1. INTRODUCTION

Multistage hydraulic fracturing is used in horizontal wells to increase the production of tight oil. Fracturing fluids are used in hydraulic fracturing to ensure proppants are suspended, but fluid residuals can cause formation damage and reduce rock permeability; meanwhile, fracture conductivity can be further reduced due to the flowback of proppants during the early stage of production. In this study, steel plates and hydraulically fractured reservoir rocks are tested in a modified API cell to understand the impacts of flowback rate, fracturing fluid, and closure stress on proppant flowback and fracture conductivity. When the closure stress increased from 21 to 30 MPa, retained permeability decreased by slickwater from 35.71 to 29.84% in steel plates; during the flowback, more than 47% of proppants flowed back, and the fracture conductivity increased by 10 times under 21 MPa, which shows the limitation of the API method on the study of proppant flowback. When shale plates are used, the critical flow rate that prevents the proppant flowback was found to be $5.5 \times 10^{-3} - 1.6 \times 10^{-3}$ m/s for the 30/50 mesh sands (around 55–340 m$^3$/d for a typical horizontal well), and the retained permeability decreased from 23.33 to 22.86% due to an increase of closure stress from 21 to 30 MPa. Results of this study can guide the optimizing of the flowback scheme in the field that minimizes the proppant flowback in different fracturing fluids.

ABSTRACT: Multistage hydraulic fracturing is used in horizontal wells to increase the production of tight oil. Fracturing fluids are used in hydraulic fracturing to ensure proppants are suspended, but fluid residuals can cause formation damage and reduce rock permeability; meanwhile, fracture conductivity can be further reduced due to the flowback of proppants during the early stage of production. In this study, steel plates and hydraulically fractured reservoir rocks are tested in a modified API cell to understand the impacts of flowback rate, fracturing fluid, and closure stress on proppant flowback and fracture conductivity. When the closure stress increased from 21 to 30 MPa, retained permeability decreased by slickwater from 35.71 to 29.84% in steel plates; during the flowback, more than 47% of proppants flowed back, and the fracture conductivity increased by 10 times under 21 MPa, which shows the limitation of the API method on the study of proppant flowback. When shale plates are used, the critical flow rate that prevents the proppant flowback was found to be $5.5 \times 10^{-3} - 1.6 \times 10^{-3}$ m/s for the 30/50 mesh sands (around 55–340 m$^3$/d for a typical horizontal well), and the retained permeability decreased from 23.33 to 22.86% due to an increase of closure stress from 21 to 30 MPa. Results of this study can guide the optimizing of the flowback scheme in the field that minimizes the proppant flowback in different fracturing fluids.

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that slickwater can be used in hydraulic fracturing to create complex fractures while maintaining proppant suspension, it remains unknown the condition of proppant flowback and the proppant pack damage by the fracturing fluids.\textsuperscript{14} Empirical equations of proppant flowback have been proposed by Stim-Lab based on a large number of experiments on proppant flowback. Stim-Lab made the concept of stability area of a proppant-filling layer and a curve of the empirical equation derived from experience which is only applicable to the case of low closure stress. The comprehensive influence of the interaction among the closure stress, the width of the proppant, and the critical gas velocity was studied in this model to help to understand the proppant flowback. When the closure stress is higher than 48.3 MPa, it cannot explain the instability of the proppant pack caused by the proppant broken under high closure stresses. The proppant-free wedge model was created by Andrew et al. (1998) to understand proppant flowback.\textsuperscript{15} This model makes use of the concept of “regions of stability” first suggested by the Stim-Lab Consortium and considers the effect of having partial or even total crushing of the proppant grains at elevated values of closure stress. Fracture width, closure stress, and drag force are translated into width ratio, closure term, and drag term to understand the instability of the proppant pack caused by the proppant broken under different closure stresses. When the closure stress is low, drag force is an important parameter affecting the backflow, and wide fractures are stable at very low drag forces. A small increase in the flow rate (larger drag term) can destabilize the pack and generate flowback. When the closure stress in “regions of stability” increases gradually, the stability of proppants increases due to the improvement of friction forces. When the critical point of the stable region is reached, with the increase of the closure stress, mechanical destabilization will occur. This means that the contact forces among grains become so large at some localized regions of the pack, that there is a partial crushing of grains resulting in a loss of stability.\textsuperscript{16} Asgian et al. (1995) used the new numerical model based on discrete elements to study the effects of fracture width, mean grain size, and pressure drawdown on proppants flowback.\textsuperscript{16} In this model, the proppant pack in fractures propped with cohesionless, unbonded proppant is inherently unstable for fracture widths greater than or equal to 5.5 times of the mean diameter of proppants. When the fracture width is less than 5.5 times of the mean diameter of proppants, the numerical experiments show that drawdowns of less than 75 psi/ft are not large enough to affect the stability of propped fractures but are large enough to transport loose proppant. The proppant filling layer may form a hemispherical “sand arch” near the perforation, and then, the existence of the sand arch directly affects the filling effect of the proppant.\textsuperscript{16} It is complex for the proppant to flow back. The proppant that flow back from the fracture will erode the proppant pack, resulting in more proppant to flow back. The faster the fracturing fluid flows, the more severely the pack is eroded. During the formation of the proppant pack, channels exist between the pack due to the continuous pumping of fracturing fluid and proppant, during which the particle of the proppant can flowback to the bottom of the well. The minimum fluidization velocity criterion is examined by Sparlin et al. (1995) to obtain the critical flowback flow rate.\textsuperscript{17} Decreasing the flowback rate of the fracturing fluid by controlling the nozzle, the proppant can remain in the fracture for a long period, improving fracture conductivity, but at the same time causing formation damage.\textsuperscript{18} The forced fracture closure technique proposed by Ely et al. (1990) is opposite to that of Robinson et al. (1988).\textsuperscript{18} At the end of pumping, the initial flowback is carried out before the fracture is naturally closed, forcing the fracture to close. Increasing the concentration of proppant in the fracturing fluid during hydraulic fracturing to pave the proppant into the fracture and play the role of proppant effectively to improve the conductivity of the fracture. Uniform proppant distribution in the vertical direction and good proppant performance as the benefits of this technique can reduce fracturing fluid leak-off and discharge the fracturing fluid from the formation in time, which can reduce the damage to the fracture conductivity.\textsuperscript{19} The influence of closure stress on proppant flowback factors is significant. According to the proppant-free wedge model, when the closure stress increases within a certain range, proppant backflow can be reduced. However, when the closure stress exceeds the critical point, proppant breakage will lead to proppant pack instability, which is rarely reached in the oilfield. Proppant flowback is governed by the type of fracture fluid, flowback rate, and closure stress; besides, the fracture can pinch out in the near-wellbore region due to large closure stress, which may affect the proppant flowback.\textsuperscript{20,21} To maintain a high fracture conductivity and thus a high production rate, proppant flowback needs to be reduced during the flowback stage of the well after hydraulic fracturing. In this study, because overburden pressure in the formation is about 60 MPa and pore pressure in the formation is 20–30 MPa, 21 and 30 MPa are chosen to mimic the effective closure stress of hydraulic fractures in the reservoir with a depth of around 3000 m. The range of the closure stress will not reach the critical point.

In this study, steel plates and hydraulically fractured reservoir rocks are tested in a modified API cell to understand the impacts of flowback rate, fracturing fluid, and closure stress on proppant flowback and fracture conductivity.

2. EXPERIMENTAL INSTRUMENT AND MATERIALS

The FCS-842 fracture conductivity test system shown in Figure 1a is used to simulate the real temperature and pressure conditions in formation to measure the fracture conductivity and evaluate the damage to proppant packs from fracturing fluids under different closure stress. The maximum experimental temperature allowed by the experimental instrument is 177 °C, the maximum closing pressure is 137 MPa, the maximum injection rate is 50 mL/min, the distance between the pressure measuring ports is 12.7 cm, and the maximum load force is 66.72 KN. The laying area of the proppant in API is 64.52 cm\(^2\), 17.8 cm in length, and 3.8 cm in width. In this study, 21 and 30 MPa are chosen to mimic the effective closure stress of hydraulic fractures in the reservoir with a depth of around 3000 m.

To simplify the experimental operation and ensure the comprehensiveness of the test, the experiment of flowback and damage is completed by the API cell modified by removing the sieve at the outlet of the API cell to obtain the sand accumulated production of the flowback shown in Figure 1b. Rock plates and steel plates shown in Figure 1c are used to be compared to explore the proppant flowback under different conditions in this device.

Hydraulically fractured reservoir rocks are tested in a modified API cell instead of steel plates to simulate the formation environment furthest. The rock model can consider the comprehensive influence of embedment of the propping
agent to the conductivity of fracture created by hydraulic fracturing.

Considering the cost in the oilfield, sands are commonly used as a proppant to support hydraulic fractures. However, the characteristics of sands that are easy to break may easily lead to the proppant flowback. Therefore, the 30/50 mesh sands with a density of 1.53 g/cm³ shown in Figure 1d are selected as the proppant for the experimental studies.

Figure 2 shows the API result of fracture conductivity in the steel plates and rock plates under different closure stresses. When the closure stress increases from 20 to 69 MPa, the conductivity of fracture in the steel plates decreases from 22.6 to 0.02 D·cm. When replacing the steel plates with the rock plates, the closure stress when the propped fracture almost loses the conductivity decreases to 69 MPa.

Several experiments are carried out in order to understand the effect of low-viscosity slickwater named DR900 on proppant flowback. The concentration of DR900 was set as 0.1% under the same conditions as the field production. Figure 3 shows the friction reduction rate of 0.1% DR900 and the rheological curve of 0.1% DR900.

As is shown in Figure 3, the friction reduction rate of 0.1% DR900 increases with the Reynolds number and be stabilized at 60% when Re is above 85,000. In this paper, it is assumed that the tubing diameter is 125 mm, the pumping rate is 10 m³/min, the density is 1000 kg/m³, and the viscosity is 4 mPa·s. The order of magnitude of Reynolds number obtained by using the above parameters is 10⁵.

The viscosity of 0.1% DR900 shown in Figure 3 decreases with shear rate, and stabilizes at 3 mPa-s when the shear rate is above 160 s⁻¹. As the shear rate is very small in this experiment, the value of viscosity is approximately 4 mPa-s in this study.

3. RESULTS AND DISCUSSION

Room temperature 30/50 mesh sands with a concentration of 6 kg/m² are used in all experiments to ensure the temperature consistency of experimental conditions and control variables. By converting the field flow rate into laboratory flow, the flow range of fracturing fluid in the experiment is 5−30 mL/min, and the actual field flow is 55−340 m³/d (it is assumed that there are 40 clusters in the whole well, the fracture height is 15 m and the fracture width is 2 mm, during which the flow rate in the API cell is the same as that in the oilfield fracture was developed as a standard to estimate proppant flowback).

3.1. Conductivity Test. On the basis of the short-term conductivity of the proppant pack experiment, a filter plug was
added at the outlet of the API cell and the initial conductivity of the proppant in steel plates without sand flowback was explored at different flow rates and different closure stresses, as shown in Table 1.

Table 1. Experiment of Sand Flowback in Steel Plates

| flow rate (mL/min) | 5  | 10  | 15  | 20  | 25  | 30  |
|------------------|----|-----|-----|-----|-----|-----|
| types of fracturing fluid | 2% KCl |
| types of proppant | 30/50 mesh quartz sands |
| sanding concentration (kg/m²) | 6 kg/m² |
| closure stress (MPa) | 21 MPa | 30 MPa |

Figure 4 shows the results of proppant conductivity with different flow rates and different closure stresses. When the flow rate increases, the conductivity of each flow rate has no obvious change. This indicates that the flow rate has little influence on the change of conductivity. When the closure stress increases from 21 to 30 MPa, the conductivity of the proppant decreases by approximately 40%. This indicates that closure stress is the main factor affecting proppant conductivity.

Table 2. Experiment of Sand Flowback in Steel Plates

| flow rate (mL/min) | 5  | 10  | 15  | 20  | 25  | 30  |
|------------------|----|-----|-----|-----|-----|-----|
| volume of displacing fluid (PV) | 100 |
| types of fracturing fluid | 2% KCl |
| types of proppant | 30/50 mesh quartz sands |
| sanding concentration (kg/m²) | 6 Kg/m² |
| closure stress (MPa) | 21 MPa | 30 MPa |

fracturing fluids and the comparison of conductivity of the proppant pack before and after sand flowback. By the way, it is noted that the fracturing fluid should be saturated without sand flowback at very low flow rates due to the higher viscosity of the fracturing fluid than 2% KCl.

Figure 5 shows the results of sand flowback and proppant conductivity with different flow rates and different closure stresses. The propped fractures are presaturated with 2% KCl solution as the fracturing fluid under different closure stresses which are 21 or 30 MPa. The blue dotted line represents the final cumulative sand flowback. Under low closure stress, the cumulative sand flowback increases rapidly with the increase of flow velocity. When the cumulative sand flowback continues to increase, there are two cases of conductivity shown in Figure 5.

When the fluid rate increases, cumulative sand flowback rapidly increases, yet the initial conductivity is stable at each flow rate. When the closure stress is 21 MPa, the proportion of cumulative sand flowback increases rapidly to 47.00% at the flow rate of 30 mL/min; then, the conductivity increases by 10 times. When the closure stress is 30 MPa, the proportion of cumulative sand flowback is 25.25%, but the conductivity decreases by 55.6%.

However, before the channel with high conductivity is formed under low closure stress, its fracture conductivity will increase compared with that under high closure stress due to its lower crushing rate. Conversion from laboratory scale to
field scale, when the daily capacity increases to 220 m³/d or higher, it is more obvious that high closure stress has an inhibition effect on proppant flowback.

Figures 6 and 7 show the results of the proppant distribution morphology with sand flowback. The sand flowback at the inlet is less than that at the outlet, resulting in the fracture width at the inlet being larger than that at the outlet. The channel with high conductivity is formed under low closure stress, and the change of joint width at the inlet and outlet caused by sand flowback can assist in proving the existence of the channel with high conductivity, which may be a deficiency of the steel plates.

Then, 0.1% slickwater named DR900 is conducted to understand the effect of fracturing fluid damage on sand flowback and conductivity. The conductivity, sand flowback, and damage of fracture fluid within the fracture are explored with different closure stresses, different flow rates, and different fracture fluids, as shown in Table 3.

The initial conductivity stabilizes quickly when only one fracturing fluid such as 2% KCl is used; the conductivity damaged by slickwater stabilizes slowly due to the displacement process which the residual slickwater dissolved in 2% KCl.

The initial conductivity tested at low flow rates is measured in advance to have the reference standard of conductivity for the fluid damage. The fracture is then saturated with slickwater. Finally, the slickwater was replaced with 2% KCl to measure the conductivity stabilized for the proppant to calculate the damage degree of the fluid. The damaged conductivity is the conductivity of a fracture presaturated with the fracturing fluid when 100 PV of the fluid is displaced by 2% KCl. The final achieved conductivity is compared to the known conductivity for the proppant being utilized to determine the degree of damage often termed the percentage retained permeability or conductivity shown in Tables 4 and 5.

As is shown in Tables 4 and 5, when the closure stress increased from 21 to 30 MPa, retained permeability decreases by slickwater from 35.71% to 29.84% in steel plates. The agglomeration of slickwater further increases the damage.
degree of the fracturing fluid due to the increase of proppant crushing caused by the relatively smaller particle size of the proppant with the increase of closing pressure.

After passing the basic conductivity and damage test, the flow rates are changed to obtain the conductivity of proppant and sand flowback per 100 PV at different flow rates.

Figure 9 shows the results of sand flowback and proppant conductivity with different flow rates and different closure stresses when the slickwater is used.

![Figure 9](image)

Figure 9. Damage of 0.1% DR900 and sand flowback in steel plates.

When the fluids change from 2% KCl to slickwater, the proportion of cumulative proppant flowback under 21 MPa decreases by slickwater from 47.0 to 15.2% in steel plates. When the closure stress increases from 21 to 30 MPa, the proportion of cumulative proppant flowback decreases by slickwater from 25.3 to 6.3%. With the use of the fracturing fluid, the flowback threshold at a low closure stress is doubled from 110 to 220 m³/d at the field scale.

The proppant conductivity and the cumulative proppant flowbacks will decrease due to the agglomeration of proppant caused by slickwater. High production pressure differential and a larger nozzle can be used to improve oilfield productivity due to the application of slickwater to reduce the sand flowback in the flowback.

However, in the experiments of steel plates, changes in proppant conductivity are not consistent with the cumulative proppant flowbacks. The proppant conductivity increases sharply with the increase of cumulative sand flowback under low closure stress, which may be due to the fact that the steel plates cannot simulate the embedding of proppant in the simulated fracture. Point contact between steel plates and proppant cannot simulate the inhibition of proppant flowback after the embedding of proppant, which was further verified by experiment in rock plates.

Similar to the experiment measured in the steel plates, the initial conductivity and damage conductivity are obtained by replacing the steel plates with the rock plates. The ratio of residual conductivity of rock plates shown in Tables 6 and 7 is defined as the ratio of the damage conductivity and the initial conductivity.

As is shown in Tables 6 and 7, the residual conductivity in the rock plates is lower than in steel plates. The conductivity measured in the rock plates is lower than the steel plates due to the crushing and the embedding of the proppant under the same flow rate. Moreover, Figure 10a,b shows crushing of proppant and embedding of proppant, respectively.

![Figure 10](image)

Figure 10. Crushing and embedding of proppant. (a) Crushing of proppant. (b) Embedding of proppant.

After passing the basic conductivity and damage test, the flow rates are changed to obtain the conductivity of the proppant and sand flowback per 100 PV at the flow rate of 5/10/15/20/25/30 mL/min, respectively.

Figure 11 shows the results of sand flowback, proppant conductivity, and damage of proppant caused by slickwater at different flow rates and different closure stresses when the rock plates are used.

Comparing the experimental results of the steel plates and rock plates at the same flow rate, as shown in Figure 11, when the closure stress is 21 MPa, the proportion of cumulative sand flowback is 2.25%, and then, the conductivity at a flow rate of 30 mL/min decreases slightly lower than that at 15 mL/min.

Lower initial conductivity may be due to a more residual fracturing fluid during long-term displacement. When the closure stress increases to 30 MPa, the proppant flowback decreases to zero with stable conductivity at a flow rate of 30 mL/min.

In terms of conductivity, similar to residual conductivity, the rock plates are closer to the on-site fracture, which can simulate the embedding and crushing of proppant, while the steel plates can only simulate the crushing of proppant, resulting in the conductivity measured in rock plates clearly lower than the conductivity in steel plates. The application of slickwater and rock plates to simulate the

### Table 6. Proportion of Residual Conductivity under 21 MPa (Rock Plates)

| types of fracturing fluid | filling layer width (cm) | Q (cm³/min) | conductivity (D·cm) | permeability (μm²) |
|--------------------------|--------------------------|-------------|---------------------|-------------------|
| 2% KCl                   | 0.34                     | 3           | 16.42               | 48.29             |
| 0.1% DR900               | 0.34                     | 3           | 3.83                | 11.26             |

### Table 7. Proportion of Residual Conductivity under 21 MPa (Rock Plates)

| types of fracturing fluid | filling layer width (cm) | Q (cm³/min) | conductivity (D·cm) | permeability (μm²) |
|--------------------------|--------------------------|-------------|---------------------|-------------------|
| 2% KCl                   | 0.34                     | 5           | 13.41               | 40.64             |
| 0.1% DR900               | 0.34                     | 5           | 3.1                 | 9.39              |

23.33%
hydraulic fracturing of real formation shows that the application of slickwater greatly increases the difficulty of proppant flowback due to the embedding of the proppant. Slickwater can not only reduce pipeline friction in hydraulic fracturing but also inhibit proppant backflow in the production to maintain fracture conductivity, which can save reconstruction cost and increase the benefit of production in the well site.

At low closure stress, it appears that the velocity threshold of proppant flowback is reduced, but the cumulative flowback is significantly reduced. With the use of the rock plates and slickwater, the flowback threshold at high closure stress is increased to above 340 m³/d at the field scale.

In order to obtain the influence of proppant crushing on conductivity and the damage to proppant by slickwater are studied by using steel plate and rock plate models under different fracturing fluid conditions. The following conclusions were drawn:

(1) When the closure stress increases from 21 to 30 MPa, permeability decreases by proppant crushing under the higher closure stress, while cumulative sand flowback rapidly increases with the increase of the fluid flow rate. When the closure stress is 21 MPa, the proportion of cumulative sand flowback increases rapidly to 47.00% at the flow rate of 30 mL/min; then, the conductivity increases by 10 times. When the closure stress is 30 MPa, the proportion of cumulative sand flowback is 30.97%.

Table 8. Summary of Crushing Rates

| closure stress (MPa) | broken quality (g) | screening quality (g) | sand flowback (g) | total mass (g) | crushing rate (%) |
|---------------------|--------------------|----------------------|-------------------|---------------|------------------|
| rock plates and DR900 |                    |                      |                   |               |                  |
| 21 MPa              | 4.83               | 30.1                 | 0.87              | 30.97         | 15.60%           |
| 30 MPa              | 7.73               | 34.7                 | 0                 | 34.7          | 22.28%           |
| steel plates and 2% KCl |                |                      |                   |               |                  |
| 21 MPa              | 7.26               | 12.52                | 18.189            | 30.709        | 23.64%           |
| 30 MPa              | 10.96              | 24.7                 | 9.77              | 34.47         | 31.80%           |
| steel plates and DR900 |                  |                      |                   |               |                  |
| 21 MPa              | 4.32               | 29.32                | 6.07              | 35.39         | 12.21%           |
| 30 MPa              | 8.27               | 35.64                | 2.43              | 38.07         | 21.72%           |
| steel plates and initial conductivity |        |                      |                   |               |                  |
| 21 MPa              | 6.43               | 36.31                | 0                 | 36.31         | 17.71%           |
| 30 MPa              | 10.83              | 36.72                | 0                 | 36.72         | 29.49%           |

Figure 11. Damage of 0.1% DR900 and sand flowback in rock plates.

Figure 12. Conductivity in rock and steel plates in different closure stresses.

4. CONCLUSIONS

In this paper, the phenomenon of proppant flowback and the damage to proppant by slickwater are studied by using steel plate and rock plate models under different fracturing fluid conditions. The following conclusions were drawn:

(1) When the closure stress increases from 21 to 30 MPa, permeability decreases by proppant crushing under the higher closure stress, while cumulative sand flowback rapidly increases with the increase of the fluid flow rate. When the closure stress is 21 MPa, the proportion of cumulative sand flowback increases rapidly to 47.00% at the flow rate of 30 mL/min; then, the conductivity increases by 10 times. When the closure stress is 30 MPa, the proportion of cumulative sand flowback is 30.97%.
25.25%, but the conductivity decreases by 55.6%. The channel with high conductivity is formed under low closure stress.

2. In the field scale, when the daily capacity increases to 220 m³/d or higher in the steel plate model, it is more obvious that high closure stress has an inhibition effect on proppant flowback. With the use of fracturing fluid in steel plates, the flowback threshold at low closure stress is doubled from 110 to 220 m³/d at the field scale. When the rock plates are used instead of the steel plates, the threshold of proppant flowback under low closure stress is greatly improved.

3. In steel plates and rock plates, the aggregation of slickwater will damage the conductivity of the proppant. The higher the closure stress is, the more serious the proppant is broken, and the more serious the conductivity damage of the proppant is.

4. The proppant flowback in steel plates and rock plates is greatly reduced by the agglomeration of slickwater. When changing 2% KCl to slickwater, the proportion of cumulative proppant flowback under 21 MPa decreases from 47.0 to 15.2% in steel plates. When the closure stress increases from 21 to 30 MPa, the proportion of cumulative proppant flowback decreases from 25.3 to 6.3%. Similar results are found in rock plates. When changing the steel plates to the rock plates, the proportion of cumulative proppant flowback under 21 MPa decreases from 15.2 to 2.3% in steel plates; when the closure stress increases from 21 to 30 MPa, no proppant flows back.

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**Notes**

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