Characteristics of Weak-Gel Flooding and Its Application in LD10-1 Oilfield

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ABSTRACT: Weak gel is a kind of three-dimensional cross-linking system with low polymer concentration and appropriate cross-linking agents, dominated by intermolecular cross-linking, supplemented by intramolecular cross-linking, and with a weak cross-linking degree. In this paper, the microstructure and properties of the weak gel were observed and evaluated under different conditions. Seepage behavior experiments and parallel core displacement experiments were carried out to evaluate profile control and flooding performance of the weak gel. Under a certain polymer concentration, with the increase in cross-linker concentration, the reticular structure of the weak gel becomes more uniform and the strength of the weak gel was further enhanced. Weak gel has more retention in porous media and greater strength. The profile control and flooding performance of the weak gel are much better than those of the polymer. A field test of weak-gel flooding was successfully carried out in LD10-1 oilfield. Most of the production wells around the weak gel injection wells responded after weak-gel injection and the accumulative oil incremental oil production of the test area was $5.78 \times 10^4$ m$^3$ up to December 2018.

1. INTRODUCTION

In recent years, polymer flooding has been industrially applied in many oilfields in China such as Daqing oilfield, Shengli oilfield, Henan oilfield, and so on and has already been effectively applied to reduce water production and to enhance oil recovery. However, the polymer is easy to be mechanically degraded in the formation, and the viscosity is greatly reduced and the plugging ability of the high-permeability channel is poor. It is difficult for traditional polymer flooding to meet the actual needs of heterogeneous oilfields.

Weak gel is a kind of a three-dimensional cross-linking system with low polymer concentration and appropriate cross-linking agents, dominated by intermolecular cross-linking and supplemented by intramolecular cross-linking and with a weak cross-linking degree. The characteristics of a weak gel are between those of disperse gels and bulk gels, which has the function of regulating and flooding in a deep reservoir. Weak gels can have the same or different mechanisms for improving sweep efficiency depending on how and where they are applied. Shen mentioned that the weak gel was capable of penetration in the porous media to a certain extent and could flow with water slowly. When water channeling occurs, it could be plugged by the flowing weak gel. Liu et al. developed a new weak gel, which had high resistance to flow but was still able to flow, so it could be injected deep into the reservoir. Han et al. provided similar ideas and referred to weak gels and colloidal dispersion gels (CDGs) as flowing gel processes. Furthermore, Song et al. and Lu et al. pointed out that weak gels were oil displacement agents in addition to their function as blocking agents. Zhang et al. developed a polyacrylamide gel formed by Cr$^{3+}$ and phenolic resin, which had good thermal stability and can be applied to enhance oil recovery in high-temperature reservoirs.

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Case studies of weak gels were carried out in many oilfields where weak gels had been extensively applied in heavy oil, unconsolidated sandstone reservoirs as an in-depth fluid diversion technology. Tiorco (USA) conducted 37 deep profile control field tests of CDGs in the 1980s and 1990s and obtained great economic benefits. In 2004, CDG adjustment and flooding technology in Daqing oilfield achieved great economic and social benefits. The water cut decreased by 8.9% and oil production increased by 9.60%. The Rainbow-Ranch oilfield in Wyoming also carried out field tests of polyacrylamide and chromium acetate weak gel. The total amount of cross-linked polymer solution injected was 0.12PV, and the cumulative oil increase was 2385 m³ in two years. The oil production was stable and achieved considerable economic benefits.

Previous studies and field tests have proved that weak-gel flooding is an effective EOR technique. However, all studies and field tests were aimed at onshore oil fields, and the mechanism of enhanced oil recovery by weak-gel flooding was not detailed enough.

In this paper, the application of weak-gel flooding in offshore oilfields was studied in detail and the field test results were summarized and analyzed. First, rheological tests and scanning electron microscopy (SEM) analysis were carried out to evaluate and observe the properties and microstructure of the weak gel under different conditions. Then, based on the geological characteristics of LD10-1 oilfield, seepage behavior experiments with different permeabilities were carried out to analyze the injection characteristics of the weak gel. Parallel core displacement experiments were also carried out to evaluate profile control and flooding performance of the weak gel. At last, field test results of weak-gel flooding in LD10-1 oilfield were analyzed and the characteristics of weak-gel flooding and its ability to improve oil recovery were clarified.

2. RESULTS AND DISCUSSION

2.1. Effect of Polymer Concentration and RPC on Weak Gel Characteristics. Gelation Process. The gelation process of the Cr³⁺ weak gel system can be divided into the following three steps.

First, an olation complex ion was formed by Cr³⁺ through complexation reaction, hydrolysis reaction, and olation reaction.

Complexation reaction

\[
\text{Cr}^{3+} + 6\text{H}_2\text{O} \rightarrow [(\text{H}_2\text{O})_6\text{Cr}]^{3+}
\]

Hydrolysis reaction

\[
[(\text{H}_2\text{O})_6\text{Cr}]^{3+} \rightarrow [(\text{H}_2\text{O})_5\text{Cr(OH)}]^2+ + \text{H}^+
\]

Olation reaction

\[
2[(\text{H}_2\text{O})_6\text{Cr(OH)}]^3+ \Leftrightarrow [(\text{H}_2\text{O})_6\text{Cr(OH)}]^4+ + 2\text{H}_2\text{O}
\]

Second, a polynuclear olation complex ion was formed through further hydrolysis reaction and olation reaction.

\[
[(\text{H}_2\text{O})_6\text{Cr(OH)}]^4+ + 2\text{H}_2\text{O} + n[(\text{H}_2\text{O})_6\text{Cr(OH)}]^3+ \rightarrow [(\text{H}_2\text{O})_6\text{Cr(OH)}]^n+ + n\text{H}^+ + 2n\text{H}_2\text{O}
\]

Finally, polynuclear olation complex ions coordinate with −CONH₂ and −COO⁻ in HPAM to form a weak gel with a reticular structure.

Because of the different properties and concentrations of the polymer and cross-linker, the reaction speed and degree are different, and the properties of the resulting weak gels vary greatly.

2.1.1. Viscosity. The mother liquor with a concentration of 7000 ppm was prepared and aged for 24 h at room temperature. Then, the mother liquor was diluted into the objective solutions with a concentration of 600, 1200, 2000, and 3000 ppm and the cross-linker was added in RPC (mass ratio of the polymer to Cr³⁺) of 180:1, 120:1, 90:1, 60:1, and 30:1. Table 1 shows the viscosities.

| polymer concentration (ppm) | RPC  | viscosity (mPa·s) |
|----------------------------|------|------------------|
| 600                        | 180:1| 5                |
|                            | 120:1| 6                |
|                            | 90:1 | 7                |
|                            | 60:1 | 9                |
|                            | 30:1 | 25               |
| 1200                       | 180:1| 8                |
|                            | 120:1| 9                |
|                            | 90:1 | 9                |
|                            | 60:1 | 14               |
|                            | 30:1 | 49               |
| 2000                       | 180:1| 55               |
|                            | 120:1| 107              |
|                            | 90:1 | 312              |
|                            | 60:1 | 675              |
|                            | 30:1 | 1324             |
| 3000                       | 180:1| 628              |
|                            | 120:1| 1051             |
|                            | 90:1 | 1391             |
|                            | 60:1 | 1752             |
|                            | 30:1 | 2619             |

As shown in Table 1, with the increase in polymer concentration, the viscosity of the weak gel increases, especially when the polymer concentration is greater than 2000 ppm. The reason is that with the increase in polymer concentration, the association among hydrophobic groups changes from intramolecular association to intermolecular association and becomes stronger; the aggregative state changes from multimolecular aggregation to the weak gel space network;20,21 and the ability of wrapping water molecules becomes stronger.

The concentration of cross-linker is also an important factor affecting the viscosity of the weak gel. With the increase in cross-linker concentration (with the decrease in RPC), the viscosity of weak gel increases. The reason is similar to the effect of polymer concentration.

2.1.2. Microstructure. The microstructure of the weak gel with different polymer concentrations and different RPCs was investigated by SEM. The result is shown in Figure 1. With the increase in polymer concentration (Figure 1a–c. In the case of polymer concentration = 600 ppm, the weak gel strength is too weak to observe its microstructure by freeze etching.), the microstructure of the weak gel gradually changed from lamellar...
to reticular, and the cross-linking between polymer molecules was enhanced, and the strength of the weak gel increased obviously. With the increase in cross-linker concentration (Figure 1c,d), the reticular structure of the weak gel becomes more uniform and the strength of the weak gel was further enhanced.

Considering the reservoir conditions of LD10-1 oil field, weak-gel performance and economic benefits of weak-gel flooding, the field tests adopted the formula of polymer concentration 1200 ppm and RPC 180:1. Therefore, the weak gel of this formulation was used in the subsequent studies in this paper.

2.2. Injection Performance of the Weak Gel. Based on the geological characteristics of LD10-1 oilfield, seepage behavior experiments with a permeability of $300 \times 10^{-3}$ μm$^2$, $500 \times 10^{-3}$ μm$^2$, $800 \times 10^{-3}$ μm$^2$, $1000 \times 10^{-3}$ μm$^2$, and $1200 \times 10^{-3}$ μm$^2$ were carried out. Meanwhile, polymer injection experiments were also carried out to analyze the injection characteristics of the weak gel and polymer through comparison.

2.2.1. RF and RRF. The resistance factor (RF) is defined as the ratio of the differential pressure during weak gel or polymer solution injection to the differential pressure during brine injection for the same porous system. The residual resistance factor (RRF) is derived as the ratio of initial to final permeability. The RF and RRF are important technical indexes for evaluating the ability of the weak gel or polymer solution to improve the fluidity ratio and reduce reservoir permeability.

Table 2 shows the RF and RRF of seepage behavior experiments. As can be seen in Table 2, the core permeability had a strong influence on the RF and RRF. With the decrease in core permeability, the RF and RRF increase obviously. The pore throat of the low-permeability core is too small for the weak gel or polymer solution to pass through.

For the same permeability core, the RF and RRF of the weak gel were greater than those of the polymer solution, although both had the same viscosity. The weak gel has a spatial structure and has a greater retention on the pores and rock surface, so it has a more obvious plugging effect on the core, as shown in Figure 2 [(a,b) for the weak gel and (c,d) for the polymer], which is manifested by a larger RF. In the subsequent water flooding process, the injection pressure of the core plugged by the weak gel was reduced less than that plugged by the polymer solution, as shown in Figure 3. Because of the cross-linking between the molecules, weak gel is stronger, and the weak gel trapped in pores and rock surfaces is more difficult to be displaced. Therefore, the weak gel has a greater effect on reducing the core permeability, which is manifested in the greater RRF.

2.3. Profile Control and Flooding Performance of the Weak Gel. Three parallel core displacement experiments were carried out with two parallel cores under different conditions. The experimental parameters are shown in Table 3, and the schematic diagram of the experimental device is shown in Figure 2. The experimental results are shown in Figure 4.
As shown in Figure 6, because of the different permeabilities, oil recovery of the two parallel cores is quite different after water flooding in the same case. Both weak-gel flooding and polymer flooding can further improve the profile of the parallel cores after water flooding and enhance oil recovery, but the displacement performance and EOR mechanism are different under different conditions.

In case 1, as shown in Figure 4a, oil recovery rate of the high-permeability core increased significantly, from 19.02% (at the end of water flooding) to 29.18%, an increase of 10.16% in the process of weak-gel flooding, while the oil recovery of the low-permeability core increased slightly, from 5.87 to 7.55%, which only increased by 1.68%. In the subsequent water flooding process, the oil recovery of the high-permeability core increased from 29.18 to 30.76%, an increase of 1.58%, and the oil recovery of the low-permeability core increased from 7.55 to 10.23%, an increase of 2.68%. In the weak-gel flooding process, the oil recovery of both high- and low-permeability cores was improved, but the mechanisms were different. For the high-permeability core, in which the weak gel was mainly injected, the weak gel could drive the remaining oil out of the swept area and reduce the remaining oil saturation because of its viscoelasticity, while for the low-permeability core, it was mainly because the weak gel plugged the high-permeability channel, changed the flow direction, and increased the swept area. In the subsequent water flooding process, the injected brine mainly flowed through the low-permeability core because the high-permeability core

![Figure 2. Retention of the weak gel (a,b) and polymer solution (c,d) in pores and rock surfaces (magnified 400 times).](image)

![Figure 3. Injection pressure of seepage behavior experiments.](image)

As shown in Figure 6, because of the different permeabilities, oil recovery of the two parallel cores is quite different after water flooding in the same case. Both weak-gel flooding and polymer flooding can further improve the profile of the parallel cores after water flooding and enhance oil recovery, but the displacement performance and EOR mechanism are different under different conditions.

| case | project | permeability ($10^{-3} \mu m^2$) | porosity (%) | PV (cm$^3$) | oil saturation (%) |
|------|---------|---------------------------------|-------------|-------------|-------------------|
| 1    | waterflooding + weak-gel flooding + subsequent waterflooding | 1015 | 0.354 | 215.1 | 72.3 |
|      |         | 505 | 0.336 | 204.1 | 70.8 |
| 2    | waterflooding + weak-gel flooding + subsequent waterflooding | 1024 | 0.351 | 213.2 | 71.9 |
|      |         | 297 | 0.329 | 199.9 | 69.5 |
| 3    | waterflooding + polymer flooding + subsequent waterflooding | 1017 | 0.347 | 210.8 | 71.7 |
|      |         | 315 | 0.325 | 197.4 | 69.7 |

Table 3. Key Parameters of Profile Control Experiments
Figure 4. Relationship between oil recovery, injection pressure, and PV. ① waterflooding; ② weak gel or polymer flooding; and ③ subsequent waterflooding.
was plugged by the weak gel. Thus, the swept area of the low-permeability core was increased further, and the oil recovery rate is improved.

In case 2, as shown in Figure 4b, oil recovery of the high-permeability core increased from 18.67 to 28.56%, an increase of 9.89% in the process of weak-gel flooding. However, there is no increase in oil recovery of the low-permeability core. Because the permeability of the low-permeability core was too low for the weak gel to be injected, all the weak gel was injected into the high-permeability core. In the subsequent waterflooding process, most of the injected brine flowed through the low-permeability core because the high-permeability core was plugged by the weak gel, and the oil recovery of the low-permeability core increased from 5.56 to 9.87%, an increase of 4.31%. There is no increase in oil recovery of the high-permeability core.

Compared with case 1 and case 2, the profile control and flooding performance of the weak gel were different because of the permeability ratio between cores. The weak gel is difficult to be injected into the low-permeability reservoir because of its spatial structure, and it cannot effectively displace the remaining oil in the low-permeability reservoir. In weak-gel flooding, the oil recovery of the low-permeability reservoir was improved mainly because the weak gel changed the flow direction and increased the sweep area of the low-permeability reservoir. The surfactant flooding or low concentration of the polymeric surfactant flooding can be used to further improve the oil recovery of the low-permeability reservoirs.

In case 3, polymer flooding was carried out after waterflooding. As shown in Figure 4c, oil recovery rate of the high-permeability core increased from 18.72 to 26.14% and the oil recovery of the low-permeability core increased from 5.49 to 8.57% in the process of polymer flooding. In the subsequent waterflooding process, the oil recovery of both high- and low-permeability cores was not improved.

Compared with case 2 and case 3, the profile control and flooding performance of the weak gel and polymer were different because of the different properties of the weak gel and polymer. Both the weak gel and polymer are viscoelastic, but the weak gel has a spatial structure, with more retention in porous media and greater strength. Therefore, the profile control and flooding performance of the weak gel are much better than those of the polymer. In addition, the polymer will be diluted and its strength will be reduced when it is in contact with water. In subsequent waterflooding after polymer flooding, the injected brine flowed through the channel formed in the polymer and the oil recovery could not be further improved.

2.4. Mechanism of Weak Gel Profile Control and Flooding. 2.4.1. Weak Gel Selectively Enters the Large Porous Channel. Weak gels injected into porous media must overcome resistance to flow. Under a certain injection pressure, it is easier to flow through large porous channels with less resistance, which are usually water breakthrough channels in the early waterflooding stage.22,23 After long-term waterflooding, the surface of porous channels has high roundness, and the flow resistance and shear degree to the weak gel are relatively low. In addition, the surface of large channels is strongly hydrophilic after long-term waterflooding, and the interfacial tension of the water-based weak gel flowing in large channels is lower. All of these make the weak gel flow more naturally in larger channels.24−26

2.4.2. Weak Gel Forces the Subsequent Flow to Change the Direction. As mentioned before, the weak gel preferentially enters the large porous channel. A large amount of the weak gel accumulates in the large channels, making the subsequent flow (weak gel or water) in the large channel difficult or even blocking the large channels.27 The subsequent injected water (or weak gel) cannot enter the large channel occupied by weak gel, and the injected water (or weak gel) is forced to enter the small channels. The weak gel forces the subsequent flow to the

Figure 5. Microscopic diagram of weak gel profile control and flooding.
unswept region and improves the sweep efficiency. Figure 5 shows the microscopic diagram of the weak gel changing the flow direction. After water flooding, injected water occupies the large channels, while residual oil exists in the small channels (Figure 5a). In the process of weak-gel flooding, the injected weak gel preferentially enters the large channels occupied by water (Figure 5b−d). With the accumulation of the weak gel in large channels, the flow resistance of the weak gel in the large channels increases and even blocks the large channels. This leads to an increase in the injection pressure gradient, and the subsequently injected water overcomes the capillary force and enters into the small channels, thus displacing the residual oil in the small channels (Figure 5e,f).

2.4.3. Viscoelasticity of Weak Gel Reduces Residual Oil. Figure 6 shows the schematic of the weak gel passing through a narrow channel under the action of viscoelasticity. When the weak gel is close to the porous throat, the additional pressure gradient is established. If the pressure gradient is higher than a certain critical value, the weak gel deforms and squeezes into the narrow porous throat. It indicates that weak gel can enter a deep reservoir. The residual oil is significantly reduced after viscoelastic fluids flow through porous media, which is consistent with that viscoelastic polymer flooding can reduce residual oil in porous media.

3. FIELD TEST

LD 10-1 oilfield, one of the most favorable oil and gas accumulation region in Bohai Bay, is located in the middle west of Liaohe depression. The reservoir structure is a fault semianticline developed in a buried hill, and the sedimentary facies is prodelta facies. The average burial depth of the reservoir is 2660 m and thickness is about 65 m. The reservoir has the physical characteristics of high porosity, high permeability, and low cementation strength, with porosity between 27 and 35% and permeability between $10^{-3}$ and $5500 \times 10^{-3} \mu m^2$. The oil viscosity varies from 13.9 to 19.4 mPa·s.

LD 10-1 oilfield was put into operation in January 2005, and water flooding began in September 2005. In March 2006, a weak-gel flooding test was carried out in A23 well and good technical and economic results were obtained.

3.1. Pressure and Profile of Injection Wells. Figure 7 shows the injection pressure of well A05, A18m, and A23 during
water flooding and weak-gel flooding. It can be seen that the injection pressure increased significantly when the weak gel was injected, which indicates that the RF of the weak gel in the formation was large. Therefore, the weak gel can block the dominant seepage channel and increase the use of the low-permeability formation. Table 4 shows the physical parameters of each perforation interval and Figure 8 shows the changes in the fluid absorption profile before and after the injection of the weak gel in well A23. It can be seen that the liquid absorption ratio of the small layers with small thickness and low permeability was significantly increased after the injection of the weak gel.

### 3.2. Performance and Effect of Increasing Oil Production

According to fluid production dynamics and tracer analysis, the response relationship between polymer injection wells and surrounding production wells in the pilot test area was obtained, as shown in Figure 9. The performance and effect of each well were shown in Table 5. Most of the production wells around the weak gel injection wells responded after weak gel injected, and only five wells did not respond significantly because of sand production, watered-out, edge water, and weak gel channeling. Compared with water flooding, the daily incremental oil production of response wells was \(7.88 - 107.38\) m\(^3\)/d and the average daily incremental oil production was \(33.2\) m\(^3\)/d by weak-gel flooding. The accumulative oil incremental oil production of this area was \(57.8 \times 10^4\) m\(^3\) up to December 2018. Because of the difference of formation conditions and well spacing, the response time and validity time of each well varied greatly. The average response time of each well was 18.0 months and the average validity time of each well was 30.1 months.

The field test of weak-gel flooding in LD10-1 oilfield has been successful, but some problems worthy of special attention have been found, such as the plugging of the weak gel to the wellbore and formation and the channeling of the weak gel. The follow-up study should be carried out to further address these problems.

### 4. CONCLUSIONS

1. With the increase in polymer concentration, the microstructure of the weak gel gradually changed from lamellar to reticular, and the cross-linking between polymer molecules was enhanced, and the strength of the weak gel increased obviously. With the increase in cross-linker concentration, the reticular structure of the weak gel becomes more uniform and the strength of the weak gel was further enhanced.
2. The profile control and flooding performance of the weak gel and polymer were different because of the different properties of the weak gel and polymer. Both the weak gel and polymer are viscoelastic, but the weak gel has a spatial structure, with more retention in porous media and greater strength. Therefore, the profile control and flooding performance of the weak gel are much better than those of the polymer.

3. A weak-gel flooding test was carried out in LD10-1 oil field in March 2006 and good technical and economic results were obtained. Most of the production wells around the weak gel injection wells responded after weak gel injection and the accumulative oil incremental oil production of the test area was $5.78 \times 10^4 \text{ m}^3$ up to December 2018.

5. EXPERIMENTAL MATERIALS AND METHODS

5.1. Experimental Materials. The polymer used in the test was partially hydrolyzed polyacrylamide (HPAM), purchased from ChemMall, China. The relative molecular weight was $2.0 \times 10^7$; the active ingredient was 90.0%. The cross-linker was organic chromium and the active Cr³⁺ was 3.6%. The oil used in this study was dead oil from LD10-1 oil field, with a viscosity of 14.7 mPa·s at reservoir temperature (65 °C). The brine used in the test included two types: (a) produced brine from a water

### Table 5. Performance and Effect of Each Well in the Test Area

| injection well | production well | response time (month) | validity time (month) | daily incremental oil production, m³/d | cumulative incremental oil production, 10⁴ m³ | cause of no response |
|----------------|----------------|-----------------------|-----------------------|-----------------------------------------|-----------------------------------------------|-----------------------|
| A1             | A26H           | 24.43                 | 53.75                 | 16.97                                   | 2.78                                          | weak gel cross-flow   |
| A38            | 35.08          | 43.69                 |                       | 7.88                                    | 1.05                                          | high watered-out well |
| A36            | 46.52          | 8.55                  |                       | 9.90                                    | 0.26                                          | edge water influence  |
| A5             | A4             | 33.11                 | 12.56                 | 8.17                                    | 0.31                                          |                       |
| A12            | 8.55           | 26.83                 |                       | 47.78                                   | 3.90                                          |                       |
| A34            | 63.45          | 10.36                 |                       | 8.27                                    | 0.26                                          |                       |
| A9             | 11.90          | 46.49                 |                       | 50.36                                   | 7.12                                          |                       |
| A11            | 13.15          | 50.37                 |                       | 107.38                                  | 16.45                                         |                       |
| A121S1         |                |                       |                       |                                         | 0.11                                          |                       |
| A44            |                |                       |                       |                                         |                                               |                       |
| A14            | A8             |                       |                       |                                         |                                               |                       |
| A15            | 7.96           | 28.21                 |                       | 41.54                                   | 3.56                                          |                       |
| A16            | A37            | 7.23                  | 7.04                  | 15.02                                   | 0.32                                          | sand production       |
| A45            |                |                       |                       |                                         |                                               |                       |
| A23            | A13            | 41.88                 | 30.11                 | 36.73                                   | 3.36                                          |                       |
| A20            | 69.07          | 37.32                 |                       | 28.30                                   | 3.21                                          |                       |
| A28            | 75.85          | 30.54                 |                       | 7.72                                    | 0.72                                          |                       |
| A39            | 82.68          | 16.93                 |                       | 26.04                                   | 1.34                                          |                       |
| A40            | 49.68          | 21.57                 |                       | 34.46                                   | 2.26                                          |                       |
| A18m/A35       | A12            | 12.79                 | 67.27                 | 21.03                                   | 4.30                                          |                       |
| A17            | 21.99          | 10.42                 |                       | 17.73                                   | 0.56                                          |                       |
| A24            | 12.23          | 41.00                 |                       | 15.06                                   | 1.88                                          |                       |
| A47            |                |                       |                       |                                         |                                               |                       |
| A43            | A22            | 16.31                 | 29.69                 | 11.92                                   | 1.08                                          | sand production       |

![Figure 10. Seepage behavior experiment process diagram.](https://dx.doi.org/10.1021/acsomega.0c03762)
well, with the electrolyte concentration of 8,870 mg/L and (b) produced brine from production wells, with the electrolyte concentration of 10,240 mg/L. The two kinds of the simulated brine were prepared according to the ion concentration data of LD10-1 oilfield in Bohai Bay with distilled water and different types of salts.

The cores used were artificial cores which were composed of clay-free quartz sands. Columnar cores with a size of φ2.5 × 10 cm were used for the seepage behavior experiments. Four prismatic cores with different permeabilities were used for profile control experiments. All the four prismatic cores have a height, width, and length of 4.5 × 4.5 × 30 cm, respectively.

5.2. Preparation of the Weak Gel. First, the mother liquor with a concentration of 7000 ppm was confected with produced brine from a water well and aged for 24 h at room temperature. Then, the mother liquor was diluted into the objective solutions with a concentration of 600, 1200, 2000, and 3000 ppm with produced brine from production wells and the cross-linker was added. The amount of the cross-linker added was determined by RPC (mass ratio of the polymer to Cr³⁺). In this paper, an RPC of 180:1, 120:1, 90:1, 60:1, and 30:1 was chosen to study the rheological properties of the weak gel.

5.3. Rheological Tests. Rheological properties, including viscosity and viscoelasticity, are important factors to evaluate the properties of weak gel. The rheological properties of weak gel were measured using a HAAKE MARS III rotational rheometer (Thermo Fisher, Germany) at reservoir temperature (65 °C).

5.4. Seepage Behavior Experiments. The seepage behavior experiment system mainly contains an injection system, core hander, peripheral pressure control system, production system, and pressure-acquisition system, as shown in Figure 10. The core hander, brine cylinder, and weak gel cylinder were placed in a thermostank to obtain the reservoir temperature.

The seepage behavior experiments were conducted according to the following steps: First, the core was placed into the core hander to ensure good seal by increasing confining pressure. Then, the core was saturated with brine and the pore volume, porosity, and permeability were measured. Next, the thermostank temperature was set to 65 °C and the saturated core was aged at 65 °C for 24 h. After that, the weak gel was injected into the core and the pressure was measured using the pressure-acquisition system until the pressure was stable. Finally, the brine was injected into the core and the pressure was measured to determine the RRF.

5.5. Parallel Core Displacement Experiments. The parallel core displacement experiments were carried out with two parallel cores with different permeabilities, as shown in Figure 11. The experimental apparatus was similar to that of seepage behavior experiments. The parallel core displacement experiments were conducted according to the following steps: First, the cores were connected in parallel and saturated with brine. The pore volume, porosity, and permeability were measured. Then, the cores were saturated with oil at 65 °C with a constant speed (0.1 mL/min). The volume of discharged water was measured to calculate the oil saturation of the cores. Next, the saturated cores were aged at 65 °C for 24 h. After that, the brine was first injected into the cores until no more oil was produced (about 3.0 PV), followed by 1.0 PV weak gel or polymer solution and finally approximately 3.0 PV brine. The injection rate was maintained at 2.0 mL/min. The produced liquid was collected and measured, and the pressure was measured using the pressure-acquisition system during flooding.

5.6. SEM Analysis. The microstructure of weak gel with different polymer concentrations and different RPCs was investigated by SEM. The occurrence form of the weak gel in a porous medium was also observed by SEM. The equipment used in this study is a Quanta 200F scanning electron microscope (FEI, USA), and all samples are prepared using the freeze-etching technique.

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Notes

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