

Article

Main Controlling Factors Affecting the Viscosity of Polymer Solution due to the Influence of Polymerized Cations in High-Salt Oilfield Wastewater

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Abstract: In view of the high salinity characteristics of reinjection oilfield wastewater in the Gasi Block of Qinghai Oilfield, with the polymer produced by Shandong Baomo as the research target, we systematically investigated the variations in the impact of six ions, Na⁺, K⁺, Ca²⁺, Mg²⁺, Fe²⁺, and Fe³⁺, in the produced water from polymer flooding on the viscosity and stability of the polymer solution. Additionally, we provided the primary research methods for complexation in reinjected wastewater. Experimental results indicate that the main factors leading to a decrease in polymer viscosity are high-valence cations, with the descending order of their influence being Fe²⁺ > Fe³⁺ > Mg²⁺ > Ca²⁺ > Na⁺ > K⁺. High-valent cations also effect the viscosity stability of polymer solutions, and their order from greatest to least impact is: Fe²⁺ > Ca²⁺ (Mg²⁺) > Fe³⁺ > Na⁺ (K⁺). This article is focused on investigating the influencing factors and extent of the impact of oilfield wastewater on the viscosity of polymer solutions. It illustrates the response mechanism of cations to the viscosity of polymer solutions in reinjection wastewater polymerization. Through this research, the goal is to provide reference control indicators and limits for the water quality of injected polymers at oilfield sites. This ensures the stability and controllability of polymers in field applications and offers theoretical guidance for polymer flooding technology.

Keywords: cation content; reinjected wastewater; influencing factors; viscosity stability

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1. Introduction

With the large-scale application of polymer flooding technology, polymer flooding has entered the stage of industrial application in oilfield research. It mainly refers to the improvement of oil–water flow ratio and expansion of micro and macro sweep efficiency of oil layers. By increasing the viscosity of the polymer solution, the solution viscosity ratio is increased and the water phase permeability is reduced, so the viscosity of the polymer solution directly affects the polymer oil displacement effect [1–3]. Various cations, anions, and complex ions are present in oilfield wastewater and may interact with molecules in the polymer solution. These interactions may include adsorption, dissociation, or coordination reactions of ions, thereby affecting the conformation and interaction of polymer molecules, forming a complex and diverse environment. Different ions affect the solubility, dispersion, viscosity, and other properties of the polymer. It has varying degrees of impact. The importance of this issue is not only related to the sustainable utilization of resources. The viscosity-increasing ability of polymers directly affects engineering processes such as water quality treatment, oil field water injection and recovery, and also directly affects the oil field production process. The ions in wastewater exist in different forms such as free state and

complex state, resulting in different forms of interactions, thus causing complex changes in the molecular structure and properties of the polymer. These ions may undergo ion exchange reactions with the polymer, affecting the stability and fluidity of its molecular chains, thereby affecting the viscosity and rheological properties of the solution. Although the technical level of polymer flooding ground technology has been increasingly improved, it faces more difficulties. Among them, the low viscosity property of polymer solution has always been a key issue restricting oil displacement efficiency [4–7]. Du et al. [8] studied the effects of adding different ions to polyacryloyl on the COO- group, including Na^+ , Mg^{2+} , Ca^{2+} , and Cl^- . It was found that cations have an important impact on the viscosity of the polymer. Sun Lin et al. [9,10] conducted a study on the effect of metal ions on the viscosity of the polymer/alkali binary flooding system. The results showed that Ca^{2+} and Mg^{2+} have a greater impact on the viscosity of polymer solution than K^+ and Na^+ . As the concentration of metal ions increases, the viscosity of the binary displacement system shows a decreasing trend. Since a large amount of water is needed to prepare a polymer aqueous solution on site, wastewater is usually used. However, a large number of metal ions exist in wastewater, and these ions will directly affect the viscosity of the polymer solution [11–13]. Fang Hongbo et al. [14] tested the viscosity changes of polymer solutions under different oxygen concentrations. The experimental results showed that after oxidative degradation of polyacrylamide solutions, the viscosity of the solution dropped significantly. Wen Feng et al. and others [15–17] believe that dissolved oxygen will affect the stability of polymers. Zhang Ke et al. [18] studied the effects and causes of viscosity of wastewater polymer solution under anaerobic and aerobic environmental conditions and determined the appropriate amount of oxygen exposure. According to Zhan's research [19], polyacrylamide has three degradation methods: oxidative degradation, photodegradation, and photocatalytic degradation. Wu et al. [20] found that adding a certain proportion of S^{2-} and Fe^{2+} to a low-concentration polyacrylamide solution will reduce the viscosity of the low-concentration polyacrylamide solution in a short period of time. Guan et al. [21] added NaCl , CaCl_2 , NaNO_3 , KNO_3 , and MgCl_2 solutions with a concentration of 1.0 mol/L to a hydrolyzed polyacrylamide (HPAM) solution with a relative molecular mass of 1900×10^4 and a mass concentration of 1 g/L, respectively, to test the effects of different types of salts on the viscosity of HPAM. Divalent ions such as Ca^{2+} and Mg^{2+} have a greater impact than the monovalent ions Na^+ and K^+ . When different types of salts are added to the solution, the positive ions neutralize the negative charges on the molecular chain, and the repulsive force between the ions in the water and the ions on the polymer molecular chain increases. Therefore, the repulsive force greatly reduces the ability of the molecular chain to unfold. This reduces the probability of molecular chain entanglement and greatly reduces the viscosity of the polymer. Therefore, when preparing the solution, the influence of salt ions on the viscosity of the solution should be eliminated as much as possible. Mingming et al. [22] added NaCl to the polymer solution and measured the viscosity of the 1500 mg/L polymer solution at different contents. The experimental results showed that as the Na^+ content increased, the viscosity decreased. After the content was greater than 500 mg/L, the viscosity decreased. The trend slowed down. The same method was used to measure the viscosity of polymer solutions with different CaCl_2 contents. The experimental results showed that CaCl_2 has a greater impact on viscosity than NaCl . When the CaCl_2 concentration is greater than 200 mg/L, the viscosity decrease trend slows down. The higher the Ca^{2+} content, the more serious the viscosity loss will be, and the HPAM solution may even flocculate or precipitate. At the same time, a FeCl_3 solution with a concentration of 2 g/100 mL was added dropwise to 100 mL of HPAM aqueous solution with a concentration of 1500 mg/L to observe and measure the change in viscosity. The results show that when the concentration of FeCl_3 exceeds 20 mg/L, the viscosity of the solution decreases significantly and even flocculates. This shows that trivalent salts have a great influence on the viscosity of the polymer solution. A trace amount of trivalent salts will cause the viscosity to decrease sharply or even flocculate. Therefore, the content of trivalent ions should be strictly controlled. Data show that foreign countries generally

require it to be controlled below 20 mg/L, and Daqing Oilfield requires it to be below 0.99 mg/L. Levitt et al. [23] found under certain conditions, polyacrylamide can also be quite stable when dissolved oxygen is present and free of Fe^{2+} and free radical-generating impurities. This shows that under some special environmental conditions, polyacrylamide can maintain relative stability, but under other conditions, especially when influencing factors such as oxygen, iron ions, or free radicals are involved, different reactions and degradation may occur [24]. In recent years, research has mainly focused on the influence of ions on the apparent viscosity of polymers and the influence on the stability of polymer solutions. There is less research on the internal mechanism of cations reducing the viscosity of polymer solutions and their influence on the microstructure of polymers. This article studies the influence mechanism of different ions on the viscosity of polymer solutions, including K^+ , Na^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , and Fe^{3+} , and reveals the changing rules of the influence of different ions and their concentrations on polymer viscosity.

2. Materials and Methods

2.1. Materials and Instruments

Partially hydrolyzed polyacrylamide was purchased from Baomo Co., Ltd. (Dongying, China), degree of hydrolysis 27%, relative molecular mass 2.3×10^7 , effective mass fraction 95%; ferric chloride, sodium chloride, calcium chloride, potassium chloride, and magnesium chloride were purchased from Aladdin Co., Ltd. (Shanghai, China), analytically pure; reinjection wastewater is provided by Qinghai Oilfield, deionized water is prepared in the laboratory through distillation.

Brookfield DV-II viscometer was purchased from Brookfield Company (Waltham, MA, USA), The digital constant temperature water bath and JT-4 precision power-increasing electric mixer was purchased from Rayleigh Analytical Instruments Co., Ltd. (Beijing, China).

2.2. Experimental Methods

2.2.1. Polyacrylamide Mother Liquor Preparation

Accurately weigh the required polyacrylamide dry powder and gradually put it into a beaker pre-filled with a certain amount of deionized water. After each addition of polyacrylamide dry powder, use an electric mixer to stir evenly at a speed of 100 r/min to ensure sufficient stirring after each addition to prevent agglomeration. During the entire stirring process, observe whether the dry polymer powder is completely dissolved and ensure that the particles suspended in the water are fully dispersed. Continue stirring until all the polyacrylamide dry powder is added to the deionized water, then continue stirring and maintain the stirring speed at 100 r/min. Continue stirring for 3 h to ensure that the polymer mother liquor is fully homogeneous, which will help improve its performance. Then, allow the polymer mother liquor to stand for 3 h to mature. The aging process helps eliminate possible air bubbles and improves the stability of the solution. After maturation, take a sample to detect the concentration of the polyacrylamide mother liquor to ensure that it reaches the required mass concentration of 5000 mg/L. If necessary, the amount of polyacrylamide dry powder or deionized water in the polymer mother liquor can be adjusted and stirred again.

2.2.2. Effects of Different Ions on the Viscosity of Polymer Solutions

Preparation of cationic aqueous solution: Weigh quantitative cationic chemicals (K^+ , Na^+ , Mg^{2+} , Ca^{2+} , Fe^{2+} , Fe^{3+}) and add them to the beaker, respectively. Pour 250 mL of deionized water into the beaker and stir with an electric stirrer at a speed of 100 r/min, stir for about 3 h and then let it sit.

Preparation of polymer solution: Take quantitative polymer mother liquor and mix it thoroughly with cationic aqueous solutions of different mass concentrations (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Fe^{2+} , Fe^{3+}), stir with an electric stirrer for 3 h, the rotation speed is 100 r/min, and place it at room temperature 24 h, measure polymer viscosity using Brookfield DV-II viscometer.

3. Results and Discussion

3.1. Effect of K^+ and Na^+ on the Viscosity of Polymer Solution

A polymer solution with a mass concentration of 2500 mg/L was prepared by diluting the polyacrylamide mother liquor with mineralized water containing only K^+ and Na^+ . The effect of K^+ and Na^+ ions on the viscosity of polymer solution is presented in Figure 1. It performs linear fitting, and the fitting results are shown in Figure 2.

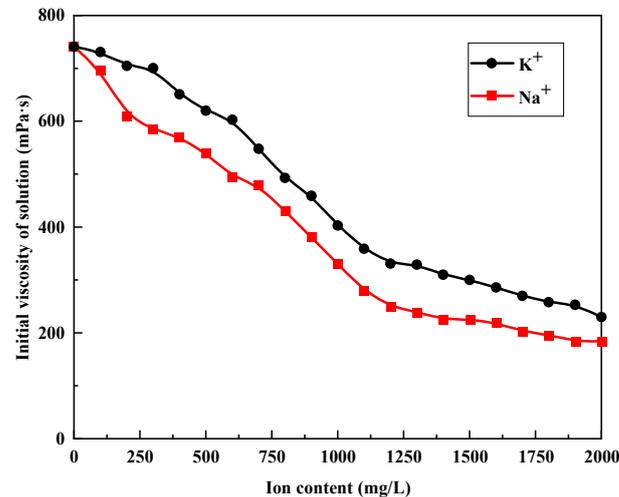


Figure 1. Effect of K^+ , Na^+ content on the viscosity of polymer solutions.

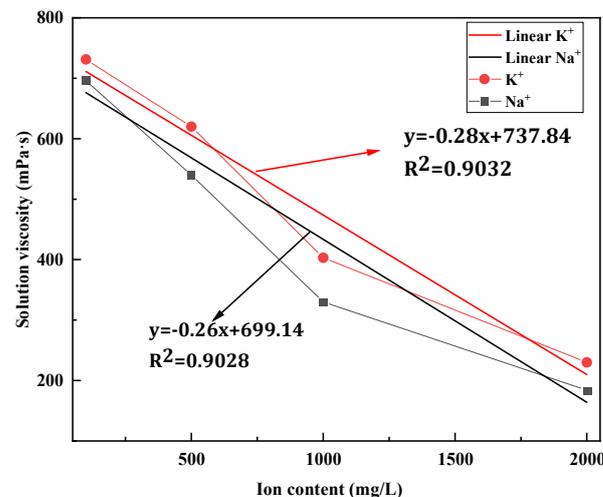


Figure 2. Linear fitting of the effect of Na^+ and K^+ content on the viscosity of polymer solutions.

As can be seen from Figure 1, it can be observed that when the concentrations of K^+ and Na^+ are in the range of 0 to 1200 mg/L, the viscosity of the polymer solution decreases with increasing ion concentration. However, when the concentrations of K^+ and Na^+ exceed 1200 mg/L, the polymer viscosity loss is relatively slow.

When the K^+ and Na^+ contents are 100~2000 mg/L, the linear fitting results of the solution viscosity and the cation content are shown in Figure 2. The difference in the distance between the straight lines indicates the difference in the influence of different ions on the viscosity of the polymer solution, and the influence of K^+ on polymerization. The influence of the viscosity of the solution is about 0.93 times that of Na^+ .

K^+ and Na^+ ions neutralize the negative charges on polymer molecules in the solution, primarily concentrating on the $-COO^-$ groups. Due to its smaller ionic radius, Na^+ more effectively approaches and neutralizes an equivalent number of negative charges compared to K^+ . Consequently, the neutralization effect of Na^+ is more pronounced. This results in a

reduction in intramolecular electrostatic repulsion, diminishing frictional forces between large molecules.

Na^+ ions, due to their smaller ionic radius, can easily penetrate water molecules to approach polymer chains. Their interaction with $-\text{COO}-$ groups is more intimate, inducing structural changes in polymer chains. This structural alteration may lead to the curling and unfolding of polymer chains, influencing the fluidity and viscosity of the solution [25,26]. As the concentrations of Na^+ and K^+ increase, the neutralization effect becomes more significant. In the lower concentration range, the neutralization effect may be relatively modest, while in the higher concentration range, it becomes more pronounced. This results in a reduction in negative charges, diminishing intermolecular electrostatic repulsion, and affecting the structure of polymer chains. The smaller ionic radius of Na^+ enhances its ability to neutralize negative charges, making it more impactful on viscosity compared to K^+ [27,28].

3.2. Effects of Ca^{2+} and Mg^{2+} on the Viscosity of Polymer Solutions

The polymer solution (concentration: 2500 mg/L) is prepared by diluting the polyacrylamide mother solution with mineralized water containing only Ca^{2+} and Mg^{2+} . The results of the influence of Ca^{2+} and Mg^{2+} ion concentrations on the viscosity of the polymer solution are shown in Figure 3.

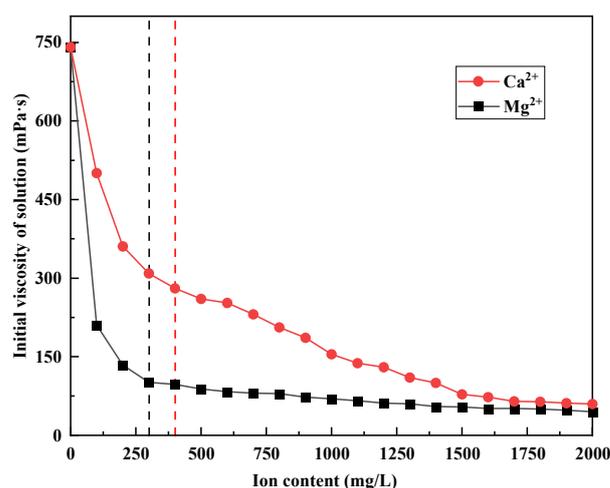


Figure 3. Effect of Ca^{2+} and Mg^{2+} content on the viscosity of polymer solutions.

It can be seen from Figure 3 that when Ca^{2+} and Mg^{2+} are present in the polymer solution, the viscosity of the polymer solution is greatly reduced. When the concentration of Ca^{2+} reaches a certain value, the viscosity of the solution drops to below 266 mPa·s; Mg^{2+} content in the range of 0–400 mg/L, with the increase in the concentration of Mg^{2+} , the viscosity of the solution decreases rapidly, down to below 97.1 mPa·s. Therefore, it is believed that the effect of Mg^{2+} on the viscosity of the polymer solution is greater than the effect of Ca^{2+} on the viscosity of the polymer solution.

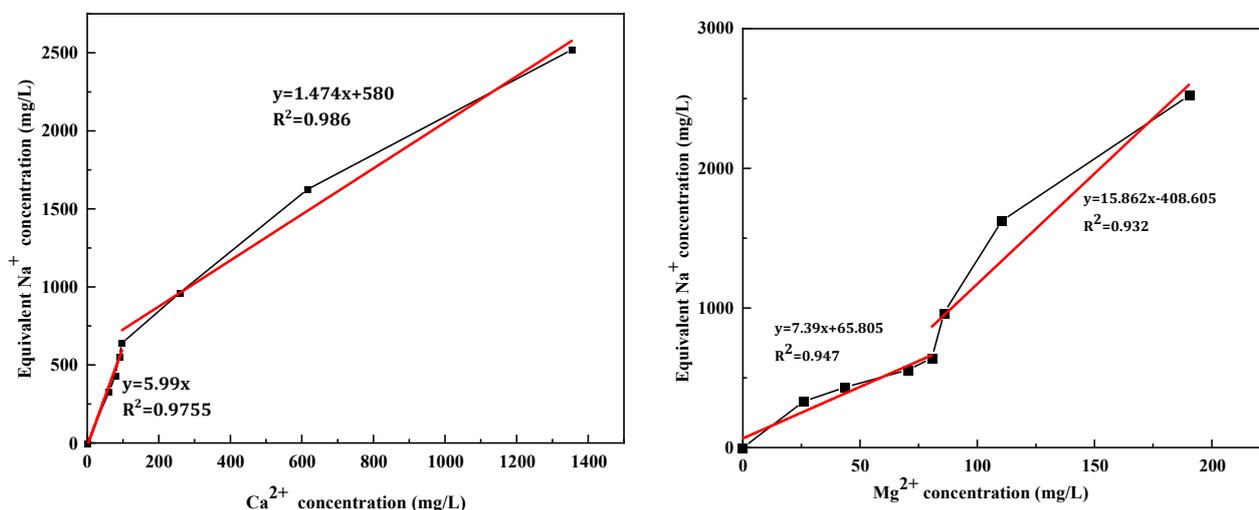
When there is only one kind of ion in the solution, namely Ca^{2+} or Mg^{2+} , different mass concentrations will lead to different viscosity values; the corresponding Na^+ mass concentration can be calculated based on the results of each viscosity value in Figure 1, which is called the viscosity corresponding to Ca^{2+} , the equivalent Na^+ mass concentration of Mg^{2+} mass concentration.

Based on the equivalent Na^+ mass concentration at the same viscosity obtained in Table 1, establish the mathematical relationship between the mass concentrations of Ca^{2+} and Mg^{2+} and them. The significance of the slope in the mathematical relationship lies in the difference in the ability of Ca^{2+} , Mg^{2+} and Na^+ to affect viscosity when the ion concentration increases. The smaller the slope, the greater the concentration, and the smaller the impact of Ca^{2+} and Mg^{2+} on viscosity; otherwise, vice versa.

Table 1. Ca^{2+} , Mg^{2+} mass concentration and equivalent Na^+ mass concentration at the same viscosity.

Viscosity (mPa·s)	Equivalent Na^+ Mass Concentration (mg/L)	Ca^{2+} Content (mg/L)	Mg^{2+} Content (mg/L)
741	0	0	0
600	330.817	61.652	25.913
550	432.625	78.589	43.746
500	556.326	89.485	70.452
450	641.234	97.356	80.689
330	964.558	259.554	85.773
250	1624.822	615.325	110.519
130	2520.061	1354.113	190.258

It can be seen from Figure 4 that at the same viscosity, the effect of Ca^{2+} on the viscosity of the polymer solution is significantly greater than that of Na^+ , which is one to six times that of the latter. The effect of Na^+ on the viscosity of the polymer solution is slightly lower than that of Ca^{2+} ; Mg^{2+} has a greater influence on the viscosity of the polymer solution. The effect of solution viscosity is 7 to 14 times that of Na^+ . The equivalent mass concentration of Na^+ is much higher than that of Mg^{2+} . This shows that the effect of Na^+ on the viscosity of the polymer solution is much smaller than the effect of Mg^{2+} on the viscosity of the polymer solution, by comparing the slopes, we can see the order of the influence of the three ions on the viscosity of the polymer solution: $\text{Mg}^{2+} > \text{Ca}^{2+} > \text{Na}^+$. Because the ionic radius of Mg^{2+} is smaller than that of Ca^{2+} , Mg^{2+} is more likely to be close to the $-\text{COOH}$ group in the polymer chain segment. The number of the other two ions in the first layer is significantly lower than the number of Mg^{2+} ions in the first cation layer, so the electrostatic shielding efficiency of Mg^{2+} ions is higher, they are more easily attracted to the polymer chain segments and are more tightly combined with the carboxylic acid groups. This tight combination makes it easier for Mg^{2+} ions to compress the polymer chain segments, thereby changing the configuration of the polymer chain and reducing the interaction force of the polymer chain [29].

**Figure 4.** Linear fitting results of mass concentration of Ca^{2+} and Mg^{2+} corresponding to Na^+ at the same viscosity.

3.3. Effect of Fe^{2+} and Fe^{3+} on the Viscosity of Polymer Solution

The polyacrylamide mother solution was diluted with mineralized water containing only Fe^{2+} and Fe^{3+} to prepare a polymer solution (mass concentration: 2500 mg/L). The results of the influence of Fe^{2+} and Fe^{3+} ion concentrations on the viscosity of the polymer solution are shown in Figure 5.

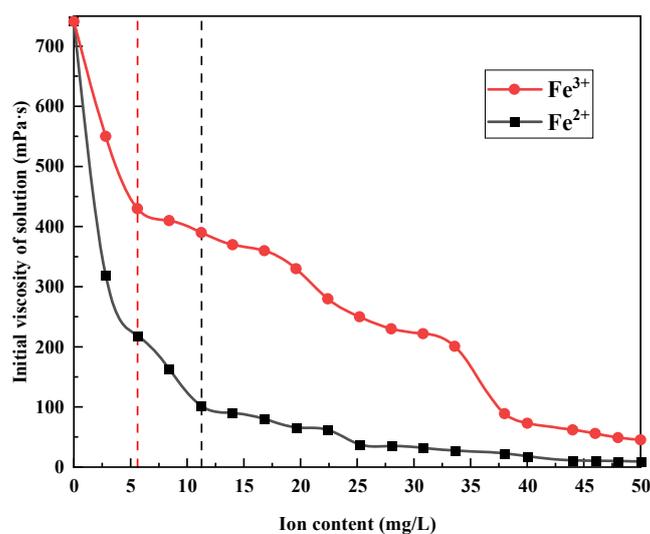


Figure 5. Effect of Fe^{2+} and Fe^{3+} content on the viscosity of polymer solutions.

It can be seen from Figure 5 that a small amount of Fe^{2+} will cause a significant decrease in the viscosity of the polymer solution; as the Fe^{3+} content increases, the viscosity of the solution first decreases significantly and then decreases slowly. In aqueous solutions, Fe^{2+} ions catalyze the production of hydroxyl radicals through the Fenton reaction. These highly reactive oxidizing agents can disrupt the C-H bonds in polyacrylamide molecular chains [30]. This attack initiates a hydrogen abstraction reaction, leading to the formation of carbon-centered radicals, which in turn cause the molecular chains to break. As a result, the original long-chain polymers are transformed into smaller molecules, significantly reducing the viscosity of the polymer solution. Furthermore, the high charge density of Fe^{2+} ions enables them to effectively bind with the negatively charged functional groups on the surface of polymer molecules, leading to the compression of the diffusion double layer. This change reduces the repulsion between polymer molecules, causing them to move closer to each other, and subsequently undergo curling and aggregation. These structural changes reduce the hydration shell of the polymer, lowering the hydrodynamic radius of the solution, which further decreases its viscosity. In the compressed double layer environment, the free radical reactions catalyzed by Fe^{2+} ions more readily promote the breakage of polymer chains, as the charge shielding between molecules is weakened, making them more prone to contact and reaction [31–33]. Overall, the role of Fe^{2+} ions in polyacrylamide solutions is multifaceted. They not only trigger the oxidative degradation process but also alter the charge interactions between molecules, leading to changes in polymer structure and a significant decrease in solution viscosity [34]. When the Fe^{3+} content is 0–6 mg/L, the polymer solution decreases significantly. After reaching 6 mg/L, the polymer is observed to flocculate and settle, resulting in a decrease in solution viscosity. It can be seen that a trace amount of Fe^{2+} and Fe^{3+} can have a serious impact on the solution viscosity, and the impact of Fe^{2+} is greater than that of Fe^{3+} . Therefore, the contents of Fe^{2+} and Fe^{3+} in the injected water need to be carefully controlled during on-site testing.

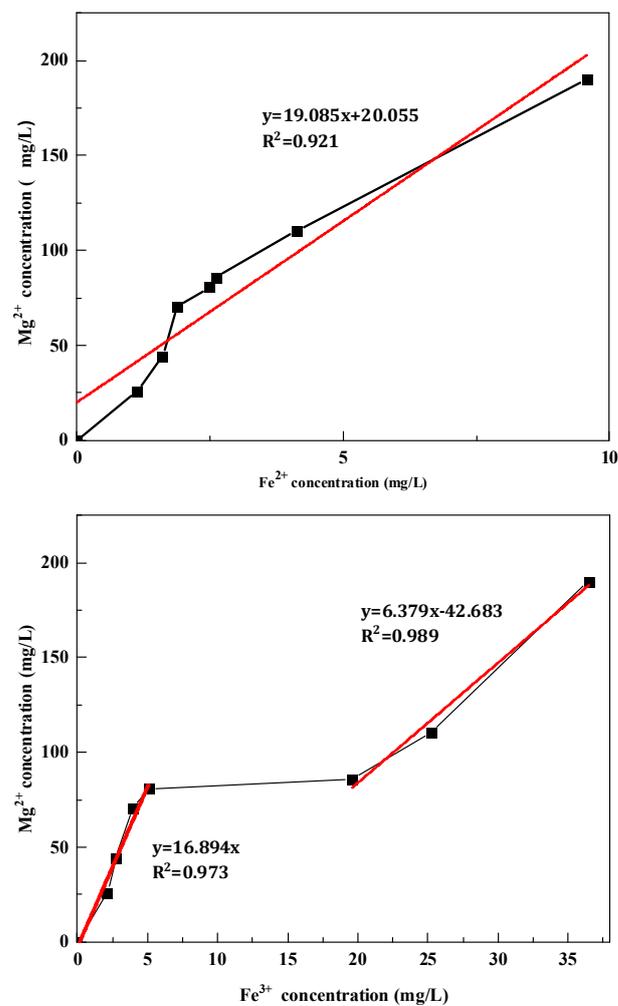
When only Fe^{2+} or Fe^{3+} exists in the solution, different mass concentrations correspond to a viscosity value; the corresponding Mg^{2+} mass concentration is obtained according to each viscosity value in Figure 3, which is called the equivalent Mg^{2+} mass concentration of the viscosity corresponding to the Fe^{2+} and Fe^{3+} mass concentrations.

Based on the equivalent Mg^{2+} mass concentration at the same viscosity obtained in Table 2, the mathematical relationship between Fe^{2+} mass concentration, Fe^{3+} mass concentration, and their relationships are established. The meaning of the slope in the mathematical relationship is the difference in the ability of Fe^{2+} and Fe^{3+} to affect viscosity relative to Mg^{2+} when the ion concentration increases.

Table 2. Fe^{2+} and Fe^{3+} mass concentration and equivalent Mg^{2+} mass concentration at the same viscosity.

Viscosity (mPa·s)	Equivalent Mg^{2+} Mass Concentration (mg/L)	Fe^{2+} Content (mg/L)	Fe^{3+} Content (mg/L)
741	0	0	0
600	25.939	1.122	2.139
550	43.732	1.613	2.732
500	70.426	1.882	3.926
450	80.664	2.481	5.066
330	85.779	2.615	19.620
250	110.510	4.130	25.217
130	190.275	9.580	36.470

It can be seen from Figure 6 that at the same viscosity, Fe^{2+} has a significantly greater impact on the viscosity of the polymer solution, and its impact is 19 times that of Mg^{2+} . The impact of Mg^{2+} on the viscosity of the polymer solution is significantly lower than that of Fe^{2+} , which is equivalent to the mass concentration of Mg^{2+} used. Much higher than the mass concentration used for Fe^{2+} , the effect of Fe^{3+} on the viscosity of the polymer solution is 6 to 16.9 times that of Mg^{2+} . By comparing the slopes, we can see the order of influence of the three ions on the viscosity of the polymer solution: $\text{Fe}^{2+} > \text{Fe}^{3+} > \text{Mg}^{2+}$.

**Figure 6.** Linear fitting results of mass concentration of Fe^{2+} and Fe^{3+} corresponding to Mg^{2+} at the same viscosity.

3.4. Effect of Cations on Viscosity Stability of Polymer Solutions

In this study, we diluted the polyacrylamide mother solution with mineralized water of a certain concentration of Na⁺, K⁺, Ca²⁺, Mg²⁺, Fe²⁺, and Fe³⁺ to prepare a polymer solution (mass concentration: 2500 mg/L), and tested the polymer solution for 0–50 days.

It can be seen from Figure 7 that the viscosity retention rate of the polymer solution configured with Na⁺ and K⁺ is more than 83% within 50 days; the viscosity retention rate of the polymer solution configured with Ca²⁺ and Mg²⁺ within 50 days is 66.4% and 62.1%. The polymer solution configured with Fe²⁺ and Fe³⁺ has a viscosity retention rate of 24.9% and 69.92% within 50 days, which has a great impact on the stability of the viscosity of the polymer solution. By comparing the viscosity retention rates, the degree of influence of different cations on the viscosity stability of the polymer solution is Fe²⁺ > Ca²⁺(Mg²⁺) > Fe³⁺ > Na⁺(K⁺).

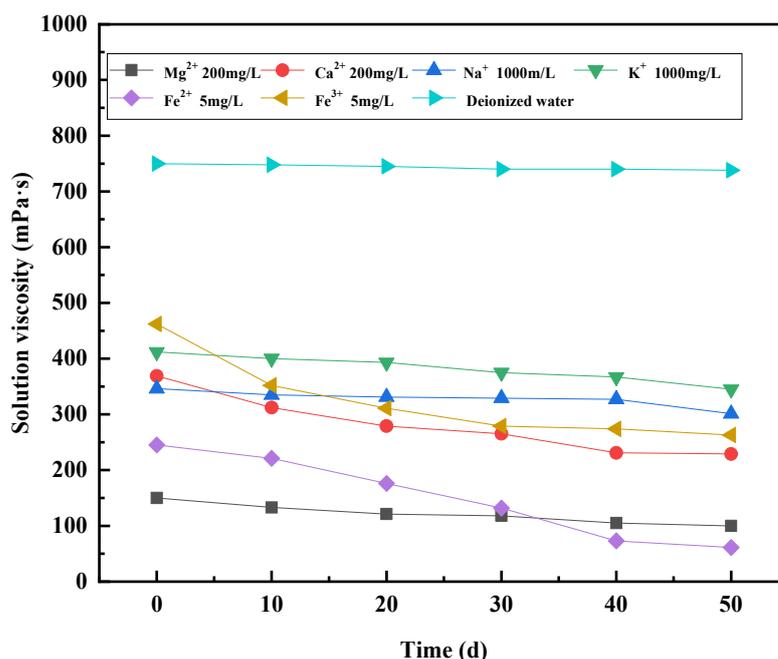


Figure 7. Relationship between polymer viscosity and cation.

Define η as the viscosity loss strength, and calculate it according to Formula (1):

$$\eta = \frac{\zeta - \zeta'}{\frac{\zeta}{\zeta_{dio}} \times t \times c} \tag{1}$$

In the formula:

- η —viscosity loss intensity, mPa·s/(mg·L⁻¹·d⁻¹);
- ζ —polymer solution viscosity, mPa·s;
- ζ' —viscosity of polymer solution after standing, mPa·s;
- ζ_{dio_dio} —viscosity of polymer solution prepared in deionized water, mPa·s;
- t —viscosity stability test time, d;
- c —Cation content in the polymer solution mg·L⁻¹.

Calculate the solution viscosity loss intensity based on the experimental results in Figure 7 and Equation (1). According to the intensity of viscosity loss, the order of the influence of cations on the viscosity stability of the polymer solution can be obtained.

It can be seen from Table 3 that the order of influence of different cations on the viscosity stability of the polymer solution is Fe²⁺ > Ca²⁺ (Mg²⁺) > Fe³⁺ > Na⁺ (K⁺). Under experimental oilfield wastewater conditions, the viscosity of polymer solution is less affected by trivalent cations and monovalent cations, and the greatest impact is made by divalent cations.

Table 3. The result of viscosity loss intensity on cation.

Ion Type	η' (mPa·s/(mg·L ⁻¹ ·d ⁻¹))	Ion Type	η' (mPa·s/(mg·L ⁻¹ ·d ⁻¹))
Na ⁺	1.5~7.6	Fe ²⁺	82.4~152.1
Ca ²⁺	19.2~100.8	Fe ³⁺	42.5~60.4
Mg ²⁺	27.06~110.5	K ⁺	0.029~8.2

4. Conclusions

(1) The effects of various cations (including Na⁺, K⁺, Ca²⁺, Mg²⁺, Fe²⁺, and Fe³⁺) on the viscosity changes of polymer solutions were studied. The study found that different cations have different effects on the viscosity of the polymer solution, and their presence leads to a decrease in the viscosity of the polymer solution. As the concentration of cations increases, the viscosity reduction effect shows a downward trend, which indicates that the concentration of cations has a certain impact on viscosity changes.

(2) Fe²⁺ have the most serious impact on the viscosity of polymer solutions because they trigger oxidative degradation by producing highly reactive oxidants, combine with the polymer surface to weaken molecular repulsion, and accelerate free radical reactions to break molecular chains.

(3) The order of their viscosity reducing effect is the following: Fe²⁺ > Ca²⁺(Mg²⁺) > Fe³⁺ > Na⁺(K⁺). Concerning the effect of viscosity stability in time the order of influence of different cations is the following: Fe²⁺ > Fe³⁺ > Mg²⁺ > Ca²⁺ > Na⁺ > K⁺.

Author Contributions: J.H. and M.F. designed this experiment; J.H. performed a series of experiments; M.L. performed evaluation test experiments; S.N. collated the experimental data; L.H. and Y.L. were responsible for supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Minxuan Li was employed by the company CNOOC China Limited Hainan Branch. Author Shuai Ni was employed by the company Qinghai Oilfield Branch Exploration and Development Research Institute. Author Lijuan Hou was employed by the company PetroChina Qinghai Oilfield Branch No.1 Oil Production Plant. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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