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Original Paper

Experimental study of dehydration performance of re-crosslinkable preformed particle gel during extruding through an open fracture

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ABSTRACT

Re-crosslinkable preformed particle gel (RPPG) has been considered to be one of the most promising gels for dealing with fracture and void space conduit (VSC) conformance problems. However, the dehydration of RPPG during its propagation in the fracture-type features and its effect on gel properties remains unclear. This paper investigates the dehydration behavior during RPPG propagating in an open fracture using matrix-free fracture model. Then the results were verified using real fractured sandstone core model. Moreover, the gel properties after extruding a fracture were studied in detail including gel dehydration and gel strength. Results reveal that the RPPG properties changed significantly with increasing propagation distance, which correlated with the gel injection rate. At high gel injection rates, the dehydration and gel strength (G') decrease with increasing propagation distance.

In contrast, the opposite result was found at low injection rates. Based on the study of the different gel injection rates, it is found that dehydration time is another key factor affecting dehydration behavior. Results also indicate that the fracture width affects gel dehydration at different locations. Dehydration was more pronounced at narrow fractures but only in the inlet section, while in the outlet section, RPPG contains more water than the initial condition. This study has profound implications for field applications. It provides new insights into the transport of RPPG in fractures and helps field engineers to optimize the gel injection operations.

1. Introduction

The open fracture or fracture-like features and void space conduit (VSC) existing in many mature oilfields are the most challenging conformance control problems (Peirce et al., 2014; Targac et al., 2020). Although only taking up a small percentage of fluid injected into a reservoir, these high-conductivity regions within the reservoir are quite effective at capturing injected water or gas. In most water or gas drive recovery, injected fluids are likely to channel through the fracture or fracture-like features resulting in early water/gas breakthrough and excess water/gas production (Imqam et al., 2016; Seright, 1995). A large portion of driving material bypasses oil-rich unswept zones/areas, leaving significant oil volumes of oil behind (Imqam et al., 2016).

Studies have shown that gel treatment has a distinct advantage for fracture-type and VSC conformance problems (Seright, 1995). Due to its selective penetration properties, the injected gel can effectively migrate through the target zone. Thereby, the unwanted void space can be plugged in, and the water permeability of the plugging zone is significantly reduced. Currently, two types of commercial gels are available for conformance control: in-situ gels and preformed particle gels (PPGs) (Bai et al., 2015). The in-situ gels are aqueous gels containing a high molecular weight polymer and a crosslinking agent. After pumping into the target formation, the mixture can gel and form a bulk gel to plug the fracture. PPGs are granular gels that can absorb water and swell up to 200 times their original volume (Bai et al., 2007a). Since PPG becomes softer after absorbing water and has strong deformability, it can pass through apertures several times smaller than its diameter (Bai et al., 2007b). Compared to in-situ gel, PPG is not sensitive to the reservoir condition, such as salinity, temperature, pH, hydrogen sulfide, etc (Zhang and Bai, 2011). Nowadays, various PPG derivatives have been developed and evaluated, such as mm-

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sized gel (Bai et al., 2007a), micro gel (Zhao and Bai, 2022), nano gel (Liu et al., 2022), degradable gel (Zhao et al., 2021), and so on.

However, the plugging performance of PPG in large-scale fracture is not very efficient. In the West Sak field, evidence has shown that the most failed VSC treatments were due to the sand and PPG production (Targac et al., 2020). In addition, laboratory experiments confirmed that after the water breakthrough, the PPG is likely to be washed out and no longer provide sufficient water resistance (Wang and Bai, 2018). Thus, many companies established gel development as a high priority (Targac et al., 2020). Re-crosslinkable or re-assembling preformed particle gel (RPPG) was then developed (Pu et al., 2019). One of the advantages of RPPG is that each particle can re-crosslink together and form a bulk gel to enhance the gel strength and plugging efficiency further (Pu et al., 2019). In addition, the RPPG inherits the advantages of the PPG, such as swelling capability, selective penetration, and deformability (Ahdaya et al., 2022; Pu et al., 2019; Wang et al., 2019b). ConocoPhillips has been using RPPG on the West Sak field since 2017 for VSC problems, and overall, the RPPG treatments have shown a 23% improvement over traditional PPG products (Targac et al., 2020). Fig. 1 shows the commercial RPPG and its swelling process in lab conditions.

Studies have shown that gel placement in fracture should be easy to achieve because the fracture permeability is usually 10^3–10^6 higher than rock matrix (Seright, 1995). However, gel dehydration during propagating through a fracture significantly affects its plugging performance. Due to the pressure difference between the rock matrix and fracture, the gel may lose water towards the reservoir and cause damage (Seright, 1999; Zhao and Bai, 2022). Besides that, due to the pressure difference along the injection direction, the carrying fluid moves ahead of the gel through the fracture. At the same time, the particles are left behind, resulting in the gel being heavily concentrated at the inlet section but leaving the far way area unplugged (Seright, 1999; Wang et al., 2019a). In both conditions, the gel properties and plugging performance could be seriously affected due to the water content changes in the polymer grid structure. Therefore, understanding the gel propagate behavior is critical to fully utilizing the RPPG plugging performance and optimizing the field operation design.

At present, many types of research on gel propagation behavior have been carried out one after another. Seright (1995, 1997, 1999, 2003) extensively investigated the effects of fracture width, fracture conductivity, and gel injection rate on preformed Cr(III)-acetate-HPAM bulk gel. He found that the gel wash-out problem could be improved by increasing the gel concentration and decreasing the fracture width and injection rate. Researchers at the University of Kansas also conducted many experiments using sand pack, fracture model, and tubing to analyze how the water channel breaks into the gel (Al-Anazi and Sharma, 2002; Ganguly et al., 2002; McCool et al., 2009). However, the mainstream fracture model contains a rock matrix, and many studies have attributed the gel propagation behavior to leak-off or longitudinal dehydration in general (Zhao and Bai, 2022). However, few studies have isolated the matrix leak-off and longitudinal dehydration.

This paper demonstrates RPPG dehydration and how it affects gel properties. Single fracture models were used to study the gel injection rate and width effect on the gel dehydration behavior and changes of the gel properties along the fracture. In addition, fracture-matrix flow experiments justified the effect of gel injection rate results mentioned above. The gel retention was measured and can provide field engineers with another perspective to understand the gel propagation through a fracture.

2. Experimental section

2.1. Material

This study used dry millimeter-sized (1–2 mm) re-crosslinkable preformed particle gels (RPPG). Dry RPPG particles were white, translucent, swellable particles (Pu et al., 2019). Its apparent density was around 1.35 g/cm^3. Because of a large number of hydrophilic functional groups, RPPG particles can swell up to 40 times their original volume after being placed in brine. Before usage, dry RPPG particles were swelled in 1% NaCl brine to achieve a pre-determined swelling ratio. Different swelling ratios were obtained by adjusting the amount of feeding brine.

2.2. Fracture model

A matrix-free fracture model was used for the core flooding test, which consists of two half cores with two stainless steel strips at the edge supporting it. The surface were sealed with epoxy. One of the stainless-steel strips was cut off to leave multiple available open spaces. Instead, three pressure sensors were placed right above the spaces to obtain the fracture pressure distribution data. The fracture length is 27 cm, and the spacing between each pressure sensor is around 6.7 cm. Thereby, the fracture is

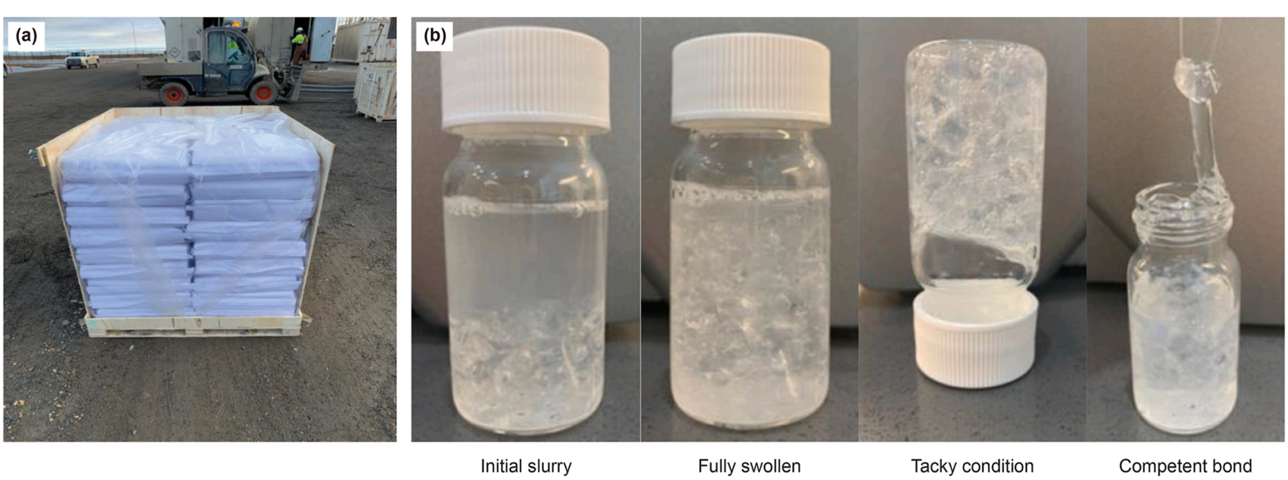

Fig. 1. Bagged RPPG product (**a**) and laboratory recrosslinking process (**b**) (Targac et al., 2020).

separated into four equal sections, and RPPG properties can be investigated with actual pressure data and distance. There is another pressure sensor in the injection tubing, which is 8 cm away from the fracture. The fracture model is placed in a core holder within a confining sleeve, which applies a pressure of 500 psi higher than the fracture system to prevent leakage. The fracture model and pressure sensor arrangement are shown in Fig. 2.

The current mainstream of fracture models has available matrices to fit the practical application scenarios (Alhuraishawy et al., 2017; Wang et al., 2019a; Zhao and Bai, 2022). However, this poses an unavoidable problem: the inability to quantitatively distinguish between matrix leak-off and dehydration along the flowing direction.

When hydrogel is facing pressure difference, absorbed water in the molecular grid of swelling gel will be re-released (Seright, 1995). Numerous studies have shown that part of the water could invade the matrix or travel ahead of the gel (Seright, 1998). The former brings matrix damage; the latter causes component separation (Seright, 1998). If there is severe component separation, the gel will be heavily concentrated at the injection end and unable to plug the far way area, resulting in inefficient in-depth plugging performance (Seright, 1999). Therefore, it is necessary to investigate longitudinal dehydration individually. It helps field engineers to estimate how far the gel can transport through the target formation. But under laboratory conditions, the presence of a matrix seriously interferes with experimental results due to the leak-off effect. In addition, it is nearly impossible to get repeatale data since gels should be manually collected from different rock surfaces (Fig. 3). Based on the above considerations, we applied a epoxy coating layer onto the fracture surface to prevent leak-off effect. In Exps. 1–6, there is no matrix and the gel flowing mechanism can be regarded as extruding through a parallel plate model. One may concerned that it may affect the results. So, we also performed more experiments (Exps. 7–9) without coating to verify if the results are still consistent. The fracture-matrix flow model has a similar assembled design but only has one pressure sensor at the inlet tubing. Table 1 shows the key parameters of fracture and RPPG. All experiments were conducted at 45 °C (113 °F).

2.3. Experimental method

The dehydration of RPPG directly affects its properties, such as gel strength, actual swelling ratio, and retention (Wang et al., 2019a). Investigating the actual properties of RPPG after propagating through a fracture, and not limited to bottle tests, is critical to field applications. To achieve that goal, re-crosslinked RPPG samples were collected from fracture and cut into four equal parts. Then the properties of each sample were measured individually. Detailed procedures are listed below.

2.3.1. RPPG preparation and injection

Dry RPPG particles were placed into 1% NaCl brine to swell. The swelling ratio is the total RPPG mixture weight divided by dry RPPG particle weight. It can be controlled by adjusting the amount of brine. When RPPG was fully swollen (no free water) (Targac et al., 2020), they were transferred into an accumulator. RPPG was pumped into the fracture by the piston inside the accumulator. When the injection pressure was stable, the core holder was shut in for 48 h (Pu et al., 2019) to ensure the RPPG particles were re-crosslinked into a bulk gel. The swelling ratio (SR) is defined by Eq. (1).

$$SR = \frac{m_{\mathrm{tg}}}{m_{\mathrm{dp}}} \tag{1}$$

where SR is the swelling ratio; m_{tg} is the total gel weight; m_{dp} is the dry particle weight.

2.3.2. RPPG collection and weight measurement

After 48 h of re-crosslinking, the fracture was re-opened, and RPPG bulk gel was collected from the fracture surface. Then the bulk gel was cut into four equal parts based on the pressure sensors' location and carefully transferred on pre-cleaned glass slips to measure the weight. Fig. 3 shows the RPPG collection.

2.3.3. Rheology measurement

The HAAKE Mars Rheometer III was used to measure the elastic modulus (G'). Plate P35 Ti L S was used as the spin. The gap was 1 mm; the frequency was 1 Hz; τ was 10 Pa; the duration was 300 s. Each RPPG sample was tested three times to reduce the error.

After the rheology test, RPPG samples were transferred to the original glass slips and put into an 80 °C oven. After two days, all water was vaporized, and only RPPG chemical components (or solid content) were left on the glass slips. Then the dry weight of RPPG was measured. Fig. 3(d) shows the dry RPPG samples.

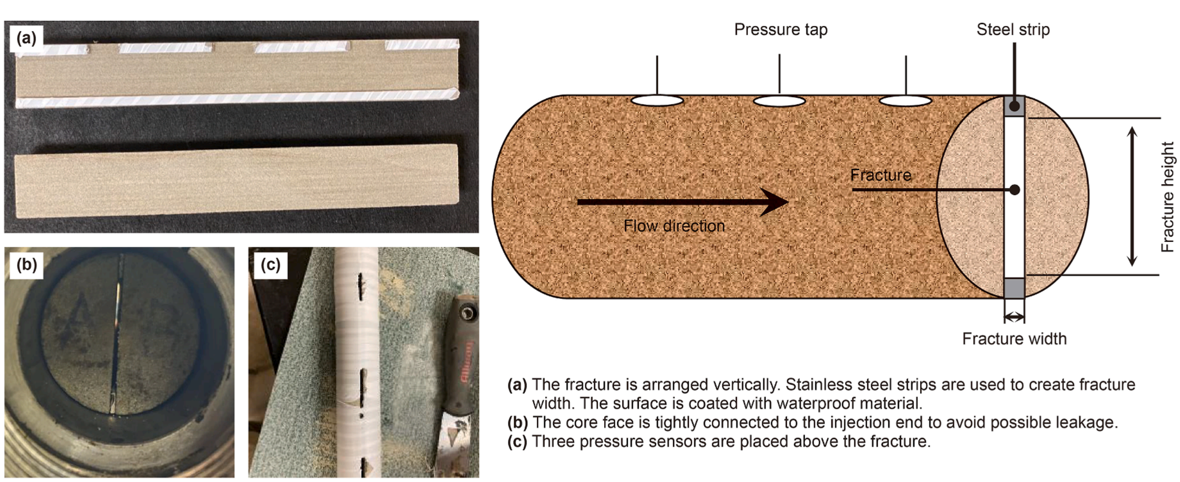

Fig. 2. Open fracture model with pressure tap along fracture.

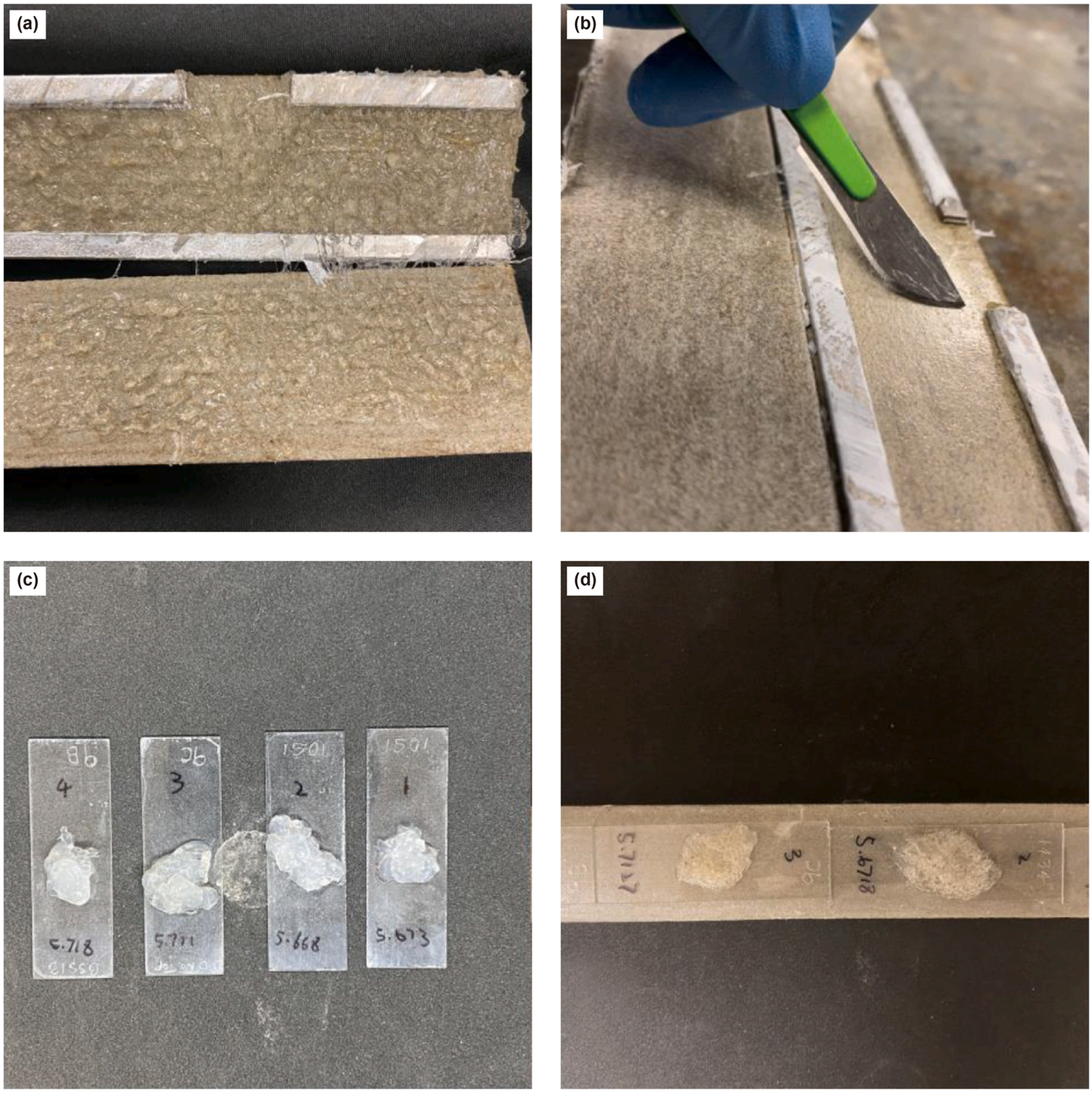

Fig. 3. (**a**) Re-open the fracture. (**b**) Collect and separate the RPPG samples carefully using a surgical scalpel. (**c**) Measure the weight. (**d**) Dry out the RPPG samples and measure the dry weight.

Table 1
Key parameters of experimental design.

Exp. No.	Injection rate, cm^3/min	Fracture width, mm	Swelling ratio	Swelled particle diameter, mm	Average ratio of swelled particle diameter to fracture width	Matrix permeability, mD
1	5	1.77	10	2.15–4.30	1.80	NA
2	2	1.77	10	2.15–4.30	1.80	NA
3	1	1.77	10	2.15–4.30	1.80	NA
4	2	1.00	16	2.52–5.04	3.78	NA
5	2	1.77	16	2.52–5.04	2.14	NA
6	2	3.30	16	2.52–5.04	0.65	NA
7	0.5	1.77	16	2.52–5.04	2.14	219
8	2	1.77	16	2.52–5.04	2.14	203
9	5	1.77	16	2.52–5.04	2.14	234

2.3.4. Dehydration calculation

Dehydration represents the weight of water loss ratio of RPPG as it propagates through the fracture. It was calculated by using Eqs. (2) and (3).

$$D = \frac{SR_{\mathrm{i}} - SR_{\mathrm{a}}}{SR_{\mathrm{i}}} \times 100\% \tag{2}$$

$$SR_a = \frac{m_{cg}}{m_{dRPPG}} \quad (3)$$

where D is the dehydration; SR_i is the swelling ratio of initial RPPG; SR_a is the swelling ratio of the collected gel sample; m_{cg} is the weight of collected gel sample; m_{dRPPG} is the dry weight of RPPG.

3. Results and discussion

3.1. Demonstration of dehydration

In Exp. 1, we injected 80 cm^3 of RPPG (the pipeline volume has been subtracted from the injection volume) into the fracture. The injection rate was 5 cm^3/min, equivalent to 475 ft/day. Considering the fracture volume of 13.38 cm^3, a total of 6.35 FV (fracture volume) of RPPG was injected into the fracture. Based on Fig. 5, the fracture pressure reached to be stable with the pressures of 45, 27, 22, and 7 psi from the inlet to the outlet of the core (p1–p4), respectively. We observed that the first thing that came out of the outlet was not RPPG particles but a very viscous liquid, as shown in Fig. 4(a). The injection pressure for each section increased slowly after 10 min (3.74 FV RPPG injected). It is because the RPPG can recrosslink during the injection process, which causes the gel properties to keep changing while propagating through a fracture. Thus, compared to other traditional gel injection, there is no typical “stable stage” for RPPG injection.

During the injection, a total of 60 cm^3 of RPPG were produced, including 3 cm^3 viscous fluid and 57 cm^3 swollen RPPG. Compared with injected RPPG and fracture volume mentioned above, there is substantial volume compression of RPPG in the fracture. In addition, the water compression is negligible, combined with the fluid production at the outlet. We believe that there is non-negligible dehydration of RPPG. The volume reduction due to the dehydration of RPPG leads to a delay in transport. Therefore, the transport delay is also caused by longitudinal dehydration, even in the absence of the matrix. Also, due to the water content change in the grid structure of RPPG, the corresponding gel properties are changed.

Fig. 6 shows the G' (elastic modulus) changes of RPPG along the fracture. The higher G', the higher the gel strength and the better the plugging performance (Imqam et al., 2016). Fig. 6 shows the actual G' of four re-crosslinked RPPG samples from the fracture. In most studies, the gel strength is measured by bottle tests, which is the gel strength in static conditions. We found that after propagating through a fracture, the gel strength of RPPG is higher than the initial RPPG. As shown in Fig. 6, the gel strength within the fracture decreased with the distance reduced by 14% at 24 cm (or 9.4 in). This information is critical to field applications but cannot be obtained from bottle tests. Under actual formation conditions, the change in gel strength would be more severe due to the longer distances and the matrix effects (leak-off). Therefore, the actual gel strength could be higher than the value we obtained from the laboratory test and the gel strength reduction could also be more significant. One possible consequence is that the gel strength at the far way location could be less than near the wellbore and the injected water will most likely break into the far way plugging zone, resulting in a compromised plugging performance. This finding indicates that gel strength is not the only indicator of gel

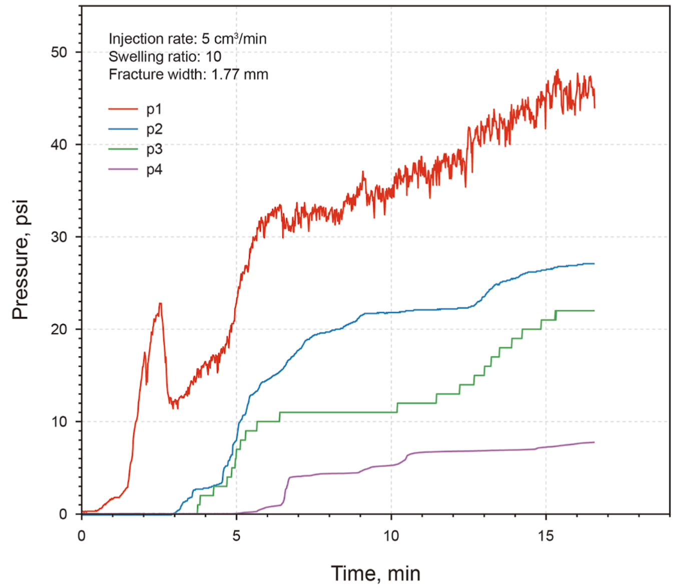

Fig. 5. RPPG injection pressure of each section.

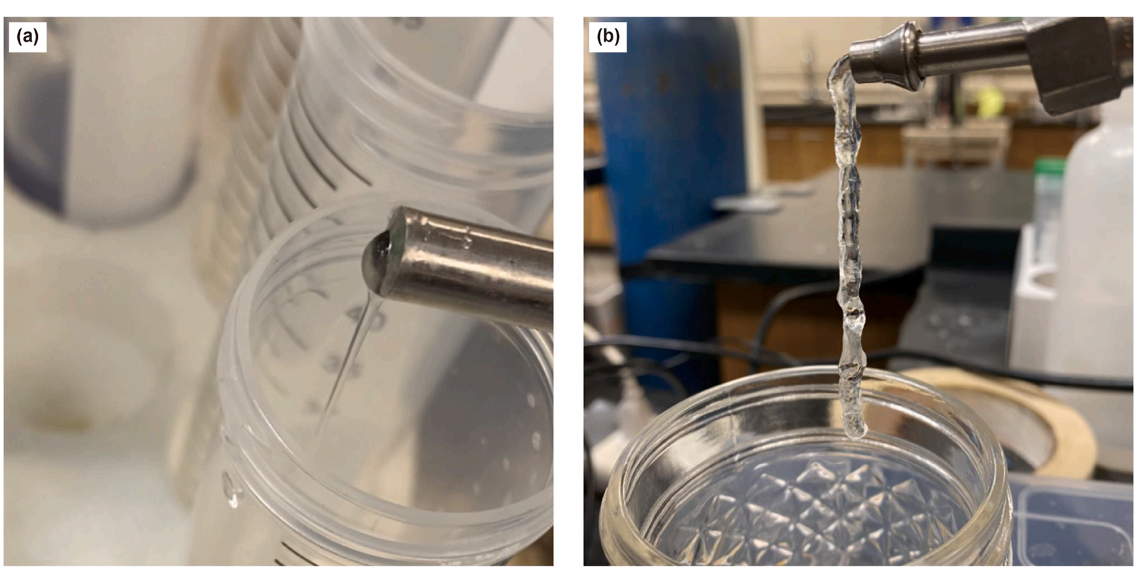

Fig. 4. (**a**) Viscous fluid was produced after 1.2 FV was injected. (**b**) RPPG produced after 2.6 FV injected.

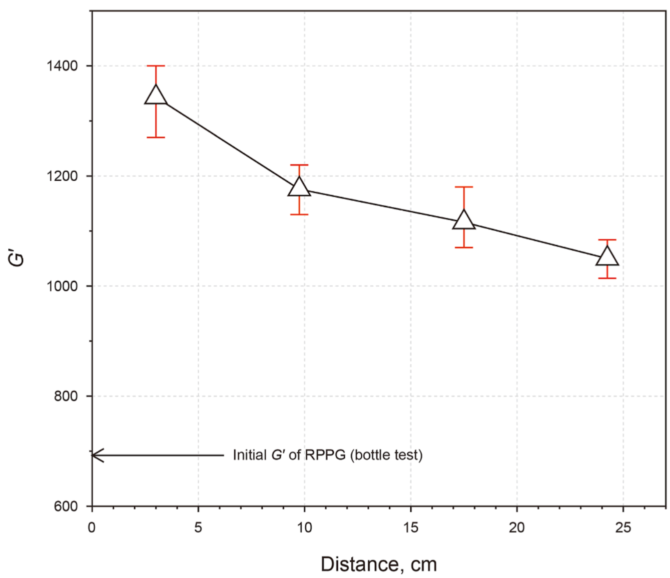

Fig. 6. Rheology test result of RPPG sample from each section.

evaluation; the gel strength stability as it propagates through the fracture is crucial for field applications.

Many studies have shown that the swelling ratio or the gel concentration directly affects the strength of the gel (Imqam et al., 2015; Pu et al., 2019; Zhao and Bai, 2022). It is found that the more water content, the softer and the lower the gel strength. We calculated the dehydration of each RPPG sample to verify if dehydration is consistent with gel strength changes. As shown in Fig. 7, all RPPG samples were dehydrated, and the value decreased from 14.8% to 8.2% along the fracture. It revealed that the RPPG at the far way contains more water resulting in lower gel strength. Besides that, another notable consequence of the dehydration was that the gel transport distance did not correlate linearly with the volume injected (Zhao and Bai, 2022). During the gel injection process, the RPPG was not produced at the outlet at 1.0 FV but at 1.3 FV. It indicates that the gel transport was delayed. This phenomenon is also frequently observed when Seright evaluated performed bulk gels transport through fractures, which was considered as the attribution to dehydration (Ganguly et al., 2002).

Seright found similar results on preformed Cr(III)-acetate-HPAM bulk gel (Seright, 1999). In his experiment, the gel at the inlet section contained 22 times the HPAM concentration and 39 times the chromium concentration of the original gel. Convert to the dehydration, HPAM has 95%, and chromium has 97% dehydration at the inlet surface. With such huge water content loss, the gel stopped propagation at 25% of the fracture length with 43 FV gel injected. Fig. 8 illustrates the component concentration change for RPPG and Cr(III)-acetate-HPAM (Cr(III) and HPAM concentration are combined) bulk gel. RPPG has an initial concentration of 10%, and Cr(III)-acetate-HPAM bulk gel has an initial concentration of 0.5417%. The comparison results show that RPPG can maintain a stable chemical content when transported in the fracture. Another interesting phenomenon is that the dehydration for both RPPG and Cr(III)-acetate-HPAM gel increased in the middle along the fracture and then decreased. Currently, there is no published or proven explanation for that. We believe it may be caused by the water dehydrated from the previous section absorbed by the following section. However, the gel rheology data does not support that because the G' keep decreasing along the fracture. Another additional theory is that re-absorbed water cannot or has a limited effect on the gel strength.

One may ask, where does the water go? To answer that question, we measured the effluent properties. Effluent here refers to the total produced material, including the viscous fluid and the RPPG. Unlike the RPPG inside the fracture, the overall effluent dehydration value is negative 1.6%. Therefore, the effluent is hydrated, not dehydrated, and the excess water is produced to the effluent. Also, the G' of effluent was 1036, which is lower than RPPG within the fracture. Note that the injection process stopped after the pressure was stable, and the water loss in the fracture also stabilized; in other words, no more water was lost at this time. Then it is conceivable that if the injection process is stopped not at the pressure stabilization but for the first production, the distal RPPG will contain more water like the effluent in this experiment, and the gel strength will be lower than the experimental results.

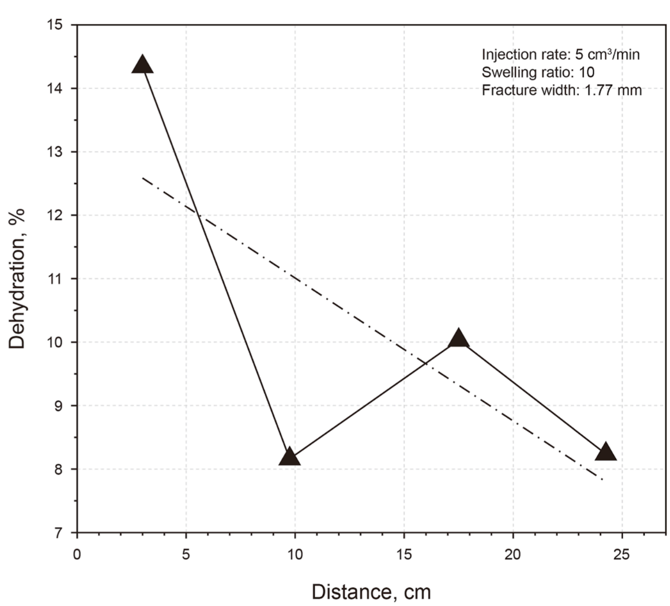

Fig. 7. Dehydration of RPPG samples.

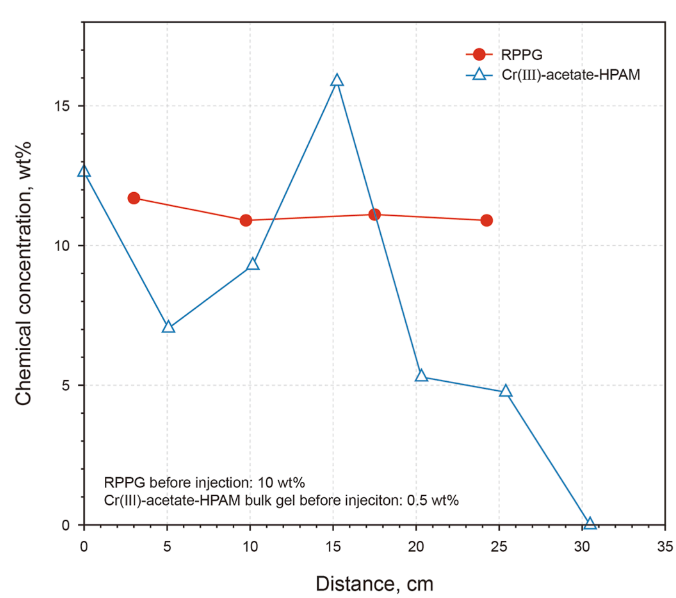

Fig. 8. Comparision of RPPG and Cr(III)-acetate-HPAM bulk gel.

Moreover, the viscous fluid cannot re-crosslink, but the following produced RPPG successfully recrosslinked. This finding is significant for field applications. To fully utilize the plugging performance of RPPG, a substantial volume is necessary for a field operation. Otherwise, the bulk gel cannot be formed at the far-way target formation, and thus the treatment fails. In summary, we found non-negligible longitudinal dehydration and change in RPPG properties.

3.2. Gel injection rate effect on dehydration behavior

More experiments were performed with different injection rates to further investigate the longitudinal dehydration behavior. Swelled RPPG (swelling ratio: 10) was injected into the matrix-free fracture model until the injection pressure was stable. Fig. 9 demonstrates the stable injection pressure lengthwise of the fracture (Exps. 1, 2, and 3). When the injection rate is 1 cm^3/min (95 ft/day), the stable pressure drops from 112 to 50 psi along the fracture. However, when the injection rate increases by a factor of 2 and 5 (2 and 5 cm^3/min), the stable pressure decreases in turn. 5 cm^3/min has the lowest stable pressure, from 45 to 7 psi along the fracture. The results of this experiment were astonishing.

For commercial PPG or in-situ gel, numerous experiments have shown that the low injection rate usually leads to a low-pressure or high resistance factor (Imqam et al., 2015; Seright, 1999; Zhang and Bai, 2011). Since there is no related research on RPPG, we could not correlate our results to others. We performed rheology tests to further investigate this phenomenon. Fig. 10 shows that under a low gel injection rate, the G' is 2293 Pa at the inlet section and increased to 3323 Pa at the outlet section. In contrast, the gel strength does not change much under a higher gel injection rate. Overall, the gel strength decreases with the gel injection rate increases. It partially explains the reverse relationship between stable injection pressure and gel injection rate because a higher pressure is required to push more robust material through the fracture.

Then we calculated the dehydration of each RPPG sample to investigate if the results were due to the water content change. As shown in Fig. 11, the RPPG dehydration at 1 cm^3/min increased along the fracture from 25.6% in the inlet section to 34% in the outlet section. The trend was reversed when 5 cm^3/min was used to inject RPPG. The dehydration decreased from 14% to 8% along the fracture.

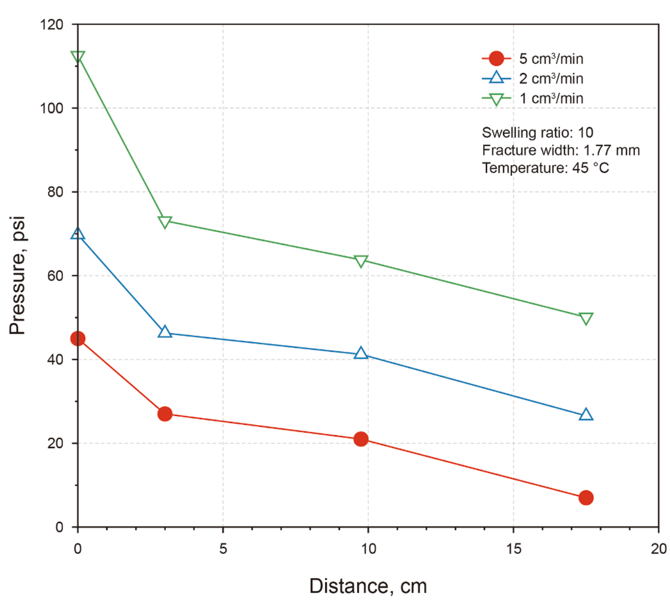

Fig. 9. Effect of gel injection rate on stable injection pressure.

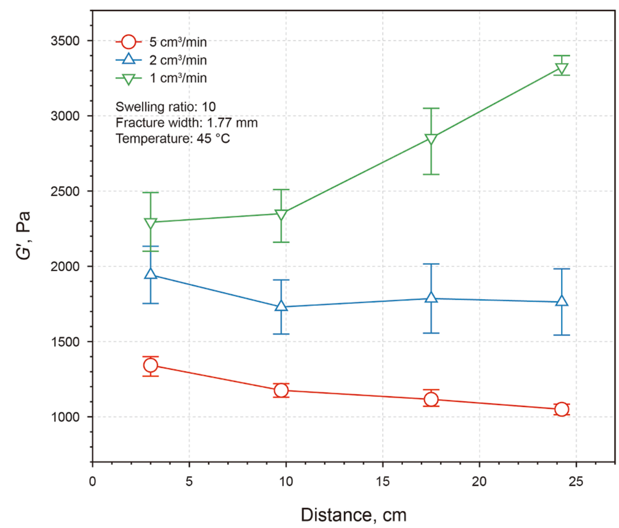

Fig. 10. Effect of gel injection rate on gel strength.

Both dehydration and rheology results indicate that under a low gel injection rate, RPPG lost more water content, and the gel strength was more significant at the far way under lower pressure. It very conflicts with our previous observation in Exp. 1. There must be another factor rather than the pressure affecting the RPPG dehydration. Evidence continues to point to the gel propagation duration. Table 2 shows the gel breakthrough information. When the first RPPG particle was produced from the outlet, we recorded the volume injected and the gel breakthrough time. It took 48 min for the RPPG to break through the fracture at an injection rate of 1 cm^3/min, and 20 and 8 min at injection rates of 2 and 5 cm^3/min, respectively. Relating this to gel propagation, when the first RPPG particles entered the fracture, this part was always ahead of the gel pack within the fracture. In other words, the gel in the outlet section stayed longer time in the fracture than the part in the inlet section. Therefore, the dehydration time of the gel front was always longer than the subsequently injected RPPG. In this case,

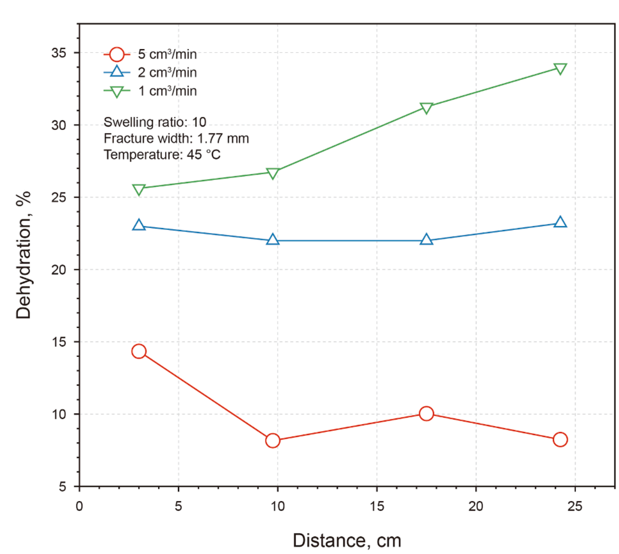

Fig. 11. Effect of gel injection rate on dehydration.

Table 2
RPPG breakthrough time.

Injection rate, cm^3/min	RPPG breakthrough time, min	The volume injected when RPPG breakthrough, cm^3	Pressure gradient at RPPG breakthrough, psi/ft	Does the effluent contains viscous fluid
1	48	48	120	No
2	20	40	43	Yes
5	7	35	36	Yes

RPPG was dehydrated more at a distant location under the long-time effect. However, the time effect was not pronounced when the injection rate was too high because the RPPG passed through the fracture too fast to reflect the time effect. As a result, the pressure effect dominates the dehydration behavior in a high gel injection rate condition, while the dehydration duration effect dominates in a low gel injection rate. This conclusion could be crucial in field applications. For example, a lower gel injection rate should be applied for a production well treatment to emphasize the effect of dehydration duration, resulting in a stronger distant RPPG.

Moreover, the re-crosslinking time may also play a significant role in that phenomenon. Studies have shown that the RPPG particles can be partially re-crosslinked in 30 min(Pu et al., 2019). When the particles' interfaces disappear, the placement mechanism changes from particle gel injection to preformed gel injection, which is totally different. That even make the situation more complex. Therefore, quantitatively studying the interrelationship between time and pressure requires more core flooding results and numerical analysis.

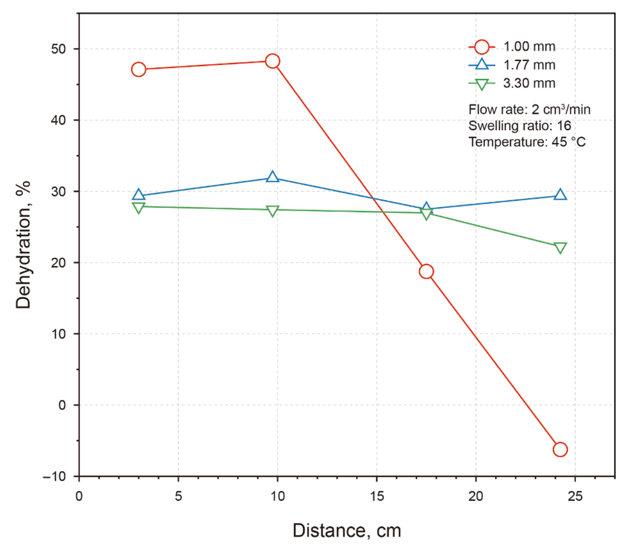

Fig. 13. Effect of fracture width on dehydration.

3.3. Fracture width effect on dehydration behavior

More experiments were performed to investigate if dehydration is more pronounced in a narrower fracture. We examined the effect of fracture width on stable injection pressure, gel strength, and dehydration. In Exps. 4, 5, and 6, the fracture width was adjusted from 1.00, 1.77 to 3.00 mm, and the FPR (fracture particle ratio: fracture width divided by swelled particle diameter) is from 3.78, 2.14 to 0.65, respectively. All other conditions remained the same, including gel properties, experimental procedures, and propagation time. The results are shown in Figs. 12–14.

We observed a higher stable pressure in a narrower fracture from gel injection results. In narrower fractures, the pressure at the inlet section is significantly higher than at the outlet section, while the pressure distribution is flatter in wider fractures. Similar conclusions can be found in many gel studies (Seright, 1999; Wang et al., 2019a; Zhang and Bai, 2011). It indicates that more pressure is needed for RPPG particles to extrude into the narrow fracture. In a narrow fracture, RPPG dehydration was much more at the inlet section and dropped dramatically at the outlet section. However, it should be noted that in the outlet section, the dehydration is even

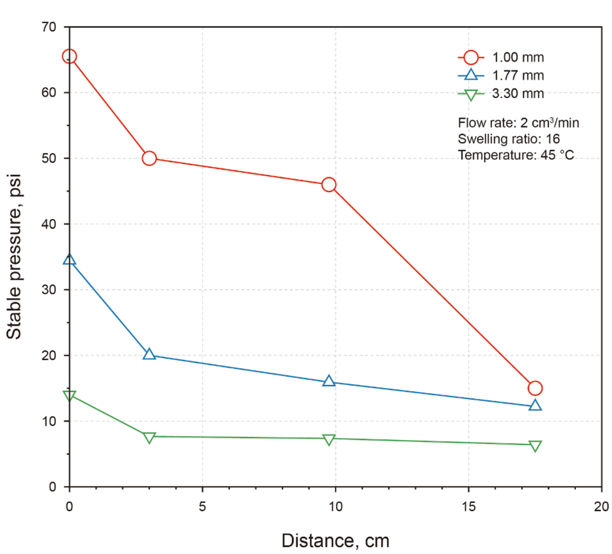

Fig. 12. Effect of fracture width on stable gel injection pressure.

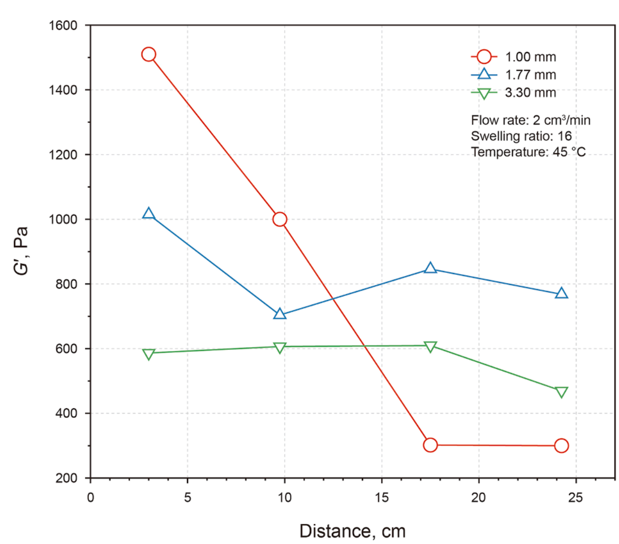

Fig. 14. Effect of fracture width on gel strength.

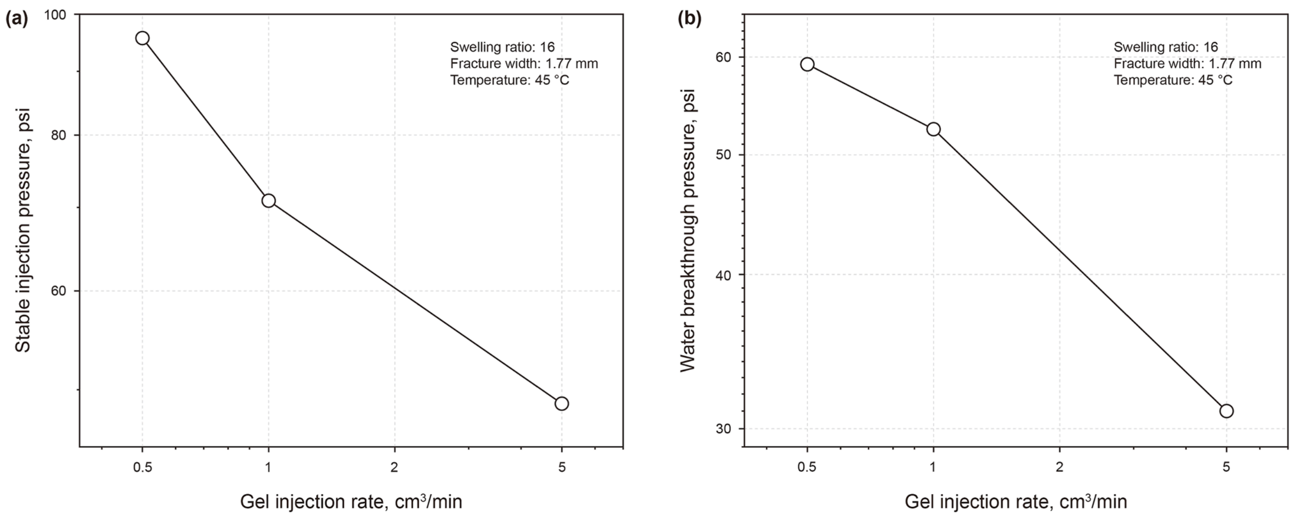

Fig. 15. Effect of gel injection rate on stable injection pressure **(a)** and water breakthrough pressure **(b)** in coreflooding with rock matrix.

less than that in a wider fracture. Why is that? Because the RPPG at a distant location is not only dehydrated but also hydrated simultaneously. The outlet section contains the liquid content dehydrated from the inlet section. Since the dehydration at the inlet is too significant, the liquid content at the outlet section could be more than expected. Such a phenomenon could lead to a softer gel at the outlet. The G' results confirmed that conjecture. For a narrow fracture, the gel strength in the inlet section is much higher than that in the outlet section, and the gel strength in the outlet section is lower than that in a wider fracture.

3.4. Coreflooding with a matrix-fracture model

We performed more experiments with rock matrices to confirm whether the results were due to the experimental conditions. Fig. 15 shows the results of Exps. 7, 8, and 9. We remained other conditions the same but increased the injection rate. Consistent with the previous conclusion, the stable pressure decreases with increasing gel injection rate. Due to the difficulties of collecting RPPG from the sandstone surface, we performed a water breakthrough pressure test to reflect the gel strength. After RPPG was re-crosslinked, 1% NaCl brine was injected into the RPPG-treated core. The water injection pressure was manually increased by 5 psi per 3 min until the water broke through the fracture. Fig. 15(b) shows that when the gel injection rate increased from 0.5, 1 to 5 cm^3/min, the breakthrough pressure decreased from 59, 52 to 31 psi, respectively. Consistent with the previous experiment, the RPPG plugging performance improved, meaning the gel strength is higher under the low gel injection rate. According to the previous study, matrix leak-off leads to a gel cake layer covering the matrix surface. Such gel cake prevents further dehydration towards the matrix because the cake itself is a highly dehydrated gel and is less “permeable” (Seright, 2001). Therefore, the effect of leak-off is limited after a long time injection process.

Hydrogels inevitably lose a certain amount of water after extruding a narrow fracture. This dehydration phenomenon was thought by someone to only have a negative effect in the past because of the damage it would bring to the formation. However, recent studies have found that dehydration also increases the strength of the gel and thus the plugging performance. This study reveals dehydration behavior of particle gel is more stable than conventional preformed bulk gel systems. One of the advantages of particle gel systems is that the chemical components are constrained in the particles rather than in the flowing solution. Therefore, the damage of particle gel to the formation is limited, but the strength is increased after extruding a fracture.

4. Conclusions

A fracture model without matrices was utilized to investigate the dehydration of RPPG propagated through a fracture. Sandstone fractured cores were used to verify that the result was valid in the presence of the matrix. The RPPG strength inside the fracture, dehydration behavior, and retention were studied. The following conclusions can be reached.

(1) The dehydration is non-negligible and affects the RPPG properties.
(2) The stable gel injection pressure decreases as the gel injection rate increases.
(3) Besides the pressure, the RPPG dehydration duration is also significant to the dehydration behavior. The time effect is more pronounced, especially since the injection rate is low.
(4) Same with other types of gel, the retention decreases from the inlet to the outlet. A higher gel injection rate causes such reduction to be more severe.
(5) The lower gel injection rate results in some improvement in plugging performance.

CRediT authorship contribution statement

Shu-Da Zhao: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Baojun Bai:** Writing – review & editing, Validation, Supervision, Software, Project administration, Investigation, Funding acquisition. **Thomas Schuman:** Validation, Supervision, Resources, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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