ABSTRACT: The development of dominant seepage channels after polymer flooding makes it more difficult to effectively exploit reservoirs, and gel plugging technology is an effective method to solve this problem. However, conventional gels experience problems such as high initial viscosity and they easily contaminate the medium- and low-permeability layers. Therefore, a low-initial-viscosity gel plugging agent is proposed in this paper. By optimizing the concentration of polymer, cross-linking agent, and other functional auxiliaries, the best gel formulation was obtained. To test the plugging ability of the gel system on the core and its oil displacement effect, a plugging performance test experiment and three-tube core parallel oil displacement experiment were performed. The research results showed that the best formulation of gel plugging agent is as follows: 500−1000 mg/L polymer LH2500, 1000−2500 mg/L cross-linking agent CYJL, 200−500 mg/L citric acid, 100−150 mg/L sodium sulftie, and 100−200 mg/L sodium polyphosphate; its initial viscosity is less than 10 mPa·s, the gelation time is controllable within 10 to 40 days, and the gelation viscosity is above 2000 mPa·s. Core flooding experiments showed that the gel system has good core plugging performance, and the plugging rate of water from 0.48 to 3.9% is more than 99%; for the secondary polymer flooding reservoir, the recovery factor can be increased by 13.6% after plugging with 0.1 PV gel. At present, the gel has been successfully used in field tests and provides good oil increase and water control effects.

1. INTRODUCTION
A total of 54 blocks in the Daqing Oilfield have experienced subsequent water flooding after polymer flooding. It is estimated that by the end of 2020, there will be 28 additional water flooding blocks, the geological reserves after polymer flooding will be close to $9 \times 10^8$ t, and the remaining oil potential is huge.\(^1\) Due to prolonged scouring, the heterogeneity of the reservoir after polymer flooding is more prominent, and water channeling has occurred in the layer. The high-permeability layer has low efficiency and seriously ineffective circulation, and the remaining oil potential is basically accumulated in the medium- and low-permeability layers.\(^2\) Determining how to improve the liquid absorption profile of heterogeneous reservoirs and tap the remaining oil potential is crucial to ensure the sustainable development of the oilfield.\(^3,4\)

Gel plugging technology is an effective method used to control the subsequent water flooding and water channeling phenomena after polymer flooding and to improve crude oil recovery.\(^6\) This technology is mainly used for deep treatment of large-dose reservoirs to reduce the permeability of high-permeability layers, change the flow direction of subsequent fluids, expand the spread volume, and improve crude oil recovery. The technology can also reduce the oil−water viscosity ratio, improve the water−displacing oil mobility ratio, and increase the sweep efficiency.\(^7\)−\(^9\) In recent years, researchers in the petroleum industry at home and abroad have conducted research on the geological characteristics of different reservoirs and developed gel plugging agents suitable for different environments.\(^10\)−\(^11\) Zhang et al.,\(^12\) based on phenolic resin cross-linked hydrolyzed polyacrylonitrile (HPAN), a high-temperature gel glue plugging agent, added partially hydrolyzed polyacrylamide (HPAM) to formulate a bipolar gel forming fluid suitable for low−medium temperature reservoirs. Laboratory experiments proved that compared with conventional gels, the bipolar gel forming fluid has stronger thermal stability in low- and medium-temperature environments. To solve the problem of poor temperature resistance of polymer gel plugging agents under high salinity, Zhu et al.\(^13\) formulated a kind of flexible water plugging agent applicable to reservoirs with high temperature and salinity. The field test showed that compared with conventional gels, this flexible
The development of the above-mentioned gel plugging agents can solve the problems faced by some specific reservoirs to a certain extent, providing a reliable technical support for the efficient production increase of oilfields. However, given the further increase in the heterogeneity of the oil reservoir after polymer flooding in Daqing Oilfield, the existing gel system is no longer applicable due to the higher initial viscosity. According to experimental research, when the viscosity of the plugging agent is greater than 20 mPa·s, the amount of plugging agent entering the medium- and low-permeability layers is about 84% of the amount entering the high-permeability layer, which will seriously contaminate the medium- and low-permeability layers. The injected formation pressure rises rapidly, and only the near-well zone can be sealed off, which does not meet the needs for deep reservoir plugging. Improving the final recovery efficiency of the reservoir remains a challenge.

Therefore, this paper proposes a low-initial-viscosity gel plugging agent, and different concentrations of polymer, cross-linking agent, and other functional additives in the gel formula were optimized to determine the optimal plugging agent formula with low initial viscosity and long gel-forming time. In addition, plugging performance test experiments were performed to evaluate the plugging effect of the low-initial-viscosity gel plugging agent. Three-tube cores were used in parallel to simulate the heterogeneous reservoirs after polymer flooding in Daqing Oilfield, and oil displacement experiments were performed. Studying the ability of low-initial-viscosity gel plugging agents to adjust interlayer contradictions under heterogeneous conditions is essential for formulating related technical policies and ensuring the efficient development of oil fields.

2. RESULTS AND DISCUSSION

2.1. Experiment on Formulation Optimization of Gel System. 2.1.1. Effect of Polymer Concentrations. The concentrations of the fixed cross-linking agent, retarder, regulator, and strengthening agent were 2000, 100, 200, and 200 mg/L, respectively. We compared the gelation time and viscosity variation of four different gel systems with polymer concentrations of 200, 500, 1000, and 1500 mg/L. The results are shown in Figure 1.

Figure 1 shows that with the increase in polymer concentration, the initial viscosity (the viscosity within 3 days) of the system increased, the gelatinization viscosity increased, and the low-viscosity period (the time when the viscosity is kept within 300 mPa·s) shortened. When the polymer concentration was 200 mg/L, the system could not be gelled. When the polymer concentration reached 1500 mg/L, the initial viscosity of the system was greater than 10 mPa·s, and the low-viscosity period considerably shortened to 10 days. When the concentrations were 500 and 1000 mg/L, the initial viscosity of the system was less than 10 mPa·s and the low-viscosity cycle was about 20 days. This indicated that the polymer concentration was too low to be suitable for colloid formation. When the concentration is too large, the probability of collision and entanglement between polymer molecules becomes large, and the polymer molecules that react with the cross-linking agent increase. As a result, the amount of colloid formed by the polymer increases, and the gelation time of the system shortens. Therefore, the polymer concentration was selected as 500–1000 mg/L.

2.1.2. Effect of Cross-linking Agent Concentration. The fixed polymer concentration was 500 mg/L, the retarder concentration was 100 mg/L, the regulator concentration was 200 mg/L, and the strengthening agent concentration was 200 mg/L. We compared the gelation time and viscosity variation...
of five different gel systems with cross-linking agent concentrations of 500, 1000, 2000, 2500, and 3000 mg/L. The results are shown in Figure 2.

As can be seen from Figure 2, with the same polymer concentration, the initial viscosity of the system did not change much with the increase in cross-linking agent concentration, but the gelatinization viscosity increased and the low-viscosity period shortened. When the cross-linking agent was used at a concentration of 500 mg/L, the system could not be gelled. When the cross-linking agent concentration was 3000 mg/L, its initial viscosity was greater than 10 mPa·s and the low-viscosity period was only 10 days. This indicates that the cross-linking agent concentration was too low to be suitable for colloidal formation. However, as the concentration of the cross-linking agent increased, the cross-linking reactive functional groups in the solution increased, resulting in an accelerated cross-linking reaction and shortening of the gelation time of the system. Therefore, the cross-linking agent concentration was selected as 1000–2500 mg/L.

2.1.3. Effect of Regulator Concentration. The fixed polymer concentration was 500 mg/L, the crosslinking agent concentration was 2000 mg/L, the retarder concentration was 100 mg/L, and the strengthening agent concentration was 200 mg/L. We compared the gelation time and viscosity variation of four different gel systems with regulator concentrations of 0, 200, 500, and 800 mg/L. The results are shown in Figure 3.

As can be seen from Figure 3, with the increase in regulator concentration, the initial viscosity of the system decreased. When the concentration of the regulator was 0 mg/L, the initial viscosity of the system did not decrease and the initial
viscosity was greater than 10 mPa·s. When the regulator concentration was 800 mg/L, the initial viscosity of the system was less than 10 mPa·s, but the adhesive viscosity was only about 150 mPa·s and the adhesive strength was too low. Therefore, the regulator concentration was selected as 200–500 mg/L.

2.1.4. Effect of Retarder Concentration. The concentrations of the fixed polymer, cross-linking agent, regulator, and strengthening agent were 500, 2000, 200, and 200 mg/L, respectively. We compared the gelation time and viscosity variation of four different gel systems with retarder concentrations of 50, 100, 150, and 200 mg/L. The results are shown in Figure 4.

As can be seen from Figure 4, with the increase in the amount of retarder, the system’s low-viscosity maintenance period gradually extended, but the gelling viscosity decreased. When the retarder concentration was 50 mg/L, the system’s low-viscosity period was only 10 days. When the retarder concentration was 200 mg/L, the low-viscosity cycle of the system was 40 days, but the gelation viscosity at 60 days was only 350 mPa·s, and the retardation time was too long. Therefore, the concentration of retarder was selected as 100–150 mg/L.

2.1.5. Effect of Strengthening Agent Concentration. The fixed polymer concentration was 500 mg/L, the cross-linking agent concentration was 2000 mg/L, the regulator concentration was 200 mg/L, and the retarder concentration was 150 mg/L. We compared the gelation time and viscosity variation of four different gel systems with strengthening agent concentrations of 0, 100, 200, and 300 mg/L. The results are shown in Figure 5.

As can be seen from Figure 5, with the increase in the concentration of the strengthening agent, the low-viscosity period of the system shortened, and the gelation viscosity increased. When the concentration of the enhancer was 0 mg/L, the low-viscosity period of the system was more than 30 days, but the gelation viscosity of the system was less than 1000 mPa·s. When the concentration of the enhancer was 300 mg/L, the system’s gelation viscosity was 3115 mPa·s, but its low-viscosity period was less than 20 days. Therefore, the concentration of the strengthening agent was selected as 100–200 mg/L.

In summary, the best formula for the low-initial-viscosity gel plugging agent was as follows: the polymer concentration was 500 to 1000 mg/L, the crosslinking agent concentration was 1000 to 2500 mg/L, the concentration of the regulator was 200 to 500 mg/L, the concentration of the retarder was 100 to 150 mg/L, and the strengthening agent concentration was 100–200 mg/L.

2.2. Plugging Performance Test Experiment. The plugging effect of the low-initial-viscosity gel system on cores with different permeabilities is shown in Table 1. Among them, the gel systems used in nos. I and II were as follows: 1000 mg/L polymer + 2500 mg/L cross-linking agent + 200 mg/L regulator + 150 mg/L retarder + 200 mg/L strengthening agent. The gel systems used in nos. III and IV were as follows: 500 mg/L polymer + 2000 mg/L cross-linking agent + 200 mg/L regulator + 100 mg/L retarder + 200 mg/L strengthening agent. The core plugging rate of the low-initial-viscosity gel plugging agent for water from 0.48 to 3.9 μm² was above 99%, and the residual resistance factor was 95.6 to 396.1, which indicates that the low-initial-viscosity gel plugging agent has a good plugging effect on the core.

2.3. Three-Tube Parallel Core Displacement Experiment. 2.3.1. Variation Curve of Instantaneous Shunt Rate with or without a Plugging Agent. The profile control ability and sweep efficiency of the low-initial-viscosity gel plugging agent in heterogeneous parallel cores were investigated. The instantaneous shunt rate can be calculated as

$$f_{sh} = \frac{Q_1^{1.8}}{Q_1^{1.8} + Q_2^{4.5} + Q_3^{2}} \times 100\%$$

(1)
where $f_{f1}$ is the instantaneous shunt rate per unit thickness of the high-permeability layer (%), $f_{f2}$ is the instantaneous shunt rate per unit thickness of the medium-permeability layer (%), $f_{f3}$ is the instantaneous shunt rate per unit thickness of the low-permeability layer (%), $Q_1$ is the outlet flow of the high-permeability layer (cm$^3$/min), $Q_2$ is the outlet flow of the medium-permeability layer (cm$^3$/min), and $Q_3$ is the outlet flow of the low-permeability layer (cm$^3$/min).

The variation curves of the shunt rate in Figures 6 and 7 show that the injection of the low-initial-viscosity gel has a certain effect on the change in the shunt rate of each layer. In the first water flooding process, the amount of water entering the high-permeability layer is significantly greater than the amount entering the medium- and low-permeability layers when the injection volume increases. This occurs due to the large pore size of the high-permeability layer and the percolation resistance being small compared with the medium- and low-permeability layers. With the increase in injection volume, high-permeability layer crude oil is gradually produced, and the percolation resistance is further reduced, leading to further strengthening of heterogeneity. Therefore, the absorption volume of the high-permeability layer increases and the shunt rate increases, while the absorption volumes of the medium- and low-permeability layers decrease and the shunt rate decreases. During the injection of low-concentration polymer, the shunt rate of the high-permeability layer first decreased and then increased, and the shunt rate of the medium- and low-permeability layers first increased and then decreased. This occurred because the polymer increases the viscosity of the water phase and redistributes the liquid absorption of each layer during the injection process. In the early stage of polymer injection, the percolation resistance of the high-permeability layer is small, so the liquid absorption is relatively large. With the increase in the injection volume, the percolation resistance of the high-permeability layer gradually increases, resulting in a gradual decrease in the shunt rate, which urges the subsequent polymer to enter the medium- and low-permeability layers with lower percolation resistance to achieve the purpose of liquid flow turning. However, in the middle and late stages of polymer injection, due to the accumulation of polymers in the medium- and low-permeability layers, the additional percolation resistance of the medium- and low-permeability layers is higher than that of the high-permeability layer, resulting in a reverse profile in the middle and late phases of injection. The absorption volume of the high-permeability layer increases and the shunt rate increases, while the shunt rates of the medium- and low-permeability layers gradually decrease. During the second water flooding process, the plugging effect of polymer on the medium- and low-permeability layers was better than that of the high-permeability layer, so the shunt rate of the high-permeability layer increased gradually, while the shunt rate of the medium- and low-permeability layer decreased gradually.
A comparison of Figures 6 and 7 shows that after the injection of high-concentration polymer, the shunt rate of the high-permeability layer again showed a trend of first decreasing and then increasing. This occurred due to the high viscosity of high-concentration polymer, which increased the percolation resistance of the high-permeability layer to a greater extent, forcing the liquid flow to the medium- and low-permeability layers to fluid diversion. However, the high concentration of the polymer still created the problem of contamination of medium- and low-permeability layers and profile inversion. Conversely, when 0.1 PV low-initial-viscosity gel was injected followed by a high-concentration polymer, the shunt rate of the high-permeability layer was greatly reduced, and the liquid absorption of the medium- and low-permeability layers significantly increased. In addition, the subsequent water flooding stage still maintained a relatively high liquid absorption. This is because the low-initial-viscosity gel plugging agent has a low initial viscosity and controlled gelation time. It can enter the deep part of the oil layer when it is transported in a porous medium. The strength after gelation was large, which can effectively plug the high-permeability layer and simultaneously avoid damage to the regulating system of the medium- and low-permeability layers.

2.3.2. Influence of the Presence or Absence of Plugging Agent on the Oil Displacement Effect. The effect of low-initial-viscosity gel plugging agent on the adjustment of interlayer interference was investigated using the core pressure difference, oil production, water production, recovery percent, and water content. The relationship between water content,
pressure, total recovery, and injected PV in the experiment is shown in Figures 8–10.

Figures 8 and 9 show that during the whole injection process, the two injected slugs had similar migration characteristics. The injection pressure in the water flooding phase first slowly decreased and then stabilized, then increasing in the low-concentration polymer injection phase. After the polymer flooding, the subsequent water flooding phase decreased rapidly and then stabilized because in the first water flooding process, as the injection volume increased, the total water cut gradually increased, the core percolation resistance of the high-permeability layer decreased slightly, the water phase permeability increased, and the injection pressure decreased. When the low-concentration polymer was injected, due to the higher viscosity of the polymer solution, the percolation resistance of the three permeable layers increased. Therefore, the injection pressure gradually increased, which also expanded the spilled volume, resulting in a significant decrease in water content and increasing the use of crude oil in the core. In the subsequent water flooding stage after polymer flooding, as the polymer of the high-permeability layer was extracted with subsequent water, the retention in the core decreased and the percolation resistance decreased, so the injection pressure decreased rapidly and then stabilized.

After the high-concentration polymer solution was injected, the injection pressure rose again and was higher than the injection pressure of the low-concentration polymer, and the water content decreased again. However, the pressure of the polymer solution injection after the plugging relatively increased, and the water content also lowered. This occurred because only increasing the viscosity of the polymer cannot achieve effective plugging of large pores, and the increase in percolation resistance was lower. However, after the low-initial-viscosity gel plugging agent was injected, due to the low initial viscosity of the gel, a large amount of plugging agent could smoothly enter the high-permeability layer. After gelatinization, the pores with a large diameter were completely closed, forming the high-concentration polymer to turn to the medium- and low-permeability layers with a low degree of use. The percolation resistance significantly improved, and the injection pressure greatly increased. Simultaneously, the low-initial-viscosity gel showed excellent profile control performance.

Figure 10 and Table 2 show that only injecting a high concentration of polymer can improve the recovery factor to a certain extent, but relatively, injection of a high-concentration polymer flooding system after plugging can increase the recovery to a greater extent. This occurs because after injecting a high concentration of polymer, the viscosity of the aqueous phase can be increased, and the relative permeability of the aqueous phase and the fluidity of the displacement fluid can be reduced, but the retention capacity of the polymer is poor, which is followed by water production, so it is unable to be implemented in the long term to effectively plug the dominant channel. However, due to its low initial viscosity and controllable glue formation time, the plugging agent can effectively plug the dominant channel and can simultaneously improve the use degree of medium- and low-permeability layers, thus improving the recovery factor. High-concentration polymer injection alone increased the recovery rate by 9.2% compared with low-concentration polymer flooding, whereas high-concentration polymer injection after low-initial-viscosity gel plugging increased the recovery rate by 13.6% compared with low-concentration polymer flooding, which increased the recovery rate by 4.4% compared with high-concentration polymer flooding without plugging.

2.3.3. Variation Curve of Instantaneous Shunt Rate of Different Dosages of Plugging Agent. As can be seen from the shunt rate shown in Figure 11, when 0.2 PV low-initial-viscosity gel was injected followed by the high-concentration polymer, a large amount of liquid was absorbed into the medium- and high-permeability layers, while the amount of liquid absorbed into the low-permeability layer was relatively low. The shunt rate of the high-permeability layer first decreased and then increased, and the shunt rate of the medium- and low-permeability layers first increased and then decreased. This occurred because the gel had a relatively low initial viscosity and easily flowed into the high-permeability layer with the lowest percolation resistance. At the stage of injecting the high-concentration polymer, the high-permeability layer, due to the plugging effect of the gel and the high viscosity of the high-concentration polymer, caused the layer to have the highest percolation resistance and decreased the shunt rate. However, with the increase in injection volume, the shunt rate of the high-permeability layer rose and the shunt rates of the medium- and low-permeability layers gradually decreased. This indicated that during the gel injection stage, the medium- and low-permeability layers were contaminated to a certain degree, and with the increase in the injection amount of high-concentration polymer flooding, the additional percolation resistance of the medium- and low-permeability layers gradually increased. When the core percolation resistance of the medium- and low-permeability layers was greater than that of the high-permeability layer, the amount of subsequent displacement fluid entering the high-permeability layer began to increase, which led to the recovery of the shunt rate of the high-permeability layer, while the suction volumes of the medium- and low-permeability layers decreased and the shunt rate decreased.

The split rate in Figure 12 shows that when 0.3 PV low-initial-viscosity gel was injected followed by the high-concentration polymer, the shunt rate of the high-permeability layer also decreased first and then increased, while those of the medium- and low-permeability layers increased first and then decreased. This occurred because the injected amount of gel was too large, resulting in serious contamination of the medium- and low-permeability layers, and the gel had a strong plugging effect on the medium- and low-permeability layers, so the decrease in the shunt rate of the high-permeability layer was relatively small. With the increase in high-concentration polymer injection amount, the percolation resistance of the medium- and low-permeability layers quickly surpassed that of the high-permeability layer, which caused the displacement fluid to turn to the high-permeability layer with low percolation resistance, resulting in the increase in the suction volume of the high-permeability layer and the recovery of the shunt rate. Compared with the injected 0.2 PV low-initial-

| Scheme number | Recovery percentage of water flooding (%) | Recovery percentage of low-concentration polymer flooding (%) | Recovery percentage of chemical flooding (%) | Total recovery (%) |
|---------------|------------------------------------------|----------------------------------------------------------|---------------------------------------------|-------------------|
| 1-1           | 37.5                                     | 17.6                                                    | 9.2                                         | 64.3              |
| 1-2           | 37.9                                     | 18.1                                                    | 13.6                                        | 69.6              |

Table 2. Comparison of the Oil Displacement Effect with and without a Blocking Agent
viscosity gel, the 0.3 PV gel not only increased the costs but also polluted the low-permeability layer and reduced the liquid flow turning effect.

2.3.4. Effect of Different Amounts of Plugging Agent on Oil Displacement. From the water content change curve shown in Figure 13 and the pressure change curve shown in Figure 14, only the amount of plugging agent was changed and other conditions were kept constant. When the low-initial-viscosity gel injection amount was 0.2 PV, a certain degree of pollution occurred in the medium- and low-permeability layers, but the profile adjustment effect was still strong. In the subsequent high-concentration polymer flooding stage, the water content changed considerably, and the corresponding injection pressure was low when the water content reached the lowest value. However, when the gel injection amount was 0.3 PV, in the subsequent high-concentration polymer flooding stage, the effect of lowering the water content worsened and the injection pressure increased significantly. This indicated that the injection amount of plugging agent at 0.3 PV is too large, and the medium- and low-permeability layers are seriously polluted due to the inhalation of more gel plugging agent, which leads to a poor profile adjustment effect. The subsequent high-concentration polymer solution wave was still produced along the dominant channel, and the effect of expanding the swept volume was poor. Therefore, the reduction of water content was smaller, and the starting pressure of the liquid at the core end markedly increased.
Figure 15 and Table 3 show that under the condition of only changing the gel dosage without changing the other conditions, the excessive gel slug size was likely to contaminate the medium- and low-permeability layers, thus affecting the recovery rate growth. When the gel injection volume was 0.2 PV, the high-concentration polymer flooding increased the recovery rate by 11.6% compared with the low-concentration polymer flooding, and the final recovery rate increased to 66.8%. When the gel injection amount was 0.3 PV, the high-concentration polymer flooding recovery rate decreased, only increasing by 7.2%. However, the injection rate increase of the high-concentration polymer without a plugging agent and implementation was only 9.2%. This indicated that the injection volume of 0.3 PV plugging agent was too large, and the medium- and low-permeability layers were seriously polluted due to inhalation of more gel plugging agent. The uneven application of each permeable layer in the low-concentration polymer flooding stage was not improved, and the degree of improvement in the recovery factor was reduced.

Comparing the experimental results at gel injection volumes of 0.1 and 0.2 PV, the analysis showed that the final recovery using a gel system with a 0.1 PV injection volume was 2.8% higher than that using a gel system with a 0.2 PV injection volume. This indicated that the injection volume of the low-initial-viscosity gel is not as high as possible, although the gel has a strong profile control ability, but due to its low initial viscosity, when the injection amount is too high, the medium- and low-permeability layers are easily polluted. In addition, large-scale slugs cause a large increase in injection pressure, which is difficult to achieve in the field practice.

Table 3. Comparison of the Oil Displacement Effect of Plugging Agents with Different Dosages

| scheme number | recovery percentage of water flooding (%) | recovery percentage of low concentration polymer flooding (%) | recovery percentage of chemical flooding (%) | total recovery (%) |
|---------------|------------------------------------------|------------------------------------------------------------|---------------------------------------------|-------------------|
| 2-1           | 37.4                                     | 17.8                                                       | 11.6                                        | 66.8              |
| 2-2           | 37.7                                     | 17.5                                                       | 7.2                                         | 62.4              |

2.4. Field Test. The statistics of production status of the well group after the plugging scheme was implemented for 2 months are shown in Table 4. The table shows that after the gel was injected, the test intake index dropped from 6.7 to 5.5 m³·(d·MPa)⁻¹, a decrease of 19.4%. The daily water injection

Table 4. Statistics of Well Group Production Status before and after Low-Initial-Viscosity Gel Plugging

| comparison | parameter                     | before plugging | after plugging |
|------------|-------------------------------|-----------------|----------------|
| injection well | daily water injection (m³) | 1705            | 1358           |
|             | apparent injectivity index (m³·(d·MPa)⁻¹) | 6.7             | 5.4            |
|             | save water (10⁵ m³)           | 2.082           |                |
| production well | daily fluid production (t)  | 2373            | 2147           |
|             | save production fluid (10⁵ t) | 1.356           |                |
|             | daily oil production (t)      | 66              | 85             |
|             | cumulative incremental oil (10⁴ t) | 0.066           |                |
dropped from 1705 to 1358 m³, saving a total of 2.082 × 10⁴ m³ of water injection. The comprehensive water cut of the 26 surrounding oil production wells was effectively controlled. The comprehensive water cut decreased from 97.3% before plugging to 95.8% after plugging. The cumulative reduced production fluid was 1.356 × 10⁴ t and the cumulative oil increase was 0.068 × 10⁴ t. The test production index decreased significantly, the oil production ability of the high-permeability reservoir was effectively suppressed, and the inefficient circulation was improved. The comprehensive water cut in production wells decreased and oil production increased, circulation was improved. The comprehensive water cut in production wells and the cumulative oil increase will be 0.56 × 10⁴ t.

3. CONCLUSIONS

(1) We proposed a low-initial-viscosity gel plugging agent, and the optimal plugging agent formula is as follows: 500–1000 mg/L polymer LH2500, 1000–2500 mg/L cross-linking agent CYJL, 200–500 mg/L citric acid (regulator), 100–150 mg/L sodium sulfate (retarder), and sodium polyphosphate as the strengthening agent. The initial viscosity of the gel system is less than 10 mPa·s, the gelation time is controllable within 10–40 days, and the gelation viscosity is above 2000 mPa·s.

(2) The gel plugging agent has low initial viscosity and less pollutes the medium- and low-permeability layers. The gelation time is long, and the core plugging rate of 0.48–3.9 m² of water permeability is above 99%, which provides strong plugging performance and can meet the needs of deep plugging.

(3) In the three-tube parallel core flooding experiment, the 0.7 PV high-concentration polymer solution was injected after the low-concentration polymer flooding, and the recovery rate increased by 9.2%. After plugging with a 0.1 PV low-initial-viscosity gel and then injecting with a 0.7 PV high-concentration polymer, the recovery rate increased by 4.4%. With the increase in gel injection amount, the effect of improving the suction profile weakened. This means that more gel injection is not always better; the best profile control effect can be achieved when the gel injection amount is 0.1 PV.

(4) Field tests verified that the low-initial-viscosity gel plugging system can suppress the inefficient injection of water along high-permeability reservoirs, reduce the comprehensive water content of production wells, and effectively improve crude oil recovery, which has a practical application value.

4. EXPERIMENTAL MATERIALS

4.1. Core. Homogeneous artificial cores were used in the experiment. These cores were made by the EOR Research Institute of Northeast Petroleum University (Daqing, China) by quartz sands (Daqing Refining and Chemical Company, Daqing, China) and cemented with epoxy resin (Daqing Refining and Chemical Company, Daqing, China). Among them, the core size of the test specimen for plugging performance was 4.5 × 4.5 × 30 cm, and the water permeability was 0.4–4.5 μm². The cores in the three-tube parallel core flooding experiment were divided into three layers: high permeability, medium permeability, and low permeability. The sizes were to 4.5 × 1.8 × 30 cm, 4.5 × 4.5 × 30 cm, and 4.5 × 2 × 30 cm, respectively. The corresponding gas permeability values were 4, 2, and 0.5 μm², respectively.

4.2. Chemicals. The polymer LH2500 used in the experiment was supplied by China Daqing Refining and Chemical Company with relative molecular mass values of 2.5 × 10⁵ and 1.2 × 10⁶ to 1.6 × 10⁷, and the degree of hydrolysis was 25%. The cross-linking agent CYJL, regulator, retarder, and strengthening agent were supplied by China Daqing Oilfield Production Technology Institute. The main component of the cross-linker CYJL is a metal chelate with an effective ion content of 2.5%, the main component of the regulator is citric acid with an effective content of 99.8%, the main component of the retarder is sodium sulfate with an effective content of 99%, and the main ingredient of strengthening agent is sodium polyphosphate with an effective content of 99.5%.

4.3. Experimental Oil and Brine. The experimental oil was a crude oil diluted by kerosene with a viscosity of 9.8 mPa·s at 45 °C. The crude oil was taken from Daqing Oilfield Limited Company No. 3 Oil Production Plant (Daqing, China).

The brine was prepared from the produced water of the No.1 Oil Production Company of Daqing Oilfield, with a salinity of 6778 mg/L. The composition of the formation brines is shown in Table 5.

5. EXPERIMENTAL METHOD

5.1. Experiment on Formulation Optimization of Gel System. To make the gel system better adapt to the formation conditions, different concentrations of polymer, cross-linking

| chemical composition | NaCl | KCl | CaCl₂ | MgSO₄ | Na₂SO₄ | NaHCO₃ | total mineralization |
|----------------------|------|-----|-------|-------|--------|--------|---------------------|
| concentration (mg/L) | 3489 | 20  | 64    | 262   | 114    | 2829   | 6778                |

Table 5. Composition of the Injection and the Formation Brines

Table 6. Graded Statistics of Reservoir Thickness and Permeability in Parts of Daqing Oilfield
agent, regulator, retarder, and strengthening agent in the low-initial-viscosity gel formulation were optimized based on the analysis of the factors affecting the gel-forming performance. Based on the analysis of the gelation time and viscosity variation, the effects of polymers, cross-linking agents, regulators, retarders, and strengthening agents on the gelation properties were studied, and the optimal formulation of low-initial-viscosity gel plugging agents was determined.

### 5.1.1. Experimental Procedure
First, the aqueous phase was added to a beaker, and then polymer LH2500 was added to prepare a polymer mother liquor with a mass concentration of 5000 mg/L. After that, we used a WH-610D multiposition magnetic stirrer (Shanghai Shengke Instrument Equipment Co., Ltd., Shanghai, China) to stir the solution for 3.5 h at a certain speed. After waiting for stirring, we took part of the mother liquor and diluted it to the concentration required for the experiment. Then, we dissol ved different amounts of cross-linking agent CYJL, regulator, retarder, and strengthening agent into the polymer solution, which was stirred well and poured into a jar to create a different gel system. An AR2000ex high viscosity rheometer (Shanghai Zhongshi Machinery Co. Ltd., Shanghai, China) was used to determine the initial viscosity of different systems at a temperature of 45 °C and a shear rate of 4.51 s⁻¹. Then, we placed it into the drying oven at 45 °C, removed it after a certain time to measure the viscosity, and observed the gelatinization.

### 5.2. Plugging Performance Test Experiment
We prepared the optimized low-initial-viscosity gel system and then injected it into homogeneous cores with permeabilities of 0.48, 1.36, 2.07, and 3.92 μm², and the slug size was 2 PV. By calculating the plugging rate and residual resistance coefficient, the plugging performance of the core with low-initial-viscosity gel was evaluated.

### 5.2.1. Experimental Procedure
We subjected the cores with different permeabilities to a vacuum at room temperature for 3–5 h and then saturated the formation water for 2–4 h. Then, a plunger pump made by Beijing Weixing Manufacturing Factory was used for water flooding at a displacement rate of 4 mL/min. After the pressure stabilized, the permeability of each core before plugging was calculated. Then, 2 PV low-initial-viscosity gels were injected at 45 °C. The waiting time for gelation was 10 days. Subsequently, 10 PV gel was flooded with water at the same displacement speed, and the core permeability after blockage was calculated after the pressure stabilized.

### 5.3. Experimental Research on the Fluid Diverting and Flooding Effect
To simulate the heterogeneous reservoirs after long-term polymer flooding in Daqing Oilfield, according to the data of 20 coring wells after polymer flooding, the oil reservoir permeability classification and thickness in Sazhong, Sabei, Sanan, and Lamadian areas were calculated (Table 6). The average permeability classification and thickness ratio of the whole area were calculated, and the core physical model parameters of the core experiment were designed. The thicknesses of the low-, medium-, and high-permeability layers were 2.0, 4.5, and 1.8 cm, respectively, with the permeabilities of 0.5, 2, and 4 μm², respectively, and the length of each layer was 30 cm. A low-concentration polymer (1.2–1.6 × 10⁻⁷, 1000 mg/L), high-concentration polymer (2.5 × 10⁻⁷, 1800 mg/L), and low-initial-viscous gel system (1000 mg/L polymer + 2500 mg/L cross-linking agent + 200 mg/L regulator + 100 mg/L retarder + 200 mg/L strengthening agent) were prepared and then injected into the three-tube parallel core. By measuring the core injection pressure, oil production, water production, recovery degree, and water content, the effects of low-initial-viscosity gels on the adjustment of interlayer contradictions were investigated.

### 5.3.1. Experimental Procedure
At room temperature, the pore volume was measured after being subjected to a vacuum and saturating with underground water. The core was then placed in a 45 °C incubator, and the parallel cores were saturated with simulated oil at 1 mL/min by a plunger pump made by Beijing Weixing Manufacturing Factory. The original oil saturation was calculated. After that, the parallel core was set for 24 h before being ready to be used. After 24 h, the parallel cores were water-flooded at 1.2 mL/min until the water content reached 98%. Immediately after, a 0.57 PV low-concentration polymer was injected, and water was flooded to 98%. The pressure change, liquid-producing capacity, water rate, and oil rate in each period were recorded. The recovery factor was calculated based on these data. After that, the
subsequent chemical flooding was conducted at a certain injection rate according to the experimental scheme. Finally, water flooding was performed again to attain a water content of 98%. Throughout the experiment, the gel injection rate was 0.6 mL/min, the remaining injection rate was 1.2 mL/min, and the waiting time for gel gelation was 10 days. The experimental setup diagram is shown in Figure 16.

3.2. Scheme Design. The scheme design of the displacement experiment is shown in Table 7.

4. Application of Low-Initial-Viscosity Gel Plugging Agent in Field Construction. Block X of Daqing Oilfield was injected with the low-concentration polymer in 2014 and is currently in the subsequent stage of waterflooding development. The injection pressure in the block is low at only 11.3 MPa, and the liquid absorption profile is uneven. The suction volume is mainly concentrated in the highly water-flooding oil layer with a permeability greater than 0.8 μm². The relative intake is as high as 64.2%, which leads to comprehensive water cut in some production wells reaching over 97.0%, which is close to the economic limit of development and produces severe inefficient circulation. Therefore, due to the strong suction capacity and high water cut in the well group, 26 injection wells were selected and field tests were conducted on the low-initial-viscosity gel plugging control.

4.1. Scheme Contents. The low-initial-viscosity gel system optimized by the laboratory experiment was selected. The injection rate during displacement was 0.18 PV/year, and the plugging cycle was 6 months.

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B.H. and W.Z. conceptualized the study, provided the methodology, conducted the formal analysis and investigation, and prepared the original draft of the manuscript; C.F. and S.H. reviewed and edited the manuscript and supervised and administered the project; and Q.Z. reviewed and edited the manuscript.

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