2% PAM
F7	Brine + 0.2% PAM + 0.1% Al ₂ O ₃
F8	Brine + 0.2% PAM + 0.3% Al ₂ O ₃
F9	Brine + 0.2% PAM + 0.1% SiO ₂
F10	Brine + 0.2% PAM + 0.3% SiO ₂

Core Characterization

Nine encapsulated sandstone core plugs were prepared with 600 μm grain sizes. Core properties were characterized using: Bulk volume: Caliper method (Equation 1), Pore volume: Brine saturation method (Equation 2), Porosity: Ratio of pore volume to bulk volume (Equation 3), Permeability: Liquid permeameter (Equation 4), Mineralogy: X-ray diffraction (XRD), Equation 1: $BV = \pi r^2 h$, Equation 2: $PV = (W_{sat} - W_{dry}) / \rho_{brine}$, Equation 3: $\phi = PV / B.V \times 100\%$, Equation 4: $K = (Q \times \mu_{brine} \times L_{plug} \times 14500) / (A_{plug} \times \Delta P)$. Where r = radius (cm), h = length (cm), W_{sat} , W_{dry} = saturated and dry weights (g), ρ_{brine} = brine density (g/cm³), Q = flow rate (cm³/s), μ = viscosity (cP), L = plug length (cm), A = cross-sectional area (cm²), ΔP = differential pressure (psi).

Rheological Measurements

Rheological properties were measured using a Cannon U-tube viscometer at temperatures ranging from 27°C to 90°C. The following parameters were determined: Dynamic viscosity (cP), Yield point (lb/100 ft²), Plastic viscosity (cP) and Gel strength (10 sec and 10 min). The rheological properties of the formulated fluids were measured using a Cannon U-tube viscometer at temperatures ranging from 27°C to 90°C. Key rheological parameters determined included dynamic viscosity (cP), yield point (lb/100 ft²), plastic viscosity (cP), and gel strength measured at both 10 seconds and 10 minutes. These measurements provided comprehensive characterization of the flow behavior and structural properties of the nano-polymer hybrid fluids under varying thermal conditions.

Fourier transform infrared spectroscopy (FTIR) analysis was conducted using a Shimadzu FTIR Spectrophotometer (Model 8400 S) to identify functional groups and chemical interactions within the formulated fluids. The analysis was performed within the scanning range of 500-4000 cm⁻¹. Sample preparation involved mixing 0.01 g of each sample with potassium bromide (KBr) and pressing the mixture into translucent pellets using a hydraulic press. The pellets were then scanned, and the resulting spectra were analyzed to identify characteristic absorption bands corresponding to the various chemical bonds present in the samples.

Scanning electron microscopy (SEM) analysis was performed using a Phenom ProX SEM-EDS system to examine the surface morphology and determine the size distribution of the nanoparticles. The samples were prepared by mounting and drying under controlled conditions before being placed in the SEM chamber, where electron beam interaction with the specimen enabled high-resolution imaging of nanoparticle morphology and surface characteristics

Core flooding experiments were conducted to evaluate the oil recovery performance of the formulated nano-polymer hybrid fluids. The experimental procedure followed a systematic sequence. Initially, the encapsulated sandstone plug samples were saturated with brine (30,000 ppm) under vacuum to establish fully saturated conditions. The initial permeability (K₁) of each plug was then determined using a liquid permeameter flow loop. Following this, crude oil was injected into the saturated plugs to establish the original oil in place (OOIP). Secondary recovery was then initiated by injecting brine into the core holder for 3-5 pore volumes to displace a portion of the oil. Tertiary recovery followed, wherein the formulated EOR fluid was injected for 3-5 pore volumes. Finally, the permeability was re-measured (K₂), and the permeability damage was calculated as the difference between initial and final permeability ($\Delta K = K_1 - K_2$). The flooding setup comprised a liquid permeameter flow loop equipped with a core holder, accumulators, pressure regulators, and flow meters. All experiments were conducted at ambient temperature with a constant flow rate maintained between 1.08 and 1.11 cm³/s. Oil recovery was calculated as the percentage ratio of the volume of oil produced to the volume of oil initially in place.

IV. RESULT AND DISCUSSION

Core Properties

Table 2: Physical Properties of Core Plugs

Plug ID	Bulk Vol (cm ³)	Pore Vol (cm ³)	Porosity (%)	Initial Perm (mD)
P1	58.55	23.36	39.90	413.54
P2	68.89	25.12	36.47	365.15
P3	60.97	24.04	39.42	359.23
P4	57.58	22.68	39.39	415.30
P5	58.46	23.19	39.68	413.27
P6	69.11	25.34	36.67	373.63
P7	58.72	23.50	40.02	412.04
P8	69.33	25.48	36.75	364.86
P9	60.57	23.89	39.44	354.51

The core plugs exhibited porosities ranging from 36.47% to 40.02%, indicating good storage capacity. The highest porosity (40.02%) was observed in plug P7, suggesting well-developed pore networks suitable for fluid storage and flow. Permeability values ranged from 354.51 to 415.30 mD, characteristic of medium-to-high permeability sandstone formations.

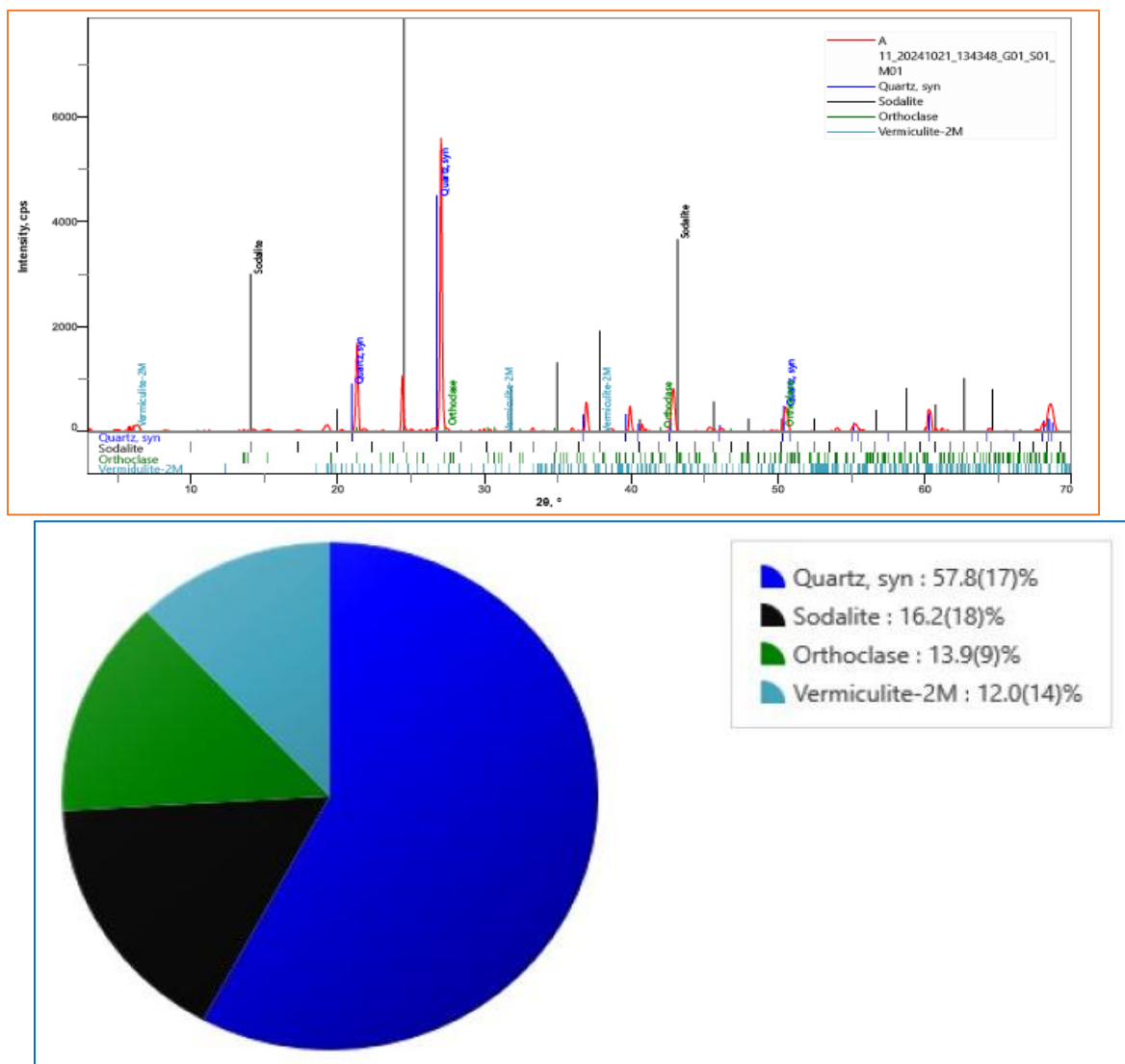


Figure 1: XRD Analysis of Core Plug Mineralogy

XRD analysis revealed quartz as the dominant mineral (57.8%), followed by sodalite (16.2%), orthoclase (13.9%), and vermiculite (12.1%). The quartz-rich composition is favorable for EOR applications due to its relatively stable surface chemistry and low reactivity with injected fluids.

Fluid Characterization

Density Analysis

Table 3: Density and pH of Formulated Fluids

Fluid	Density (g/cm ³)	pH
Brine	1.0208	6.8
Brine + 0.1% Al ₂ O ₃	1.0199	6.9
Brine + 0.3% Al ₂ O ₃	1.0174	6.6
Brine + 0.1% SiO ₂	1.0205	5.6
Brine + 0.3% SiO ₂	1.0214	5.8
Brine + 0.2% PAM	1.0201	6.9
Brine + 0.2% PAM + 0.1% Al ₂ O ₃	1.0205	6.5
Brine + 0.2% PAM + 0.3% Al ₂ O ₃	1.0226	6.7
Brine + 0.2% PAM + 0.1% SiO ₂	1.0212	6.5
Brine + 0.2% PAM + 0.3% SiO ₂	1.0215	6.1

Density measurements showed minor variations among formulations. SiO₂-based fluids exhibited slight density increases with concentration (1.0205-1.0214 g/cm³), while Al₂O₃-based fluids showed slight decreases (1.0199-

1.0174 g/cm³). Hybrid systems, particularly Al₂O₃-PAM, demonstrated more pronounced density increases (up to 1.0226 g/cm³) at higher nanoparticle concentrations, reflecting enhanced particle loading within the polymer matrix. pH values ranged from 5.6 to 6.9, indicating acceptable chemical stability for EOR applications.

Viscosity Analysis

Table 4: Viscosity of Formulated Fluids

Fluid	Dynamic Viscosity (cP)
Brine	1.02
Brine + 0.1% Al ₂ O ₃	1.12
Brine + 0.3% Al ₂ O ₃	1.39
Brine + 0.1% SiO ₂	1.08
Brine + 0.3% SiO ₂	1.86
Brine + 0.2% PAM	10.74
Brine + 0.2% PAM + 0.1% Al ₂ O ₃	11.60
Brine + 0.2% PAM + 0.3% Al ₂ O ₃	13.94
Brine + 0.2% PAM + 0.1% SiO ₂	11.04
Brine + 0.2% PAM + 0.3% SiO ₂	14.61

PAM addition dramatically increased viscosity from ~1 cP to 10.74 cP due to polymer chain entanglement and extended chain architecture in solution. Hybrid systems showed further enhancement, with 0.3% SiO₂-PAM achieving the highest viscosity (14.61 cP), followed by 0.3% Al₂O₃-PAM (13.94 cP). This viscosity enhancement is attributed to synergistic interactions between nanoparticles and polymer chains, including hydrogen bonding and electrostatic interactions [5, 10]. The higher viscosity of SiO₂-PAM compared to Al₂O₃-PAM systems suggests stronger interactions between SiO₂ nanoparticles and PAM chains, likely due to the higher surface reactivity of silica nanoparticles [16].

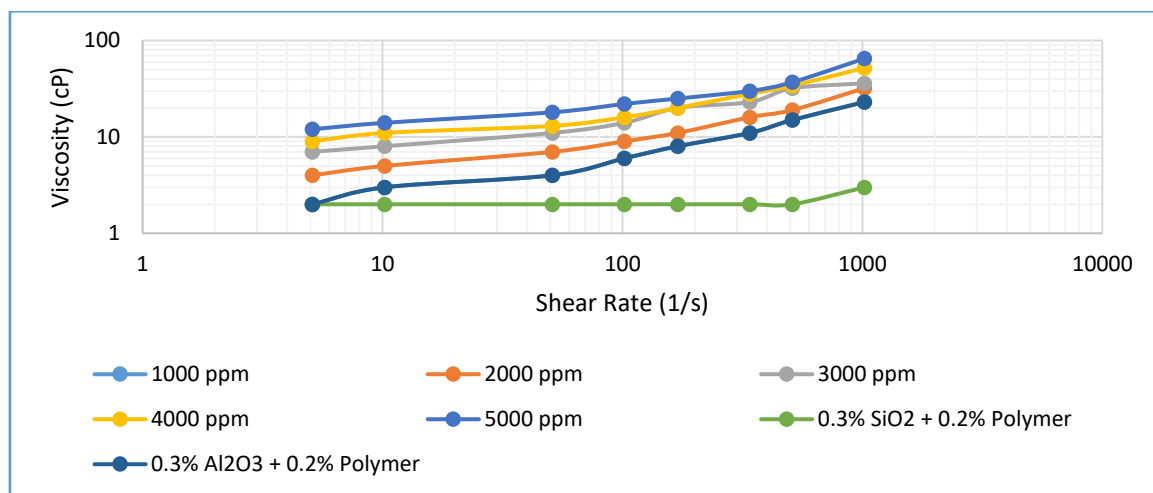
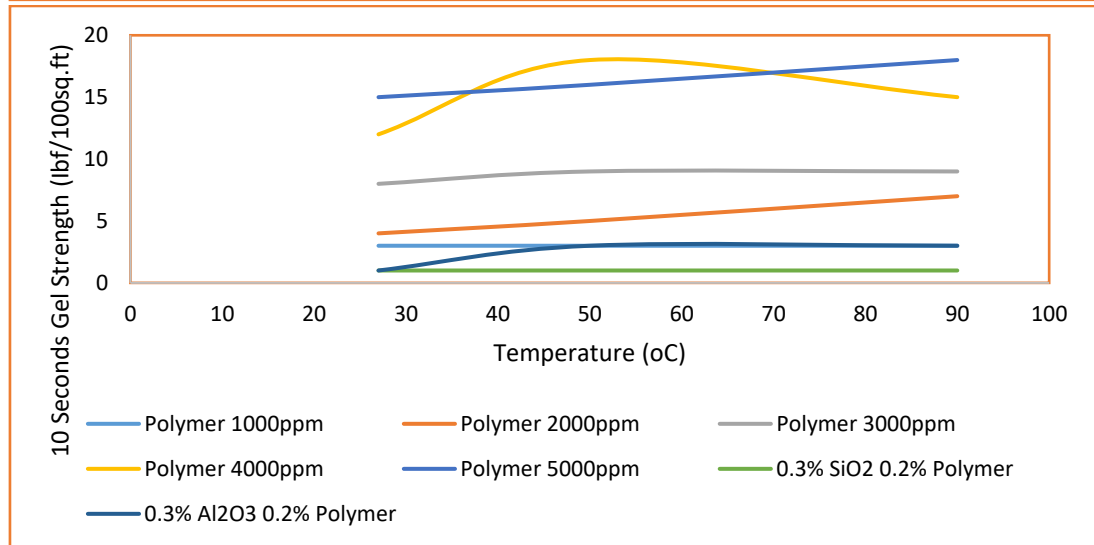
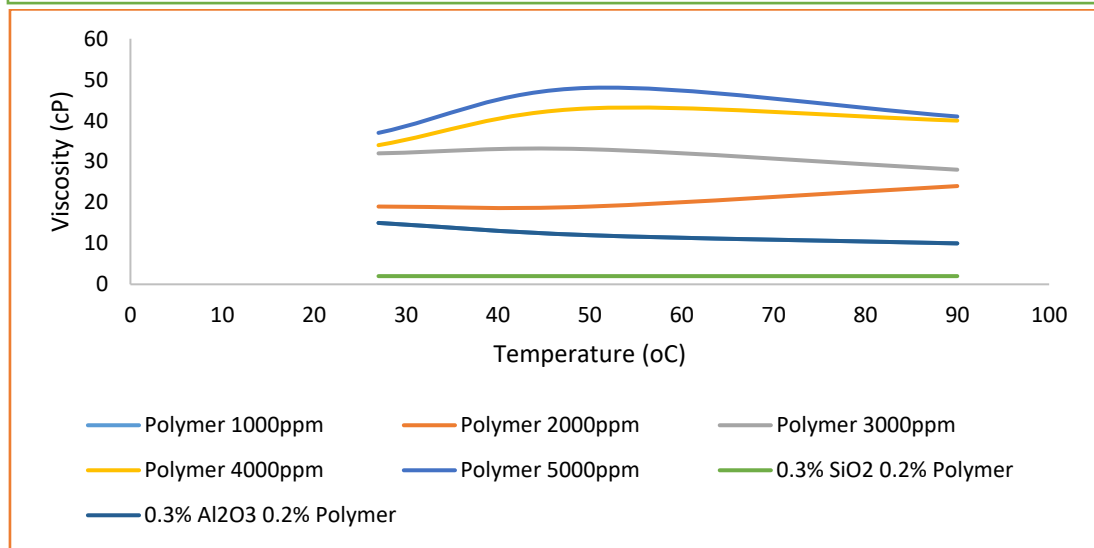
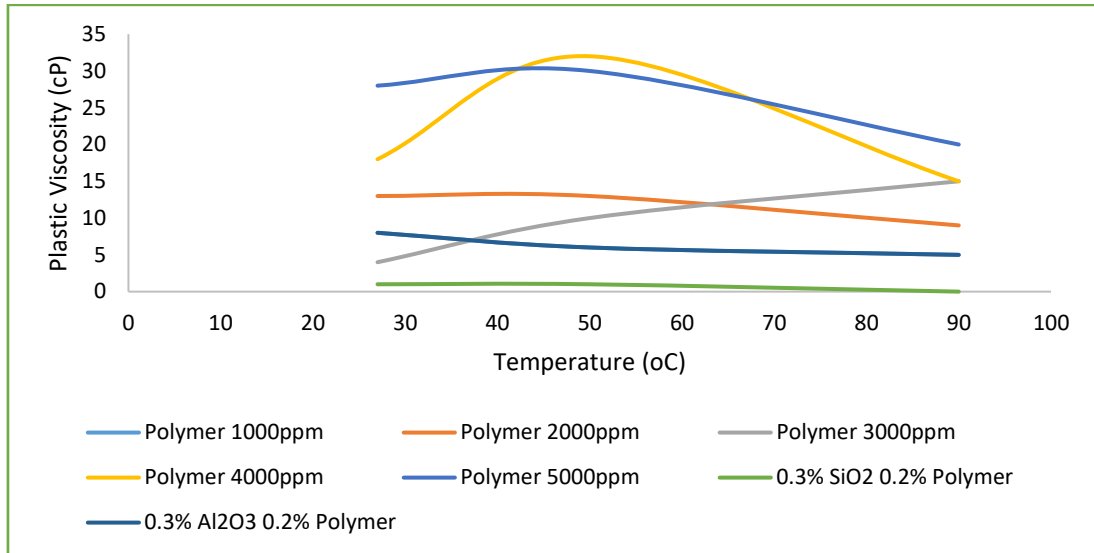


Figure 2: Viscosity vs Shear Rate at 27°C

The viscosity-shear rate relationship (Figure 2) revealed shear-thinning behavior for PAM solutions, consistent with the characteristic non-Newtonian behavior of polymer solutions [17]. Hybrid systems demonstrated reduced shear sensitivity, indicating improved structural integrity of the polymer network in the presence of nanoparticles. This enhanced stability is crucial for maintaining mobility control under reservoir shear conditions.



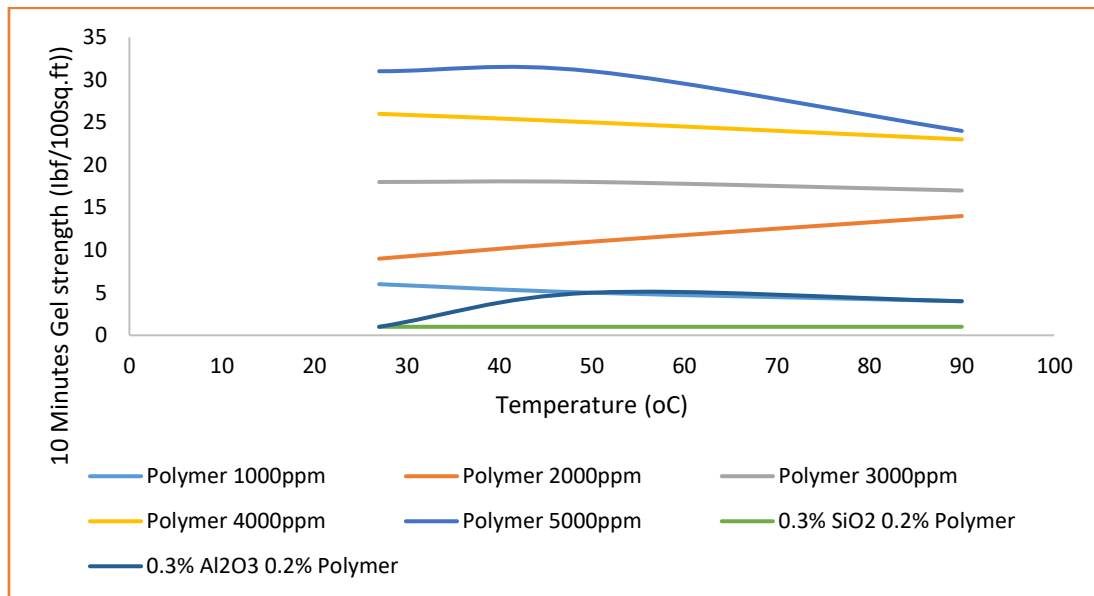
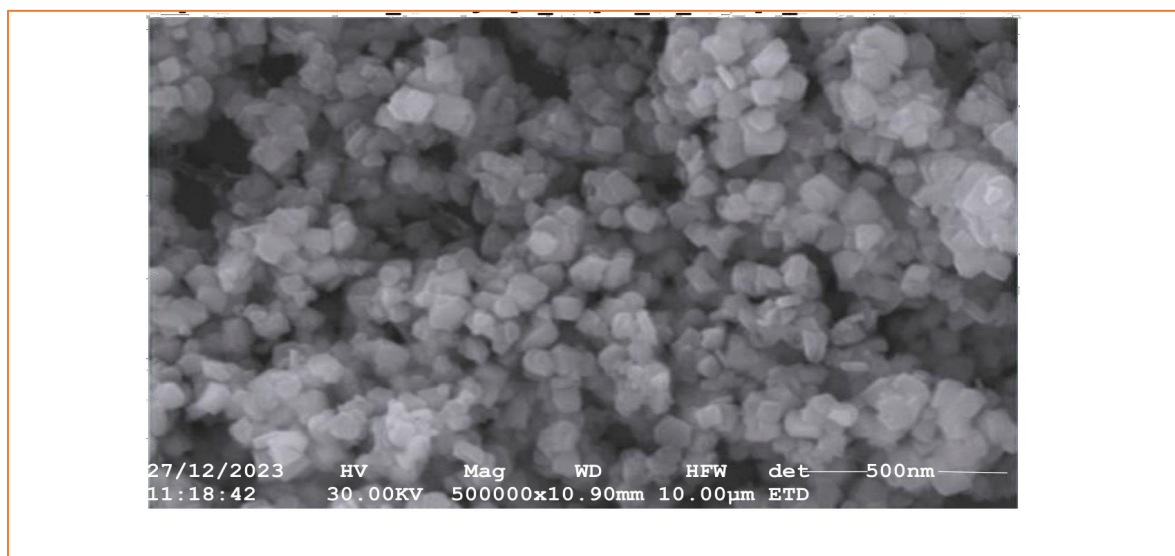


Figure 3: Effects of Temperature on Viscosity

Viscosity decreased with increasing temperature for all formulations (Figure 3), consistent with reduced intermolecular interactions at higher temperatures. However, hybrid systems exhibited lower temperature sensitivity compared to PAM-only systems, demonstrating improved thermal stability. This enhanced thermal resistance is particularly valuable for EOR applications in high-temperature reservoirs.

SEM Characterization

SEM analysis (Figure 4) revealed that SiO₂ nanoparticles exhibited agglomerated morphology with irregular clusters and crystalline structure (particle size: 20.12 μm, 2.51 μm, density: 2.10 g/cm³). Al₂O₃ nanoparticles displayed smooth, regular, and spongy surface morphology (particle size: 20.28 μm, 2.47 μm, density: 2.12 g/cm³). The observed agglomeration is typical for nanoparticles and can be mitigated through proper dispersion and surface modification.



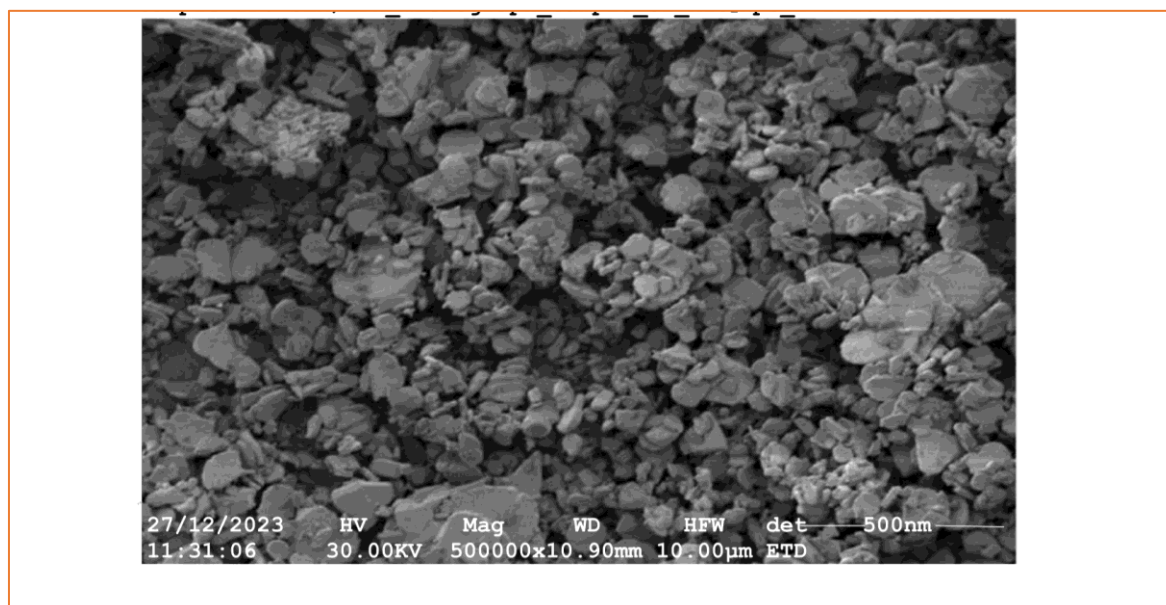


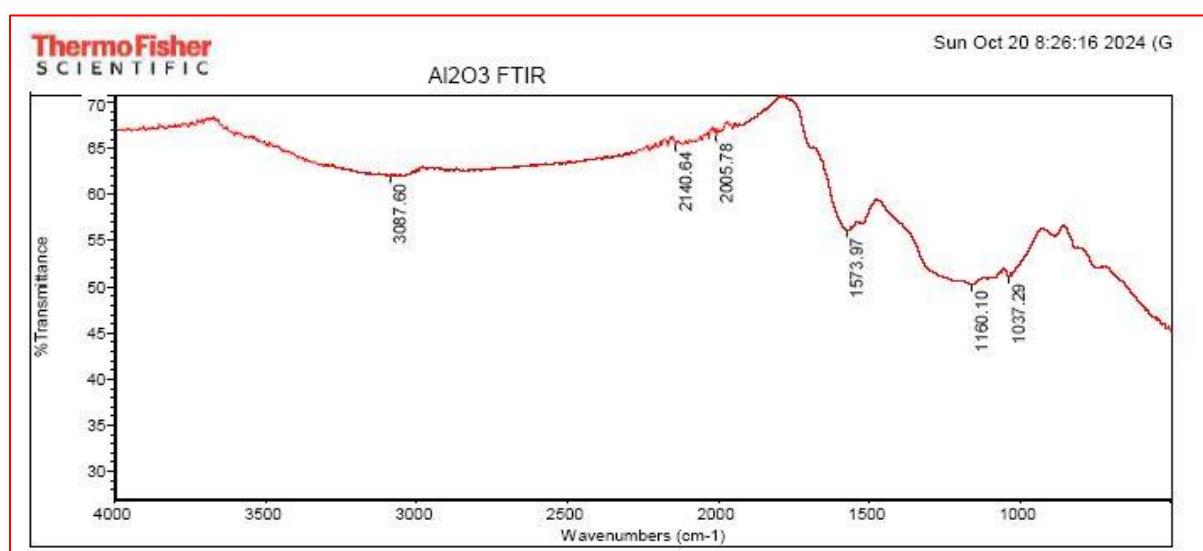
Figure 4: SEM Micrographs: (a) SiO₂ Nanoparticles, (b) Al₂O₃ Nanoparticles

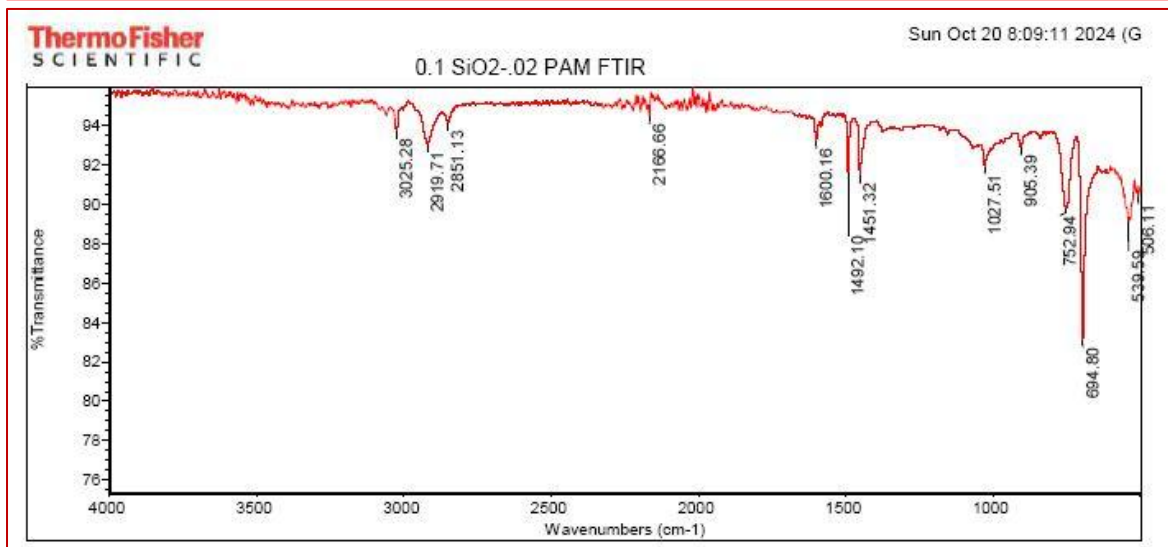
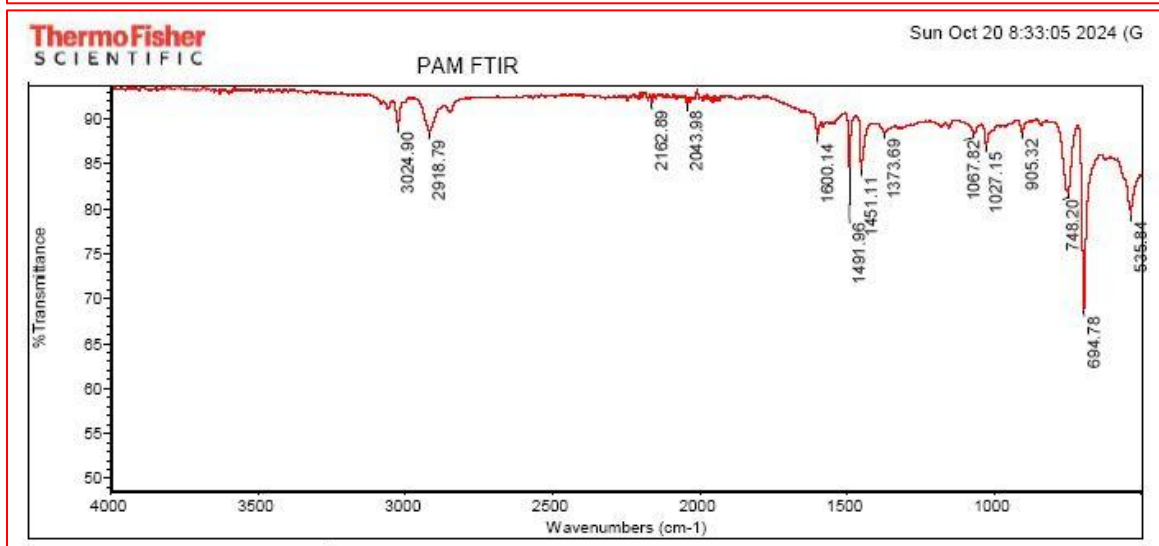
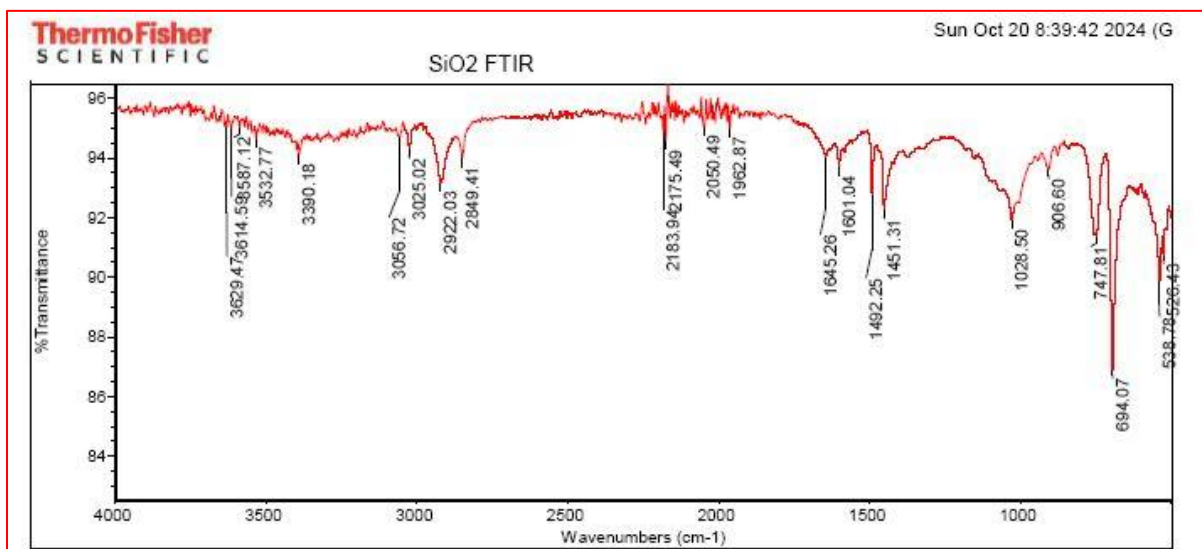
FTIR Characterization

FTIR spectra (Figure 5) confirmed successful integration of PAM with nanoparticles. Key absorption bands identified include:

- Si-O-Si stretching: ~1080-1100 cm⁻¹ (SiO₂ nanoparticles)
- Al-O stretching: ~600-1000 cm⁻¹ (Al₂O₃ nanoparticles)
- N-H stretching: ~3400 cm⁻¹ (PAM amide groups)
- C=O stretching: ~1650 cm⁻¹ (PAM carbonyl groups)
- C-H stretching: ~2920-2850 cm⁻¹ (PAM hydrocarbon backbone)

The presence of both polymer and nanoparticle characteristic peaks in hybrid spectra confirmed successful integration of organic (PAM) and inorganic (nanoparticles) components. Intensity variations between samples reflected differences in relative component concentrations.





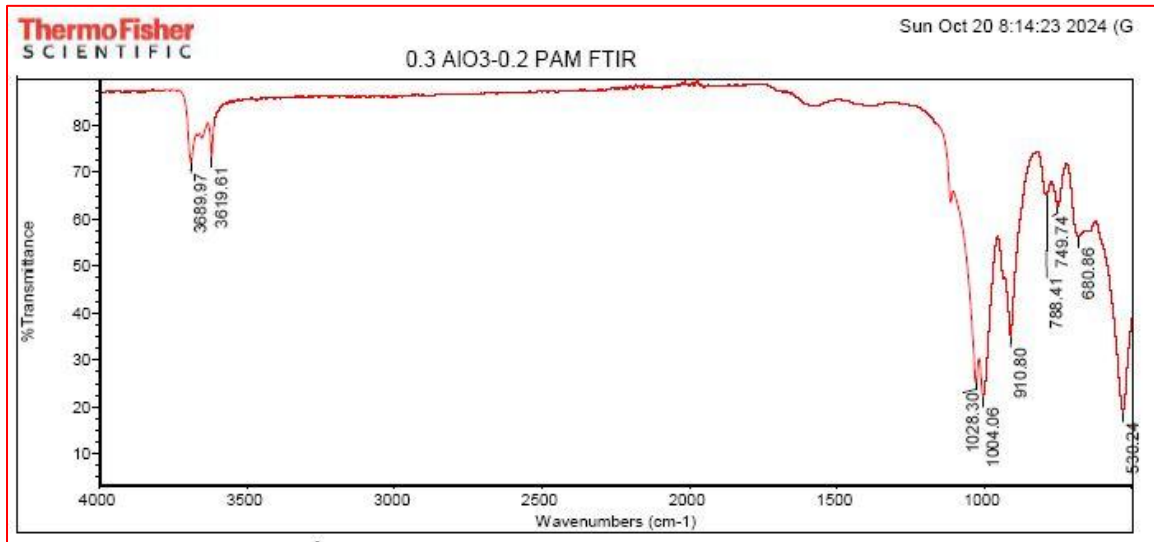


Figure 5: FTIR Spectra: (a) Al₂O₃, (b) SiO₂, (c) PAM, (d) SiO₂-PAM Hybrid, (e) Al₂O₃-PAM Hybrid

Core Flooding Performance

Oil Recovery

Table 5: Oil Recovery Summary

Fluid	Recovery (%)	Incremental Recovery over Brine (%)
Brine + 0.1% SiO ₂	71.74	—
Brine + 0.1% Al ₂ O ₃	72.73	—
Brine + 0.3% Al ₂ O ₃	75.00	—
Brine + 0.3% SiO ₂	76.19	—
Brine + 0.2% PAM	77.27	1.08
Brine + 0.2% PAM + 0.1% Al ₂ O ₃	77.08	0.89
Brine + 0.2% PAM + 0.3% Al ₂ O ₃	79.55	3.36
Brine + 0.2% PAM + 0.1% SiO ₂	77.08	0.89
Brine + 0.2% PAM + 0.3% SiO ₂	81.82	5.63

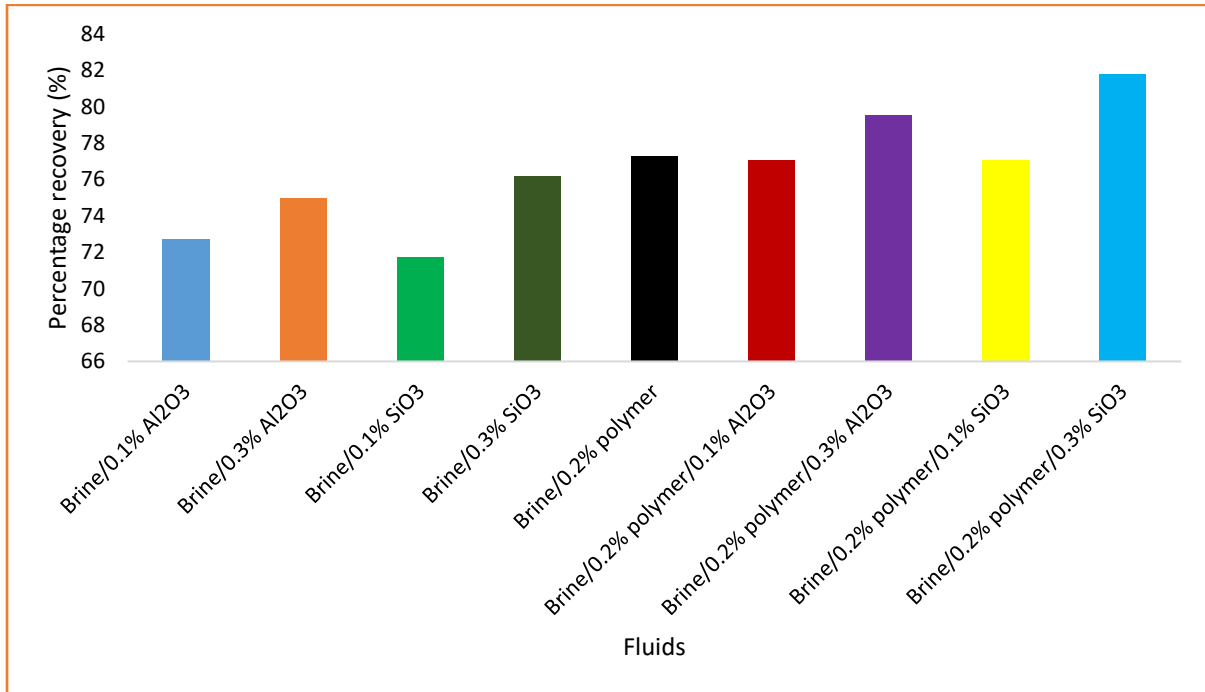


Figure 6: Oil Recovery Comparison

Core flooding results demonstrated that nano-polymer hybrid systems significantly outperformed individual nanoparticle and PAM-only systems. The 0.3% SiO₂-PAM hybrid achieved the highest oil recovery (81.82%), followed by 0.3% Al₂O₃-PAM (79.55%). PAM-only systems recovered 77.27%, while individual nanoparticle systems recovered 71.74-76.19% depending on nanoparticle type and concentration.

Several mechanisms contribute to the superior performance of SiO₂-PAM hybrids:

- **Enhanced Viscosity:** The high viscosity (14.61 cP) of 0.3% SiO₂-PAM improves mobility ratio and sweep efficiency, reducing the tendency for viscous fingering [3].
- **Wettability Alteration:** SiO₂ nanoparticles can adsorb onto rock surfaces, creating water-wet films that facilitate oil detachment and mobilization [7, 14]. FTIR analysis confirmed the presence of surface hydroxyl groups that promote favorable interactions with sandstone surfaces.
- **Interfacial Tension Reduction:** Nanoparticles at the oil-water interface reduce interfacial tension, lowering capillary forces that trap oil in pores [13].
- **Pore-Scale Displacement:** The structural disjoining pressure generated by nanoparticle ordering at the contact line enhances oil displacement from pore surfaces [9].
- **Improved Polymer Stability:** Nanoparticles enhance polymer stability through cross-linking and hydrogen bonding, maintaining viscosity under shear and temperature stress [5, 10].

The concentration-dependent recovery enhancement suggests that 0.3% nanoparticle concentration provides optimal loading for maximum synergy with PAM. This concentration allows sufficient nanoparticle availability for wettability alteration and interfacial effects while avoiding excessive aggregation or pore plugging.

Permeability Damage Analysis

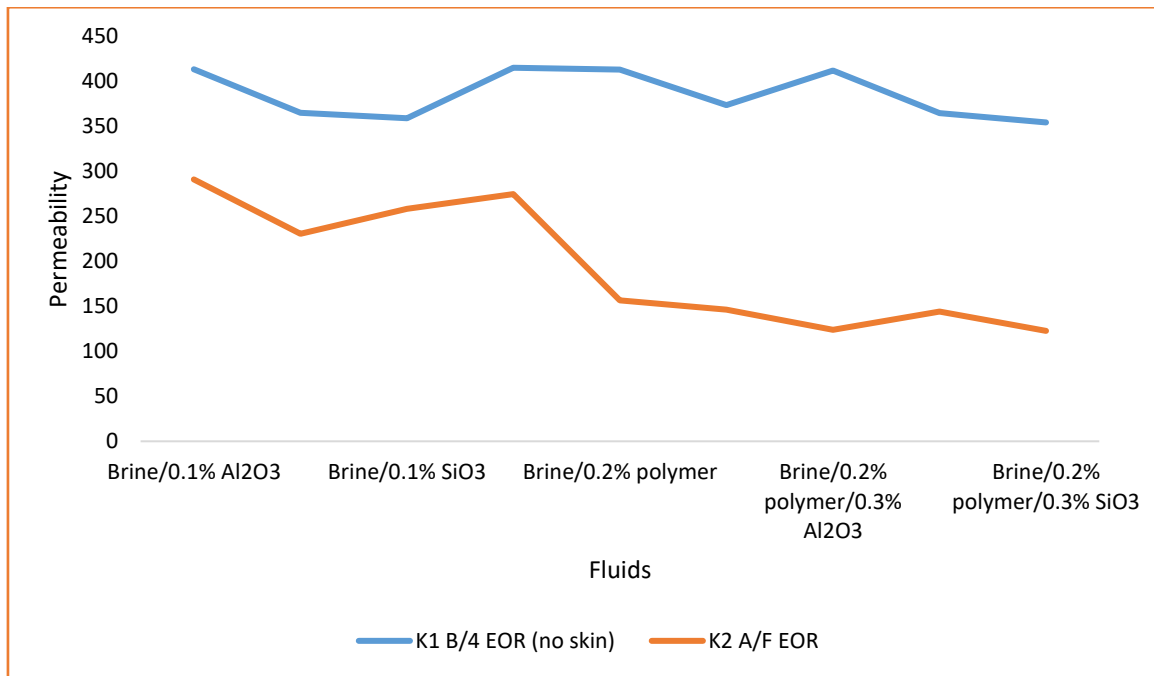
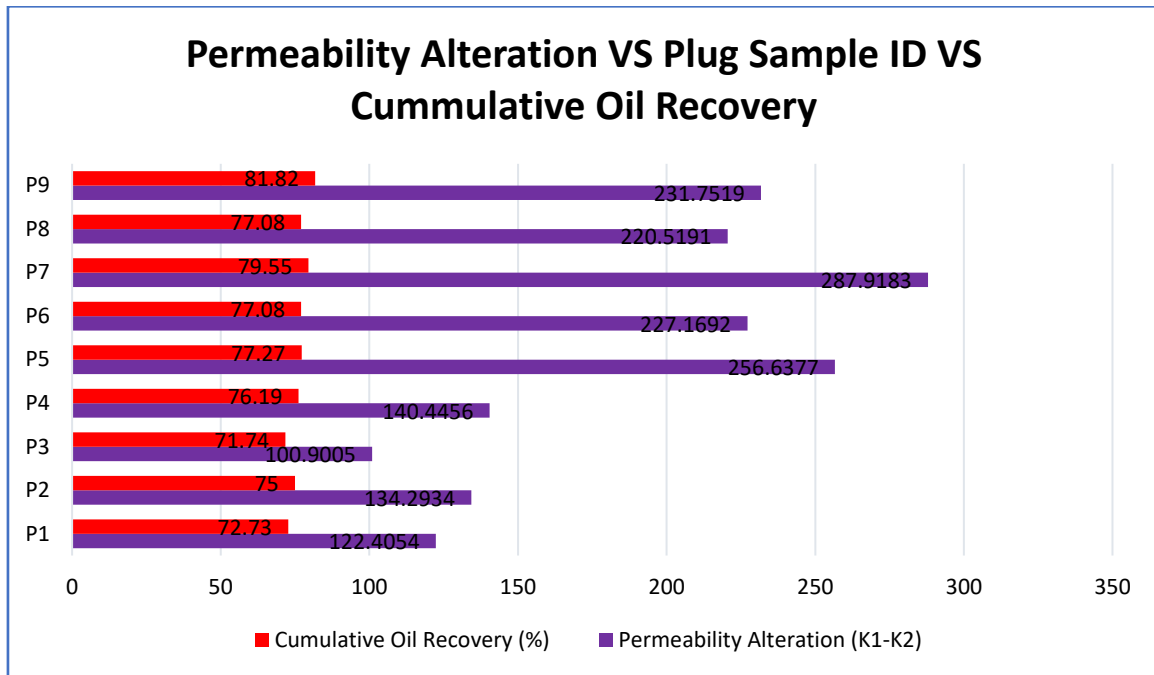


Figure 7: Permeability Alteration

Plug ID	K ₁ (mD)	K ₂ (mD)	ΔK (mD)	Fluid	Recovery (%)
P1	413.54	291.14	122.41	0.1% Al ₂ O ₃	72.73
P2	365.15	230.86	134.29	0.3% Al ₂ O ₃	75.00
P3	359.23	258.33	100.90	0.1% SiO ₂	71.74
P4	415.30	274.85	140.45	0.3% SiO ₂	76.19
P5	413.27	156.63	256.64	0.2% PAM	77.27

P6	373.63	146.46	227.17	0.2% PAM + 0.1% Al ₂ O ₃	77.08
P7	412.04	124.12	287.92	0.2% PAM + 0.3% Al ₂ O ₃	79.55
P8	364.86	144.34	220.52	0.2% PAM + 0.1% SiO ₂	77.08
P9	354.51	122.76	231.75	0.2% PAM + 0.3% SiO ₂	81.82

Permeability damage analysis revealed important trade-offs between recovery enhancement and formation damage:

- Individual Nanoparticles: Moderate permeability reductions (100.90-140.45 mD), with SiO₂ showing slightly higher damage than Al₂O₃ at 0.3% concentration. The relatively low permeability loss indicates acceptable injectivity for nanoparticle-only systems
- PAM-Only: Significant permeability reduction (256.64 mD) due to polymer adsorption and mechanical entrapment in pore throats. Polymer molecules can bridge pore constrictions, reducing effective pore radii and impairing permeability [4]
- Hybrid Systems: Most pronounced permeability reductions (220.52-287.92 mD), with the highest damage observed for 0.3% Al₂O₃-PAM (287.92 mD). The increased permeability damage in hybrid systems is attributed to combined effects of polymer adsorption and nanoparticle aggregation/pore plugging.

The non-linear relationship between permeability loss and oil recovery is noteworthy. Although hybrid systems caused higher permeability damage, they also achieved superior oil recovery. The 0.3% SiO₂-PAM hybrid (231.75 mD reduction, 81.82% recovery) appears to provide the optimal balance between enhanced displacement and acceptable formation damage.

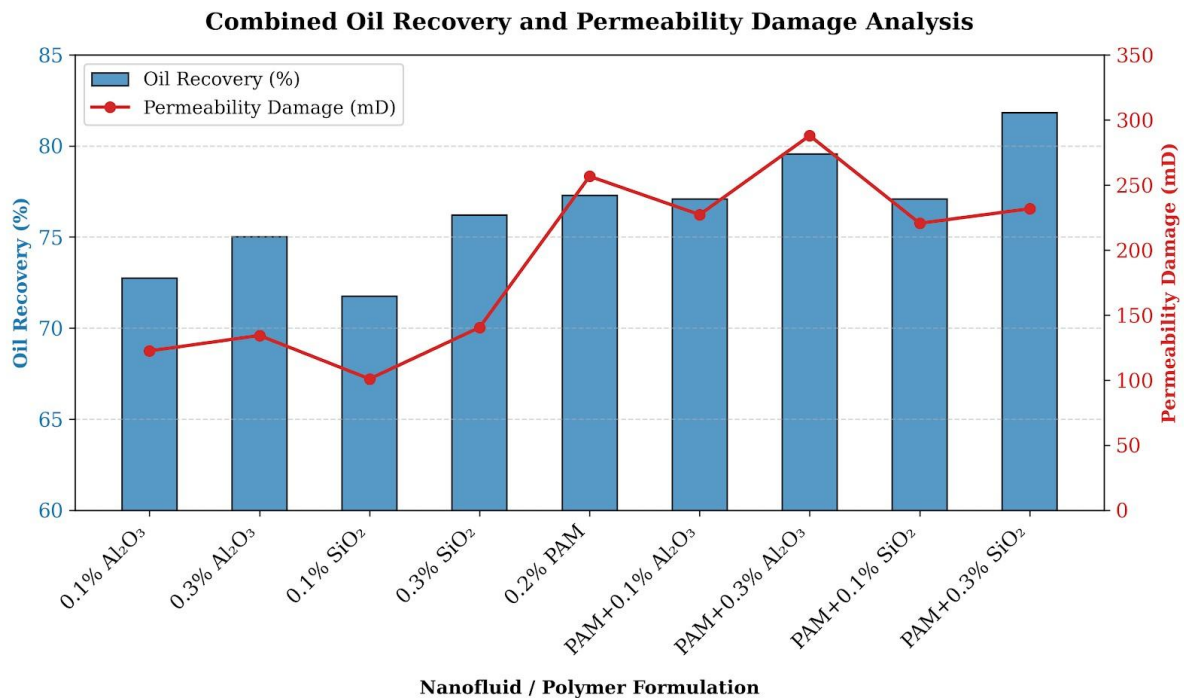


Figure 8: Relationship between Permeability Damage and Oil Recovery

The observed permeability damage can be attributed to several mechanisms:

- Polymer Adsorption: PAM molecules adsorb onto rock surfaces through hydrogen bonding and electrostatic interactions, reducing effective pore radii [4].
- Nanoparticle Aggregation: Nanoparticles can aggregate and deposit in pore throats, creating flow restrictions [14].

- Hybrid Effects: Combined polymer-nanoparticle interactions may create larger aggregates or bridging structures that enhance pore plugging [5, 10].
- Pore Geometry: The quartz-dominated mineralogy with minor clay content provides surfaces for adsorption and potential for permeability reduction.

While formation damage is generally undesirable, the moderate permeability reductions observed in this study may be acceptable given the significant improvements in oil recovery. Field application would require careful evaluation of injectivity, fracture gradients, and economic considerations.

4.6 Mechanistic Understanding

Based on the experimental results, a conceptual model for the enhanced oil recovery mechanisms of nano-polymer hybrids in sandstone reservoirs can be proposed:

- Viscosity Enhancement: Nanoparticles increase polymer solution viscosity through cross-linking and hydrogen bonding, improving mobility ratio and sweep efficiency.
- Wettability Modification: Adsorption of hydrophilic nanoparticles onto sandstone surfaces creates water-wet films that reduce oil adhesion and promote oil mobilization.
- Interfacial Effects: Nanoparticles at the oil-water interface reduce interfacial tension, lowering capillary forces and improving oil displacement from pores.
- Pore-Scale Displacement: Structural disjoining pressure from nanoparticle ordering enhances oil mobilization from pore surfaces.
- Chemical Interactions: FTIR analysis confirmed hydrogen bonding and electrostatic interactions between nanoparticles and PAM, enhancing structural stability.

Proposed EOR Mechanisms of Nano-Polymer Hybrid Fluids in Sandstone Reservoirs

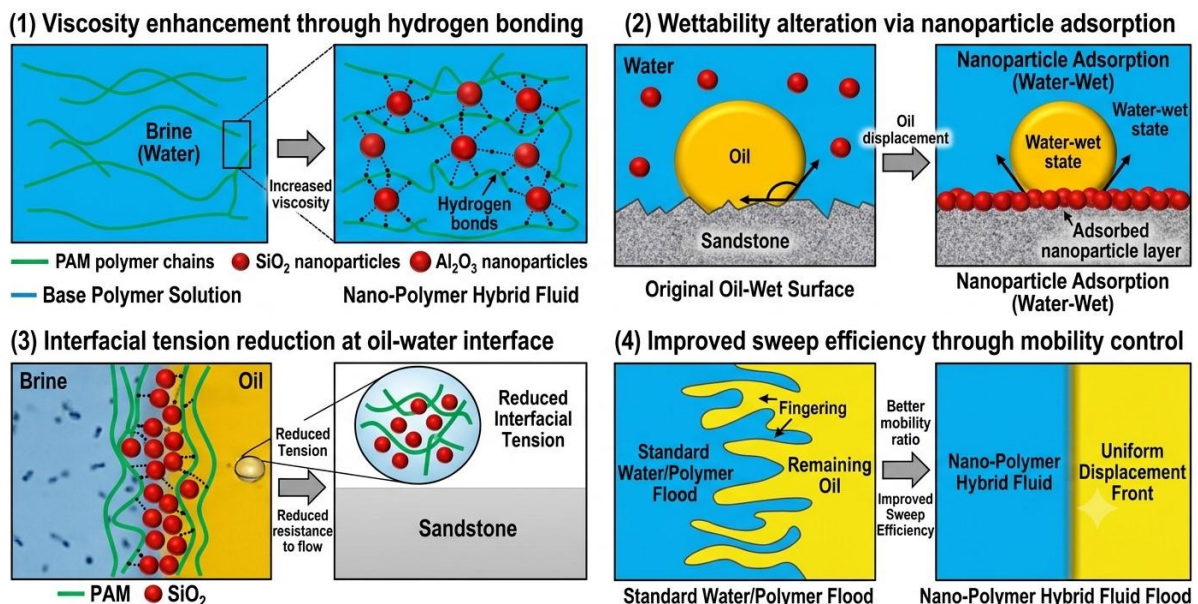


Figure 9: Proposed EOR Mechanism of Nano-Polymer Hybrid Fluids

The superior performance of SiO_2 -PAM compared to Al_2O_3 -PAM hybrids may be attributed to:

- Higher surface reactivity of SiO_2 nanoparticles
- Stronger hydrogen bonding between Si-OH groups and PAM amide groups
- Better dispersion stability in brine environment
- Favorable electrostatic interactions with sandstone surfaces

V. CONCLUSION

This study systematically investigated the performance of SiO₂-PAM and Al₂O₃-PAM hybrid nanofluids for enhanced oil recovery in sandstone reservoirs. The experimental results demonstrate that nano-polymer hybrids exhibit significantly enhanced rheological properties compared to individual components. Among all formulations tested, the 0.3% SiO₂-PAM hybrid achieved the highest viscosity (14.61 cP), substantially exceeding PAM-only (10.74 cP) and nanoparticle-only systems (1.08-1.86 cP). Density variations across all formulations were minor, and pH values ranging from 5.6 to 6.9 indicated acceptable chemical stability for EOR applications.

Characterization of the core plugs revealed a quartz-dominated mineralogy (57.8%), with porosities ranging from 36.47% to 40.02% and permeabilities between 354.51 and 415.30 mD, providing representative media for evaluating EOR performance under reservoir-like conditions.

Core flooding experiments demonstrated that the 0.3% SiO₂-PAM hybrid achieved the highest oil recovery (81.82%), surpassing PAM-only (77.27%) and individual nanoparticle systems (71.74-76.19%). The observed concentration-dependent recovery enhancement indicates that optimal nanoparticle loading occurs at 0.3% concentration, beyond which further increases may not yield proportional benefits.

However, permeability damage analysis revealed important trade-offs. Hybrid systems caused more pronounced permeability reductions (220.52-287.92 mD) compared to individual nanoparticles (100.90-140.45 mD) and PAM-only (256.64 mD). Notably, the 0.3% SiO₂-PAM hybrid provided the best balance between recovery enhancement (81.82%) and acceptable permeability damage (231.75 mD), suggesting that formulation optimization must carefully consider both recovery performance and formation integrity.

The relationship between nanoparticle concentration, oil recovery, and permeability damage reveals a fundamental optimization challenge. Higher nanoparticle concentrations improve recovery through enhanced viscosity and interfacial effects, but simultaneously increase the risk of formation damage from nanoparticle aggregation and pore plugging. This trade-off must be carefully managed for successful field applications.

Mechanistically, the synergistic effects of nano-polymer hybrids arise from multiple contributing factors including viscosity enhancement, wettability alteration, interfacial tension reduction, and improved polymer stability. SiO₂ nanoparticles demonstrated stronger interactions with PAM compared to Al₂O₃, resulting in superior rheological and recovery performance.

In summary, this study reveals that SiO₂-PAM and Al₂O₃-PAM hybrids are potential EOR techniques for sandstone reservoirs, and SiO₂-PAM is more effective than Al₂O₃-PAM under the conditions investigated. The optimum formulation, 0.3% SiO₂ and 0.2% PAM, discovered achieves an excellent balance between the oil recovery enhancement (81.82%) and acceptable formation damage (231.75 mD) and so provides a realistic approach of improving hydrocarbon recovery from mature sandstone reservoirs.

VI. RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed:

- **Concentration Optimization:** Further studies should investigate concentrations between 0.1% and 0.3% to precisely identify the optimal nanoparticle loading for specific reservoir conditions. Field applications should consider injection rate, reservoir temperature, and formation permeability when selecting nanoparticle concentrations.
- **Mechanistic Studies:** Additional research should include direct measurements of wettability alteration, interfacial tension reduction, and contact angle changes to better understand the underlying mechanisms. Atomic force microscopy and contact angle measurements could provide valuable insights into surface interactions.
- **Economic Analysis:** Comprehensive economic evaluations should be conducted, considering nanoparticle production costs, fluid preparation expenses, and incremental oil revenue. This analysis is essential for field-scale implementation decisions.
- **Compatibility Studies:** The compatibility of nano-polymer hybrids with reservoir brines, crude oils, and formation minerals should be evaluated under representative reservoir conditions, including high temperature and pressure.
- **Field Validation:** Laboratory results should be validated through field pilot tests to assess performance under realistic reservoir conditions and identify any scale-up challenges.

- **Nanoparticle Surface Modification:** Surface modification of nanoparticles could further enhance their stability and performance in high-salinity and high-temperature environments.

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