Published by SET Publisher

Journal of Basic & Applied Sciences

ISSN (online): 1927-5129

Feasibility of Oil Mud Reinjection from Offshore Platforms in Bohai Oilfield

Guoying Jiao, Shijie Zhu*, Jun Wang*, Zhuangzhuang Huang and Mei Xu

Institute of Petroleum and Natural Gas Engineering, Chongqing University of Science and Technology, Chongqing 401331, China

Article Info:

Keywords:
Offshore platform,
produced sludge,
solid particles,
viscoelasticity,
enhanced oil recovery.

Timeline:
Received: April 06, 2023
Accepted: May 02, 2023
Published: May 12, 2023

Citation: Jiao G, Zhu S, Wang J, Huang Z, Xu M. Feasibility of oil mud reinjection from offshore platforms in bohai oilfield. J Basic Appl Sci 2023; 19: 68-76.

DOI: https://doi.org/10.29169/1927-5129.2023.19.06

Abstract:

Sludge produced by offshore oilfields can be difficult to treat. thus, it is necessary to explore the feasibility of its reinjection into reservoirs for environmental protection and economic benefits. In this study, oil sludge produced from an oilfield in the Bohai Sea was ground and refined, and a reinjection system using a polymer solution was developed. To determine the feasibility of the reinjection system, we analysed its stability, solution performance, injection performance, and oil displacement effect. The experiment results indicate that when the particle concentration of the system is ≤ 200mg/L, the system dispersion, anti-shearing, and anti-ageing stability can be enhanced. When the particle concentration is ≤100 mg/L, the system can easily manage the viscous nature of the solid particles, thereby achieving optimal stability. At a particle concentration of 100mg/L, the system can run with optimal performance and achieve good oil displacement efficiency. Therefore, a system with a particle concentration of 100mg/L can be used for long-term reinjection of offshore platforms in the Bohai oil reservoir, achieving environmentally friendly treatment of produced sludge while further enhancing the oil recovery rate of the reservoir.

*Corresponding Author
E-mail: zhusj@cqust.edu.cn, 2009070@cqust.edu.cn

1. INTRODUCTION

The formation energy of a reservoir decreases with the development of reservoir production. After artificial water/gas injection, the reservoir will recover and even reach a dynamic equilibrium of demand [1]. However, this can lead to the displacement and migration of solid particles in the reservoir porous media under formation pressure; thus, a viscous fluid called oily sludge is produced [2]. This sludge is a multiphase dispersion system rich in mineral oil. Its composition is complex, and the system is in a highly stable state. For chemical-flooding reservoirs (polymer flooding or two/three element composite flooding), a high-viscosity chemical-flooding agent can increase the crude oil recovery by carrying more mud sand [3].

In recent years, with the gradual improvement in environmental laws and regulations and technological progress of enterprises, pollution control technology of oily sludge has attracted increasing attention [4]. The output of chemical flooding from offshore oilfield development and production creates a large amount of oily sludge, and effectively disposing of the solid substances in the sludge is difficult with current technology such as conditioning mechanical dewatering, incineration, or pyrolysis; furthermore, the high cost of transporting them to the land is an obstacle [5-9]. To overcome these challenges, researchers have developed an injection profile control technology to treat solid waste particles of offshore platforms that produces a solid material output that is isolated after treatment and used in the manufacture of plugging agent reinjection [10-14]. However, current offshore oilfields already experience injection issues with high-viscosity displacement fluid, and injecting solid particles is even more difficult; therefore, improving the injection method is the first step to achieving the reinjection.

In this study, a viscous-liquid injection system is used to inject solid particles from oil sludge [15, 16]. Potential factors affecting injection are analysed, such as particle size, concentration, and dispersion stability. Additionally, the pressure change into conduction solid particles in the final process is analysed to determine the feasibility of reinjecting oily sludge particles.

2. EXPERIMENT

2.1. Experimental Condition

For the experiment, oil sludge from the bottom of a tank in Bohai XX oilfield was recovered and refined using a colloid mill (see Figure **1**). A sample of sludge was weighed (mass = m_1), then heated at 300 °C in a muffle furnace to remove the oil and other impurities. After burning, the sludge was weighed again (mass = m_2). The solid content is computed in this study by the following:

$$S = \frac{m_1}{m_2} \times 100\% \qquad \text{Equation 1}$$

Figure 1: Sample of oilfield sludge.

The polymer used consisted of hydrophobically associating polymer AP-P4, industrial products, and solid powder; its relative molecular mass was 6.6×10^6, solid content was 88.9%, and hydrolysis degree was 21.7%. Table **1** lists the composition of the water used in the experiment.

First, solid particles were dispersed in distilled water to achieve the desired target concentrations (see Equation 2). The quantitative AP-P4 in polymer solution was added, and the dispersion system was mixed with a magnetic stirrer to ensure the sludge was uniformly dispersed in the polymer and the polymer concentration in the final system was constant.

$$m = \frac{CV \times 10^{-6}}{s} \qquad \text{Equation 2}$$

Where m is the mass of solid particles in the system (g), C is the concentration of particles in in the dispersed system (mg/L), V is the volume of the dispersed system (mL), and S is the solid content.

The patterns of polymer-containing sludge configured for different concentration systems are shown in Figure **2**.

Table 1: Water Composition

Component (mg/L)	Na^+, K^+	Ca^{2+}	Mg^{2+}	SO_4^{2-}	HCO_3^-	Cl^-	TDS
Water composition	2549	569	228.9	37	190.6	5466.5	9041

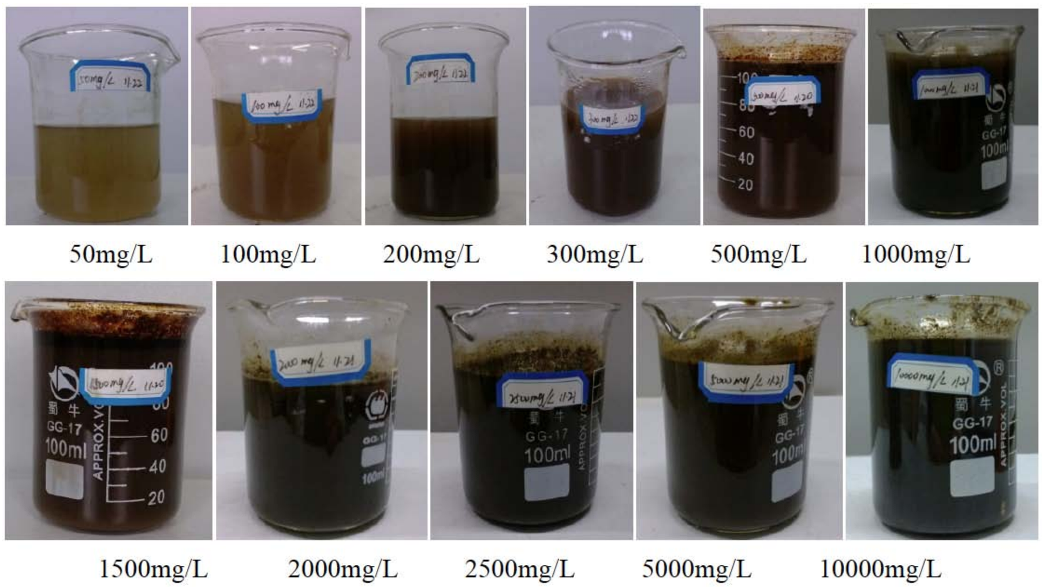

Figure 2: Original dispersion systems with different concentrations of polymerised sludge.

2.2. Experimental Method

2.2.1. Basic Performance Evaluation of the System

(1) Determination of particle size distribution and dispersion degree of solid particles

The particle size distributions in different solid contents were measured using a laser particle size analyser (Mastersicer 2000); the measurements were taken for three days to ensure the dispersion stability of solid particles [17, 18].

(2) Viscoelasticity measurement of system

The viscoelastic solution system affects the carrying capability: a more viscous solution can carry solid particles more easily. Therefore, we used a MARS III Haake rheometer to analyse the changes in the elastic and viscous moduli of the solutions under different sludge concentrations (experimental temperature of 65 °C) [19-21].

(3) Determination of system stability

The viscosity of the solution was measured using a Brookfield DV-III viscometer at the experimental temperature [22], and the system stability was determined as follows.

1) Shear stability: The shear viscosity of a 200 ml solution sample was measured by shearing for 20 s with a 1 800S/800G Waring mixer. The viscosity retention rate after shearing was then calculated to evaluate the shear stability of the system.

2) Aging stability: The solution was placed in a constant-temperature oven at 65 °C. The viscosity was measured on day 0, 3, 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90, and the viscosity retention rate after aging was calculated to evaluate the anti-aging stability of the mixture.

2.2.2. Determination of System Injectivity

(1) Sand injection experiment: Gravel packing sand control completion is an effective method of preventing sand production in unconsolidated sandstone reservoirs. Therefore, a sand control section with a ø 25×200mm sand-filled pipe was chosen to simulate the injection of a sand control section with different particle concentrations. The parameters were as follows: A) permeability: approximately 2000mD; B) porosity: 30%; C) injection velocity: 6 mL/min; D) polymer solution concentration: 1750 mg/L; and E) particle concentration: 0, 50, 100, 300, 500, 1000, 1500, and 2000 mg/L.

Figure 3: Sand-filled pipe for displacement (left) and artificial core (right).

(2) Injection experiments of porous media: The artificial core was ø 25 × 80 mm, which can be used to characterise the reservoir, and the experimental parameters were as follows: A) permeability: approximately 2000mD; B) porosity: 30%; C) injection velocity: 6 mL/min; D) polymer solution concentration: 1750mg/L; and E) particle concentration: 0, 50, 100, 300, 500, 1000, 1500, and 2000mg/L.

(3) In the above two experiments, the output liquid must be returned during the displacement process to dry; then, the dry weight of the produced particles is calculated.

(4) Experimental equipment and core is shown in Figure **3**:

2.2.3. Oil Displacement Efficiency Experiment

The experimental procedures to conduct the macroscopic oil displacement test were as follows: A) Measure the gas permeability; B) Vacuum saturate the core sample with brine (Table **1**) and calculate the porosity according to the weight difference; C) Measure the water permeability by injecting brine at different flow rates; D) Inject oil at successive flow rates of 0.1, 0.2, 0.5, and 1.0 mL/min to displace water until no more water is produced; E) Inject system solution (0.3PV) at 1.0 mL/min at 95% water saturations; F) Conduct a post- waterflooding at a flow rate of 1.0 mL/min until the instantaneous water cut reaches 95%. Throughout the displacement test, a 10 mL glass tube was used to collect the effluent every 5 min.

3. RESULTS ANALYSIS

3.1. Particle Size Distribution and Dispersion Stability of Solid Particles

The particle size distribution and stability are shown in Table **2**.

It can be seen from Table **2** that the distribution of particle size d (0.5) is mainly concentrated in the range of 55–65μm. Additionally, with an increase in storage time, the particle size of the dispersion system with different particle concentration decreases, indicating that large particles continue to settle over time. When the particle concentration is 100mg/L, the particle size of the system is maintained at approximately 55μm, which indicates that solid particles in this concentration have adequate dispersion stability in the polymer.

3.2. Viscoelasticity of the System

The relationships between the elastic modulus G′ and the viscosity modulus G″ of the solution under different sludge concentration conditions are shown in Figure **4**.

From Figure **4**, when the oscillation frequency is ≤ 1 Hz, the viscous modulus G″ is higher than the elastic modulus G′, and the system is in a melt state; when the oscillation frequency is > 1 Hz, the elastic modulus G′ is higher than the viscous modulus G″, and the system is in a gel state. In the vicinity of the oscillation frequency 1 Hz, the mixed dispersion system changes from a solid to gel state. Therefore, a fixed oscillation frequency of 1 Hz was used to study the influence of particle concentration on the viscoelasticity of the

Table 2: Particle Size Distribution and Stability of Different Particle Contents

Concentration (mg/L) d(0.5) (μm)	50	100	200	300	500	1000	1500	2000	2500	5000	10000
First day	55	58	56	65	58	69	65	43	60	62	64
Second day	16	54	26	47	41	51	57	35	30	36	34
Third day	14	54	17	33	36	36	56	38	21	27	19

*d(0.5) is the median particle size; the particle size of 50% in the sample is less than d(0.5) μm, that is, the particle size corresponding to 50% of the particle size distribution (0 to 100%).

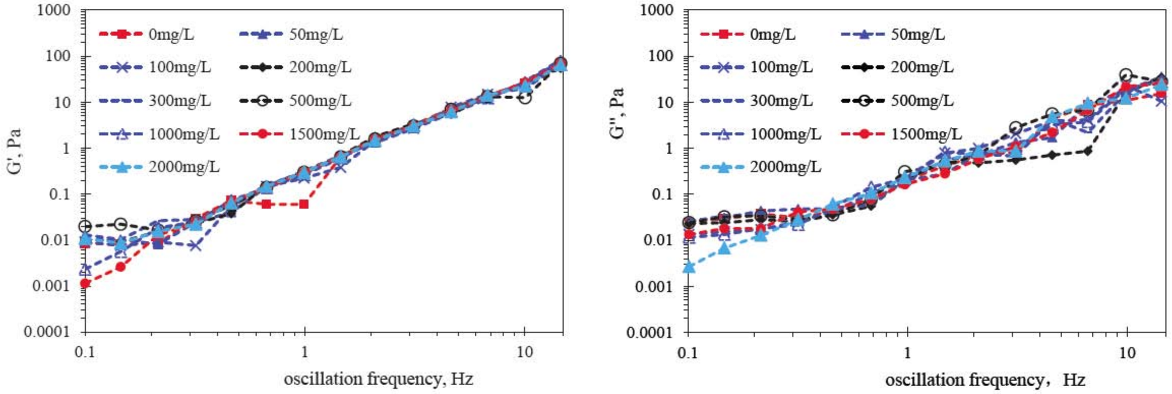

Figure 4: Relationship between elastic modulus G′ and viscosity modulus G″ of the solutions with different sludge concentrations.

mixed system at a certain frequency, as shown in Figure **5**.

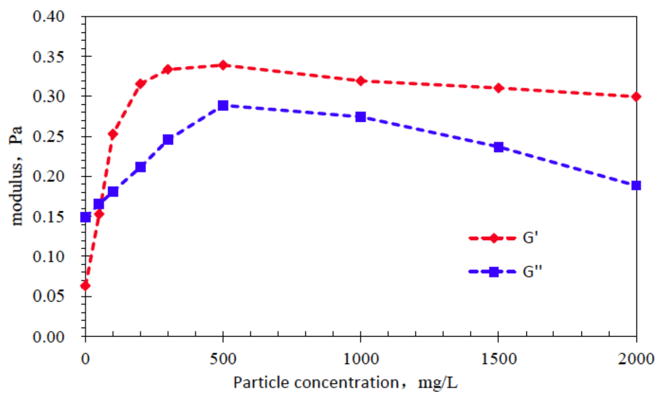

Figure 5: Modulus changes at different particle concentrations.

When the particle concentration is < 100 mg/L, the viscosity modulus of the mixed system is greater than the elastic modulus, whereas when the particle concentration is > 100 mg/L, the elastic modulus of the mixed system is greater than the viscous modulus. This indicates that the addition of solid particles changes the viscoelasticity of the polymer solution, which may be due to the influence of particles on the system. Thus, particle concentration control is more suitable around 100 mg/L.

3.3. Stability of System

In the injection system, mechanical shearing is inevitable in the pipeline and wellbore when entering the stratum, and the aging stability of the system, i.e., the thermal stability, needs to be determined for long-term injection.

3.3.1. Aging Stability

The aging stability test data are shown in Figure **6**.

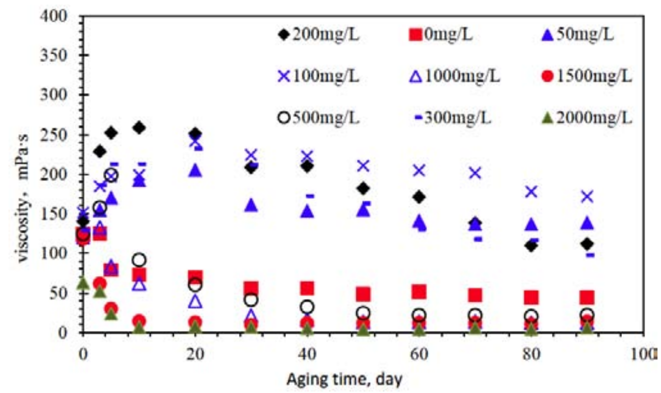

Figure 6: Aging test data of different sludge concentration systems.

As shown in Figure **6**, the AP-P4 pure polymer solution viscosity decreases gradually with an increase in aging time and finally tends to a constant trend. A particle concentration of 100 mg/L exhibits the highest stability with a high aging time, and when the particle concentration is < 300 mg/L, the viscosity of the solution first increases and then decreases slowly. When the particle concentration is > 300 mg/L, the viscosity decreases with aging time finally tends to be constant; the final solution viscosity is lower than that of the pure polymer solution. This indicates that the appropriate amount of particles can increase the aging stability of the polymer solution, an excessive amount of particles can reduce the aging resistance of the polymer, and at a particle concentration of 100 mg/L, the stability of the aging process is optimal.

3.3.2. Shear Stability

The effects of shear on the solution viscosity and viscosity retention rate are shown in Figure **7**.

As is shown in Figure **7**, the shear viscosity of the solution is greatly reduced after the pure polymer

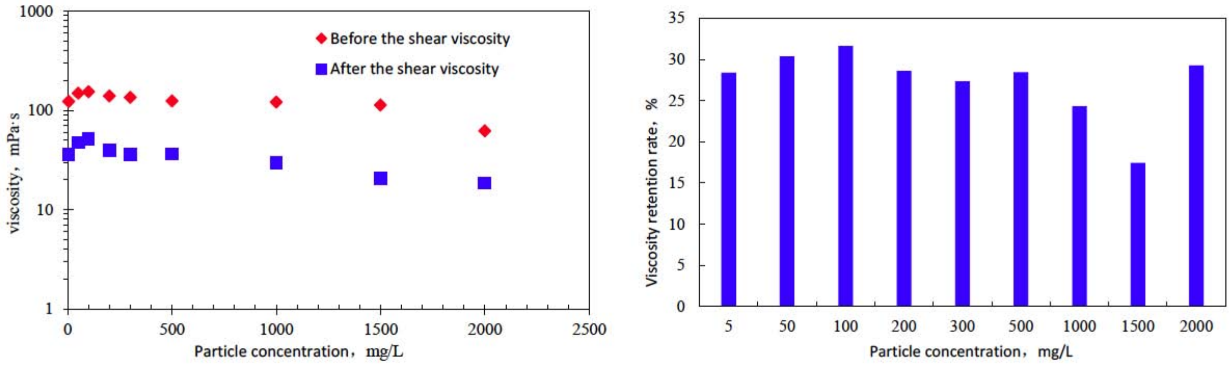

Figure 7: Influence of shear action on viscosity of solution system.

solution viscosity: the retention rate is 28.4%. With the addition of sludge, the viscosity retention rate of the < 200 mg/L solution increases slightly, indicating the sludge can enhance the anti-shear ability of the polymer solution to a certain extent.

3.4. Injection Property of System

Because of the sedimentary environment, most offshore oilfields are loose sandstone reservoirs with fluvial facies. The proportion of heavy oil content in a reservoir is > 50%. Chemical flooding enhances oil recovery, resulting in serious sanding of oil wells, and sand filling is usually performed during completion. Therefore, the injection pressure transmission experiment was conducted using two methods: artificial core and sand-filled pipe.

3.4.1. Injection Experiment of Sand Control Section

Part of the injection pressure curve of the sand control section is shown in Figure **8**.

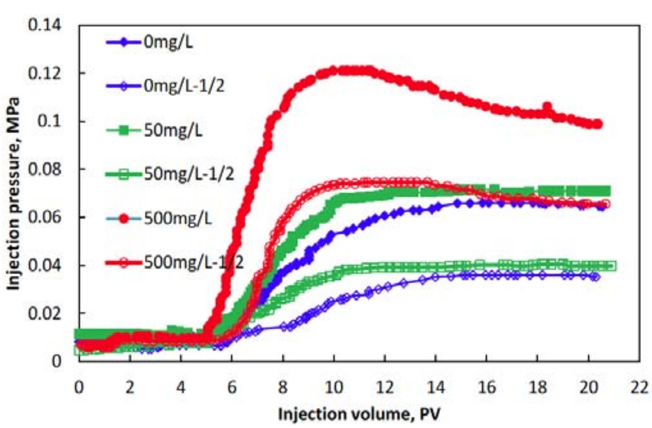

Figure 8: Injection pressure curve under different particle concentration conditions.

It can be seen from Figure **8** that systems with different solid particle concentrations can be injected into the sand-filled pipe, and the maximum injection pressure is remains below 0.12 MPa. However, the concentration does affect the changes in the pressure curve: 0 mg/L and 50 mg/L increase rapidly after reaching the injection volume and then stabilise; 500 mg/L injection pressure is extremely high, then decreases gradually and stabilises. Therefore, the Darcy Equation (Equation 3~5) is used to analyse permeability variation in fully filled and half-filled sand models.

$$Q = \frac{kA\Delta P}{\mu L} \quad \text{Equation 3}$$

$$\Delta P = \frac{Q\mu L}{KA} = P_1 - P_0 \quad \text{Equation 4}$$

$$K = \frac{Q\mu L}{(P_1 - P_0)A} \quad \text{Equation 5}$$

According to the characteristics of the curve, the pressure after injection tends to increase rapidly and then stabilise in most systems. At the end of the curve, the transition position is segmented, and the linear relationship of the back section is established, which is shown in Table **3**.

Analysis of Figure **8** and Table **3** reveals the following: the system with *K* permeability changed little in different positions in the process, indicating that at a low concentration, the solid particles travelled smoothly through the sand-filled pipe; the injection pressures of the 100, 300, and 500mg/L samples first increased and then decreased, which shows the retention of particles in the process of migration. In the subsequent high-pressure remigration, particle concentrations of 1000 and 2000mg/L were stranded in the sand-filled pipe, thereby causing an increase in the injection pressure. The experimental results indicate that the injection of the sand-filled pipe section can be achieved with a certain concentration (< 500mg/L) solid solution system.

Table 3: Analysis of Transport Relationship of Solid Particles

Serial number	Particle concentration (mg/L)	Viscosity (mPa·s)	Turning point, *K* (mD)		Slope, *a*	Permeability changes at the end of the experiment	
			Fully filled model	Half-filled model		Fully filled model	Half-filled model
1	0	35.84	221.37	214.86	/	/	/
2	50	47.17	270.84	246.53	/	/	/
3	100	51.14	182.87	146.81	-0.0023	212.73	165.46
4	300	35.84	119.76	158.81	-0.0043	197.44	169.89
5	500	36.43	122.72	114.22	-0.0015	157.96	123.74
6	1000	29.52	136.76	120.35	0.0004	132.26	117.99
7	2000	18.48	107.61	99.11	0.0023	80.13	78.46

3.4.2. Experiment of Porous Medium Injection

The results of the core injection experiment are as follows:

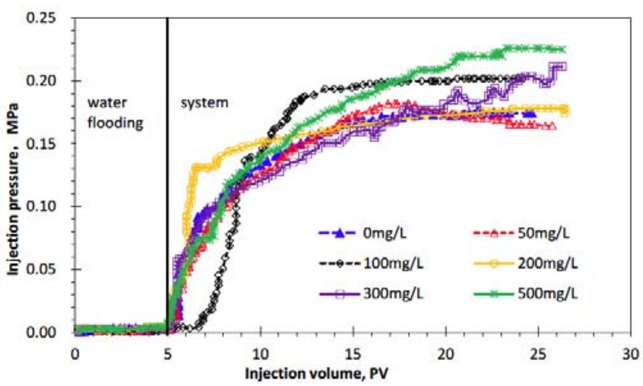

Figure 9: Core injection pressure curves for injection concentrations ≤ 500 mg/L.

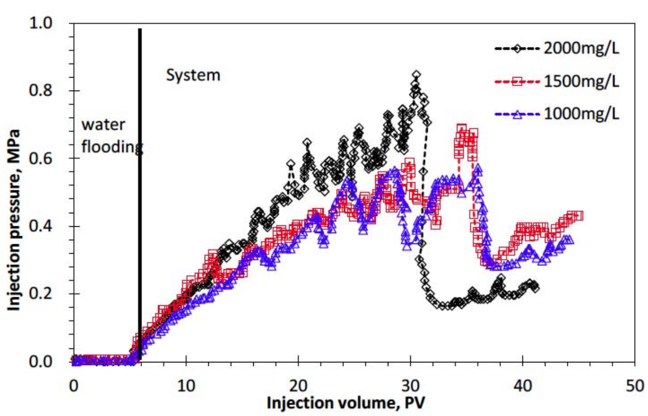

Figure 10: Core injection pressure curves for 1000, 1500, and 2000 mg/L concentrations.

Figures **9** and **10** show that with a particle concentration of ≤ 100 mg/L, the injection pressure is relatively stable, which allows for optimal conductivity; in the 100–500 mg/L systems, it can also be injected with the injection concentration increased, and part of a solid particle system is difficult to carry, resulting in accumulation at the core; when the particle concentration is ≥ 1000 mg/L, the injection pressure continues to rise (much higher than the maximum pressure of 0.2 MPa for lower concentrations), and the pressure fluctuation range is large, which indicates that the sludge particles accumulated in the core.

Using the material balance method with the core injection experimental data of the solid and dry distillation liquid output, the solid particle injection retention surface output was calculated (Table **4**).

An analysis of Table **4** indicates that the concentration of solid particles injected into the system impacts the amount able to enter the core and thus, enter the formation; additionally, their output exhibits certain conductivity in porous media. With an increase in the concentration of solid particles injected (particle concentration is 500 mg/L), the stranded core section and the internal pressure increase, resulting in increased rapid injection. Therefore, reasonable adjustment of solid particles into the long-distance transportation concentration contributes to the solid particles enabling reinjection under stable injection.

3.5. Oil Displacement Effect of Sludge-Containing System

The results of oil displacement experiments with different concentrations of polymeric sludge are shown in the Table below.

As shown in Table **5**, the injection pressure gradually increases with an increase in sludge concentration, and the total recovery rate shows a significant improvement when the sludge concentration is 100–200 mg/L. This

Table 4: Grain Quality under the Condition of Different Concentrations into the Core

Particle concentration (mg/L)	Injection volume (mL)	Particle mass (mg)	Inlet cross section holdup (mg)	Amount of produced particles (mg)	Amount of particles entering the core (mg)
50	120	6	0.5	3.2	2.3
100	125	12.5	0.7	4.7	7.1
200	121	24.2	1.5	16.9	5.8
500	130	65.0	2.3	50.4	12.3
1000	160	160.0	15.2	102.3	42.5
2000	180	360.0	28.3	280.2	51.5

Table 5: Oil Displacement Effect of Polymer Sludge with Different Concentrations

Sludge concentration (mg/L)	Water drive recovery rate (%)	Recovery rate after system displacement (%)	Subsequent water drive recovery rate (%)	Total recovery rate (%)
0	24.68	8.32	16.62	49.62
50	24.71	8.86	19.36	52.93
100	25.28	9.43	22.53	58.04
200	25.78	9.63	22.77	58.18
500	25.31	8.68	18.66	52.65

indicates that the interaction between mud and sand particles and polymers forms an agglomerate structure, enhances the performance of polymer AP-P4 solution, increases the swept volume of subsequent water flooding, and thus, significantly improves oil recovery. As the concentration of sludge further increases, the interaction between mud and sand particles and polymers forms flocculent settlement, leading to a decrease in the viscosity of the solution in the system and an acceleration of the settling of mud and sand particles, thereby hindering their ability to migrate deeper and affecting the sweep efficiency of subsequent water flooding. Ultimately, the overall recovery rate decreased.

4. CONCLUSIONS

(1) The small particle size of ground solid particles is mg/L has sufficient hydraulic conductivity and moderate retention rate, and can achieve long-term reinjection beneficial for their suspension in polymer solutions. The relatively stable system has a particle concentration of 100 mg/L, which exhibits the highest viscoelasticity, aging stability, and shear stability.

(2) As the particle concentration increases in the reinjection system, the retention amount increases, and the injection pressure continues to rise. Controlling the particle concentration of the system is crucial. The reinjection of polymer containing particle systems into formations can have a stronger flow control effect than conventional polymer systems, effectively improving sweep efficiency and thus enhancing oil recovery.

(3) Under the conditions of the target reservoir, a system solution with a particle concentration of 100.

ACKNOWLEDGEMENTS

This work was funded by the Natural Science Foundation of Chongqing (cstc2021jcyj-msxmX0522 and CSTB2022NSCQ-MSX1246)

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCE

[1] Li YC. Petroleum production engineering, Petroleum Industry Press, Beijing, 2005.

[2] Ayotamuno JM, Okparanma RN, Amadi F. Enhanced Remediation of an Oily Sludge with Saline Water. Afr J Environ Sci Technol 2011; 5(4): 262-267.

[3] Fang MJ, Zeng XL, Liang D, *et al*., Study on the sanding law and sanding production simulation experiment of heavy oil. J Southw Petrol Uni 2010; 32(6): 135-138 (in Chinese).

[4] Zhu WY, Tang JC, Wang F, *et al*. Pollution of oil sludge and its disposal techniques in China and Abroad. Pet Ind Appli 2012; 3(18): 1-5 (in Chinese).

[5] Wei YK. Research Status and Progress of Sewage Sludge Treatment. Man Tech SME 2016; 34(0): 66-67 (in Chinese).

[6] Wei YL, Lv L, Yang ZG, *et al*. Advances on recycling technique for oily sludge. Oil Che 2015; 32(1): 151-158 (in Chinese).

[7] Yan XY, Qiao W, Li P, *et al*. Reduction of oily sludge by hydrothermal method. Env Pro Che Ind 2014; 34(4): 340-343 (in Chinese).

[8] Yin XQ, Hu FF, Jing B, *et al*. Research on Treatment Technology as Resource of Polymer-Containing Oily Sludge. J Adv Mater Res. 2014; 955/956/957/958/959: 2677-2682. https://doi.org/10.4028/www.scientific.net/AMR.955-959.2677

[9] Yu LL, Wang D, Ji WB. Conditioning-Mechanical Separation Technology for Oily Sludge Treatment in Oilfield. J Che Mach 2011; 38(4): 413-416 (in Chinese).

[10] Chang H, Yu CT, Wang BK. Preparation of Profile Control Agent for Oilfield from Oily Sludge. Env Pro Che Ind 2014; 34(2): 161-165 (in Chinese).

[11] Shu Z, Zheng CJ, Ye ZB. *et al*. Progress and Research of Oily Sludge Profile Control Technology. App Che Ind 2012; 41(7): 1232-1235 (in Chinese).

[12] Sheng J. Modern Chemical Enhanced Oil Recocery, Gulf Professional Publishing, Oxford 2010; pp. 212-217.

[13] Si R, Lu Y, Deng X, *et al*. Content Indicators and Control Technology of Suspended Solid and Oil of Reinjection Water in Weibei Oilfield. Res Eva & Develop 2016.

[14] Rousseau D. Injectivity Decline from Produced-Water Reinjection: New Insights on In-Depth Particle-Deposition Mechanisms. SPE Production and Operations 2008; 23(4): 525-531. https://doi.org/10.2118/107666-PA

[15] Shu Z, Zheng CJ, Ye ZB, *et al*. Effect of Oily Sludge on The Properties of Oily Sludge-Polymer Reinjection System. Oil Che 2013; 30(4): 600-604 (in Chinese).

[16] Chen WJ, Jing B, Hu K, *et al*. Effects of Oliy Sludge in Offshore Oilfield on Performance of Sludge-Polymer Mixture. Env Pro Che Ind 2017; 37(2): 227-231 (in Chinese).

[17] Martos C, Coto B, Pea JL, Rodríguez R, Merino-Garcia D, Pastor G. Effect of Precipitation Procedure and Detection Technique on Particle Size Distribution of $CaCO_3$. J Cry Gro 2010; 312(19): 2756-2763. https://doi.org/10.1016/j.jcrysgro.2010.06.006

[18] Cowles RJH. Particle Characterization for Oil Sand Processing - 2: Particle Size Measurements by Laser Diffraction. Pet Sci Tech 2000; 18(1-2): 203-220. https://doi.org/10.1080/10916460008949841

[19] Wang D, Cheng JC, Yang QY, *et al*. Viscous-elastic Polymer Can Increase Microscale Displacement Efficiency in Cores, SPE 63227, 2000. https://doi.org/10.2118/63227-MS

[20] Qi PP, Daniel HE, Heesong KOH, Matthew TB. Reduction of Residual Oil Saturation in Sandstone Cores by Use of Viscoelastic Polymers. SPE Journal 2016. https://doi.org/10.2118/179689-MS

[21] Cao RY, Cheng LS, Lian PQ. Flow Behavior of Viscoelastic Polymer Solution in Porous Media. J Dis Sci Tech 2015; 36(1): 41-50. https://doi.org/10.1080/01932691.2014.882260

[22] Lazzari S, Jaquet B, Wu H, Morbidelli M. Shear Stability of Inverse Latexes during Their Polymerization Process. Ame Ins Che Eng 2015; 61(4): 1380-1384. https://doi.org/10.1002/aic.14721