# Performance Evaluation and Optimization of Temporary Plugging Agent Used in Diverting Fracturing

Haiyang Ma[1], Qingzhi Wen[2](✉), Mingliang Luo[1], Tingting Yu[1],
Gang Lei[2], Xiaofei Duan[1], and Liu Yang[1]

[1] College of Petroleum Engineering, China University of Petroleum
(East China), Qingdao 266580, China
`{978894602,68348424,826206564,`
`478938178,444864384}@qq.com`
[2] Beijing Innovation Center for Engineering Science and Advanced Technology,
College of Engineering, Peking University, Beijing 100871, China
`wenqingzhi_pku@163.com`, `lgl987cup@126.com`

**Abstract.** Temporary plugging and diverting fracturing is an important method for oil and gas reservoirs stimulation, in which the temporary plugging agent (TPA) plays a vital role. The degradability and plugging performance of JRS-1 fiber TPA and QXD-1 granular TPA were evaluated by the self-designed experimental device. Meanwhile, the fiber TPA and the granular TPA were mixed into a new type of composite TPA. The mixing ratio of fiber and granule was further optimized according to the plugging performance. The results show that the fiber and granule both can be degraded more than 95%, the degradation speed meets the construction requirements, and the damage to reservoir is small. Both the fiber and granular TPA can block the simulated fracture. When the fiber and granule in the composite TPA account for 35–45 wt% and 55–65 wt%, respectively, the plugging effect is better than that of the fiber or granule used alone. When the ratio of the fiber and granule is 40 and 60 wt%, respectively, its plugging performance is the best, and the composite temporary plugging layer can stand the pressure up to 7 MPa above. The results can provide reference for improving the diverting fracturing effect.

---

This paper was prepared for presentation at the 2018 International Field Exploration and Development Conference in Xi'an, China, September 18–20, 2018.

J. Lin (ed.), *Proceedings of the International Field Exploration and Development Conference 2018*, Springer Series in Geomechanics and Geoengineering, https://doi.org/10.1007/978-981-13-7127-1_10

**Keywords:** Diverting fracturing · Composite temporary plugging agent · Performance evaluation · Degradability · Plugging performance

## 1 Introduction

Hydraulic fracturing has become one of the important stimulation techniques for the economic development of unconventional reservoirs [1–3]. Many scholars have suggested that the fracturing method in unconventional reservoirs should take natural fractures into consideration, link original micro-fractures in the reservoir, and increase the stimulated area as much as possible [4, 5]. However, in many cases, due to the influence of in situ stress, conventional fracturing can only produce a single fracture or just expand the original fracture. To solve this problem, temporary plugging and diverting fracturing technology is used to transform the reservoirs by plugging the original fracture with the temporary plugging agent (TPA), which can create new fractures in different directions and increase reconstruction volume [6–9].

As TPA is a key factor for this technology, which has great influence on the construction result, many researchers have focused on the plugging performance evaluation of TPA [10–14]. Cohen et al. carried out the fiber bridging experiments to discuss the effect of fiber cake permeability and spurt loss on the plugging ability of fiber-laden acid fluid system [10]. Droger et al. found that temporary plugging layers could form under two conditions which respectively are bridging with fiber and plugging with fiber [11]. Sau et al. used the fiber TPA to block the 3D-printed cores. Through the experiment, they optimized the injection rate of fiber plugging fluid and the fiber concentration [12]. Wang et al. tested the plugging ability of fiber through the dynamic filtration experiments. The effects of injection rate, fracture width, and horizontal principal stress difference were considered in these experiments [13]. Gomma et al. concluded that far-field steering required small size granules, but near-wellbore and perforation steering both required large size granules [14].

Although many successful experiments and applications have been reported in the literature, most of the reports are limited to fiber TPA or granular TPA used alone. There are few studies on composite TPA with fiber and granule. What's more, whether the plugging effect of composite TPA is better than that of fiber or granule used alone. And whether there is an optimal proportion of composite TPA to make it the best plugging performance. To solve these questions, the work needs to be done are as follows:

(1) to evaluate the degradability of the fiber TPA and granular TPA;
(2) to compare the plugging ability of the composite TPA with that of the fiber TPA and granular TPA;
(3) to optimize the mixing ratio for the composite TPA.

# 2 Methodology

## 2.1 Experimental Materials and Setups

The experimental materials include the JRS-1 fiber TPA (hereinafter referred to as fiber) and QXD-1 granular TPA (hereinafter referred to as granule), as shown in Fig. 1. The technical specifications of the two TPA materials are summarized in Table 1. The other experimental materials mainly include 40/70 ceramsite, simulated formation water, guar gum, etc.

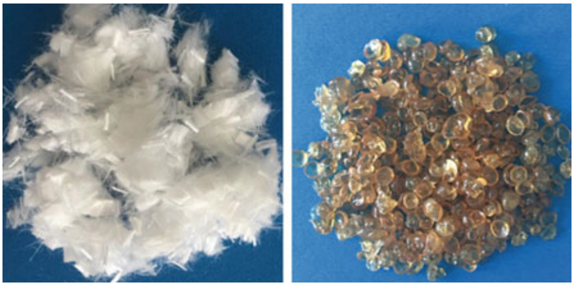

**Fig. 1** The fiber (left) and granule (right)

**Table 1** Technical specifications of the TPA materials

| Technical specifications | JRS-1 fiber TPA | QXD-1 granular TPA |
|---|---|---|
| Appearance | white, straight, silk shape | yellow, translucent, column shape |
| Length (mm) | 6 | 2–3 |
| Diameter (μm) | 40 | 4000 |
| Density (g $cm^{-3}$) | 1.1 | 1.2 |
| Dispersibility | Dispersed evenly | — |

The experimental setups include the following: self-designed temporary plugging performance evaluation device (TPPED), as shown in Fig. 2, analytical balance, measuring cylinder, thermostat water bath, beaker, filter paper, and drying oven.

It can be seen from Fig. 2 that the apparatus mainly comprises pressurization module, pressure reducing valve module, temporary plugging fluid (TPF) container module, and measuring module (used to measure and record experimental data). The pressurization module is a high-pressure nitrogen cylinder, providing the stable high-pressure gas for the experiment. The pressure reducing valve module can adjust the pressure to the required pressure. The structural diagram of TPF container, used to place the simulated fracture and hold the experimental fluid, is illustrated in Fig. 3.

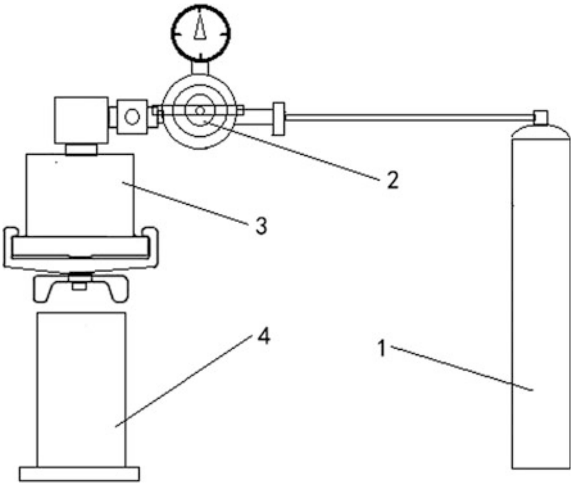

**Fig. 2** Principle diagram of TPPED. (1 The pressurization module; 2 The pressure reducing valve module; 3 The TPF container module; 4 The measuring module)

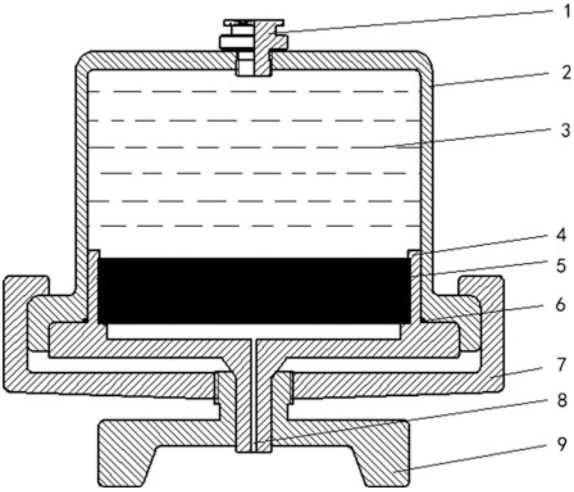

**Fig. 3** Structural diagram of the TPF container module. (1 The deflated hexagonal connector; 2 The container cup; 3 The TPF; 4 The container seal cap; 5 The simulated fracture or the holes; 6. The O-ring; 7. The compression screw; 8. The outlet 9. The compression bolt)

## 2.2 Experimental Procedure

### 2.2.1 Degradation Experiment

In order to evaluate the degradability of the TPAs in different temperatures, the constant temperature bath is used to control the experimental temperature. The experimental temperatures are set to 25, 70, 90 °C, respectively. Based on the downhole environment, simulated formation water is chosen as the base fluid. The experimental steps are as follows:

Use the thermostat water bath to control the experimental temperature at a constant value; add a certain mass of the TPA to the base solution to degrade a period of time; use the filter paper to filtrate the residue of the TPA; fully dry the residue in the drying oven; use the analytical balance to weigh the residue mass; calculate the degradation rate (DR) of TPA in different time periods; the calculation method is shown in Eq. (1); change the experimental temperature or base fluid; and repeat the above steps.

$$DR = \frac{M1 - M2}{M1} \times 100\% \tag{1}$$

where $DR$ is the degradation rate of TPA (%), $M1$ is the initial mass of TPA (g), $M2$ is the residue mass of TPA (g).

### 2.2.2 Temporary Plugging Experiment

Firstly, the temporary plugging performance of fiber, granule, and composite TPA with different proportions of fiber and granule will be tested by the self-designed TPPED, respectively, then through the TPPED to test the pressure-bearing capacity of the temporary plugging layers. During the experiment, the simulated fracture width is 1 mm, and the experiment will last for about 30 min. The relevant experimental parameters are listed in Table 2.

**Table 2** Experimental parameters of plugging experiment

| Temperature °C | Materials | Fluid | Experimental pressure (MPa) |
|---|---|---|---|
| 25 | Fiber, ceramsite | TPF: 0.4%<br>Guar gum fracturing fluid + 1 wt% TPA + 5% ceramsite | 0.4, 0.6, 0.8 |
| | Granule, ceramsite | | |
| | [a]Composite TPA (fiber + granule), ceramsite | | |

[a] The proportions of the granule in composite TPA are 20, 40, 50, 60, 80%, respectively

In addition, the working process can be summarized as the following:

Prepare TPF, and pour TPF to the TPF container; select and install the desired simulation fracture, through the compression bolt and compression screw sealing the TPF container; connect the TPF container to the high-pressure gas source, and check the air tightness; then through the pressure reducing valve adjusting the experimental pressure; record the experimental data according to the measuring module at the same time; decompression and empty the remaining gas; open the TPF container to observe the temporary plugging layer in the simulated fracture; reconnect the device to test the pressure bearing capacity of the temporary plugging layer.

# 3 Results

## 3.1 Degradation Experiment

Degradability is a crucial property for TPA. The degradation speed of TPA can neither be too fast nor too slow. If the degradation speed is too fast, it may cause the TPA to be unable to give full play to the plugging performance. However, if the degradation speed is too slow or even the TPA cannot degrade, the flow conductivity of the original fracture may not be recovered and may cause pollution to the reservoir.

The DRs of TPAs at different temperatures are shown in Table 3. From Table 3, we can see that when the experimental temperature is 25 °C, the DRs of fiber and granule after 4 h are all 0%. When the experimental temperature is 70 °C, the DRs are less than 5% after 2 h and less than 10% after 4 h. According to the field experience, after the TPF into the formation, most of the reservoir temperatures will drop to around 60–70 °C due to the cooling effect of the liquid. This ensures that the plugging performance of TPA is not affected by degradation when actually applied. When the temperature is raised to 90 °C, the DRs of TPAs are more than 50% after 4 h, which have increased obviously. And 24 h later, the fiber and granule can be degraded 98.3 and 95.8%, respectively. After construction, the formation temperature will gradually rise. Some formation even can reach above 100 °C. Therefore, the TPA can degrade rapidly in the high-temperature condition, and the flow conductivity of the original fracture can be recovered. To sum up, the degradability of the fiber and granule used in this paper can meet the requirement of temporary plugging.

**Table 3** The DRs of TPAs at different temperatures

| Solution | Temperature °C | Time (h) | DRs of TPAs % | |
|---|---|---|---|---|
| | | | Fiber | Granule |
| Simulated formation water | 25 | 2 | 0 | 0 |
| | | 4 | 0 | 0 |
| | 70 | 2 | 4.3 | 3.5 |
| | | 4 | 8.1 | 5.2 |
| | 90 | 2 | 33.5 | 35.9 |
| | | 4 | 56.1 | 61.1 |
| | | 24 | 98.3 | 95.8 |

## 3.2 Temporary Plugging Experiment

### 3.2.1 Fiber Plugging Experiment

The relation curves of leakage versus time at different pressures are shown in Fig. 4. As shown in Fig. 4, the leakage curves all show the same trend, the speed of loss is quick at the beginning, then the speed gradually slows down, and finally, the curves tend to be steady. As the leakage increases, fiber will be pressed into the simulated fracture and form a tight temporary plugging layer. With the accumulating of the fiber, the temporary plugging layer will become tighter, and the speed of leakage will become slower and slower. And the system finally reaches a balanced state without leakage at each experimental pressure. And the system finally reaches a balanced state without leakage at each experimental pressure, which means that the fracture is blocked successfully.

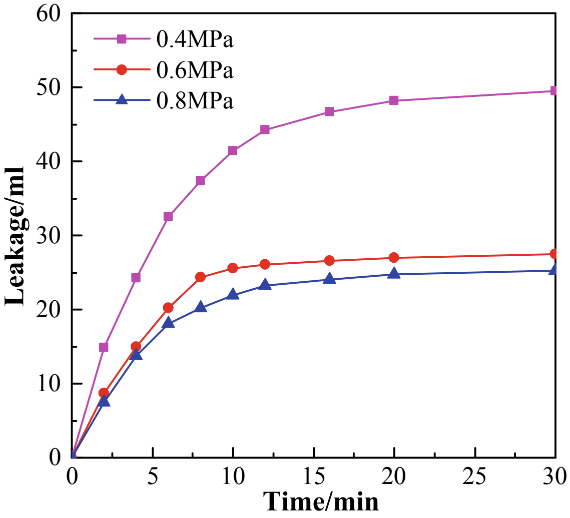

**Fig. 4** Leakage of fiber TPF at different pressures

In addition, as shown in Fig. 4, the final fluid leakage of fiber TPF reduces by 44.4% with the pressure increases from 0.4 to 0.6 MPa. When the pressure increases from 0.6 to 0.8 MPa, the final fluid leakage of fiber TPF reduces by 8%. During the whole process, the overall decrement is 49.5%. The main reason is that as the pressure increases, the transient leakage of TPF becomes greater. So the fiber, accumulating in the cracks, is more easily entangled in a short time, an effective plugging layer will be formed quickly, the latter fiber will be easier to be captured, and a benign cycle is formed. Thus, as the pressure increases, the leakage will be reduced.

The fiber temporary plugging layer is shown in Fig. 5.

### 3.2.2 Granule Plugging Experiment

The relation curves of leakage versus time with different pressures are shown in Fig. 6. It can be seen from Fig. 6 that all curves have similar rules. At the beginning of the experiment, the loss rate is quick and then gradually slows down. The reason for this phenomenon is that the temporary plugging layer gradually becomes tighter with the time. And as shown in Fig. 6, with the experimental pressure increasing from 0.4 to 0.6 MPa, the fluid leakage of granule TPF is increased by 51.3%. When the pressure increases from 0.6 to 0.8 MPa, the fluid leakage of granule TPF increases by 51.3%, and the overall amount of increase is 76.3% from 0.4 to 0.8 MPa.

It should be noted that the experimental rule of granule (seen in Fig. 6) is contrary to that of the fiber (seen in Fig. 4), which can be explained with the different plugging principle of the fiber TPA and the granular TPA. Because of the entanglement

**Fig. 5** Fiber temporary plugging layer in the simulated fracture

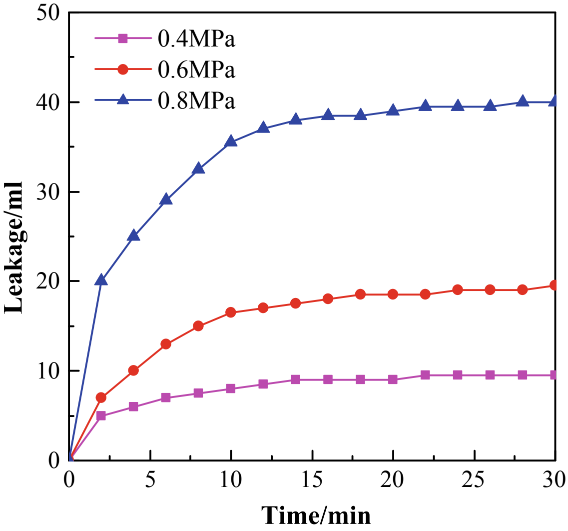

**Fig. 6** Leakage of granule TPF at different pressures

deformation between the fibers which do not have the fluidity, and the squeezing force and friction force generated between the fiber and the fracture coarse surface, the fiber TPA will form a filter cake with a complex network structure. Thus, as the pressure increases in a certain pressure range, the fiber will be compacted in a shorter time and the amount of leakage will be less. However, due to the effect of viscosity and dilatability which is generated by the granule dissolution, the granular TPA will be stuck together to the surface of the crack and proppant. As the pressure increases, due to the own certain mobility of granular TPA and the faster flow rate of TPF, it is more difficult to block the stimulated fracture with the dissolved matter of TPA. Thus, in order to form an effective temporary plugging layer, more granular TPF needs to flow through the plugging point of the fracture.

### 3.2.3 Composite TPA Plugging Experiment

The relation curves of leakage with time in different pressures are shown in Fig. 7. It can be seen from Fig. 7 that all the composite TPAs can successfully block the simulated fracture. In the initial stage, the slope of the curve is large, which means that the leakage rate is quick. With the increase in experimental time, the leakage rate gradually slows down and even tends to be 0, which demonstrates that the experimental pressure can be maintained, and an effective temporary plugging layer is formed. Figure 7 also shows that the leakage of the composite TPA with a given proportion increases as the pressure increases.

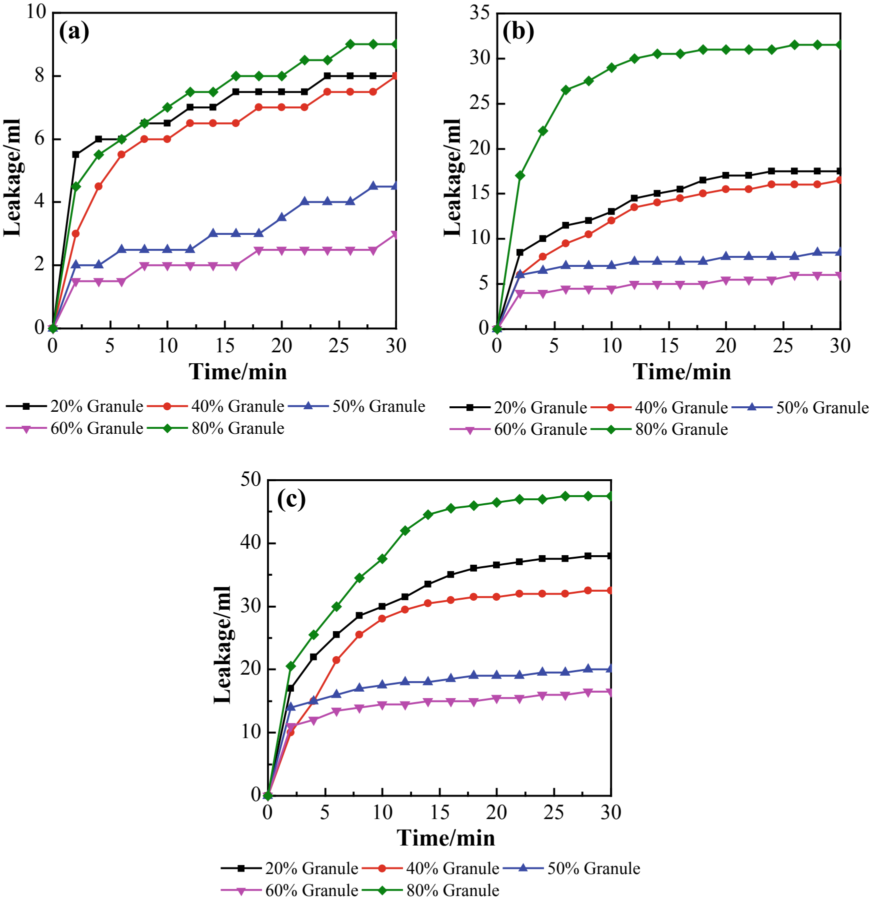

**Fig. 7** Leakage of different composite TPFs. **a** at 0.4 MPa; **b** at 0.6 MPa; **c** at 0.8 MPa

The final leakage of the composite TPFs at different pressures is shown in Fig. 8. From Fig. 8 we can see that when the granule proportion is 60%, the leakage of composite TPFs all reaches the bottom of the “funnel,” and the value of leakage is all the minimum in each curve. That illustrates that 60 wt% granule and 40 wt% fiber are the best-mixed mode, which can ensure that the plugging capacity of composite TPA is the strongest among all the composite TPAs.

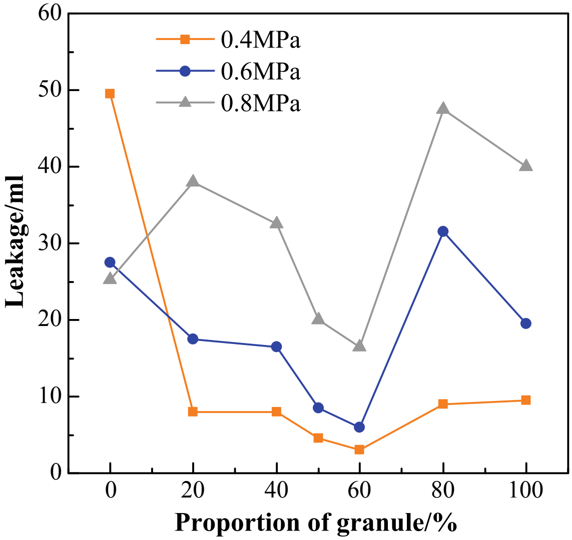

**Fig. 8** Final leakage of different composite TPFs at different pressures

Figure 9 shows the temporary plugging layer of the composite TPA (60 wt% granule and 40 wt% fiber). As we can see from Fig. 9, the fiber, the granule, and the ceramsite have a clear division of labor, and they successfully block the simulated fracture together. The ceramsite in the TPF corresponds to the existing proppant in the fracture and provides flow resistance for TPF throughout the process. When the TPF flows through the simulated fracture, the fiber will bridge and intertwine with each other between the fracture surfaces and the proppant, forming a complex and interlaced network structure, increasing the movement resistance of the TPF. In addition, due to the dilatability, viscosity, and poor fluidity of the granular TPA, the granular TPA will attach to the surface of the fiber and have a compaction effect on the fiber layer. With the accumulation of the granular TPA, the leakage channel of the fiber layer will be filled gradually and finally forming a composite temporary plugging layer. With the experiment going on, the above processes constantly repeat and cycle, and the composite temporary plugging layer will superpose continuously and enhance the ability to decrease leakage. Finally, an effective tight temporary plugging layer is formed.

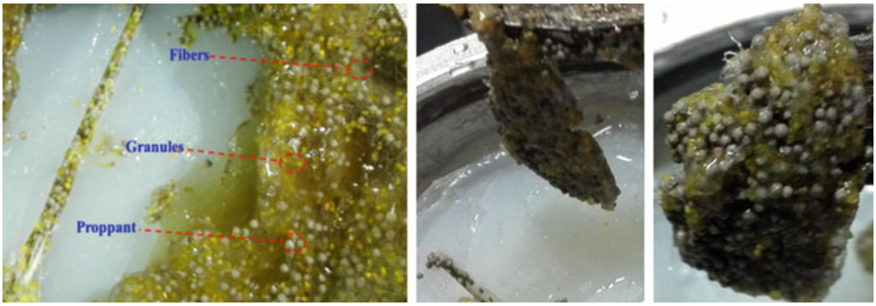

**Fig. 9** The composite temporary plugging layer in simulated fracture

### 3.2.4 Pressure-Bearing Experiment

The pressure-bearing experimental results of fiber temporary plugging layer, granular temporary plugging layer, and composite temporary plugging layer (60 wt% granule and 40 wt% fiber) are shown in Table 4. It can be seen from Table 4 that the pressure-bearing capacity of the fiber temporary plugging layer is the weakest, the maximum can bear the pressure is 3.7 MPa, the pressure-bearing capacity of granular temporary plugging layer is 4.5 MPa, and the pressure-bearing capacity of the composite temporary plugging layer is stronger than fiber and granular temporary plugging layers which can reach 7.1Mpa. The result means that the composite TPA (60 wt% granule and 40 wt% fiber) has excellent plugging performance and can meet the requirements of the blocking and steering of reservoirs.

**Table 4** Pressure-bearing experimental results of temporary plugging layers

| TPA | Fiber TPA | Granular TPA | Composite TPA |
|---|---|---|---|
| Pressure (MPa) | 3.7 | 4.5 | 7.1 |

## 4 Conclusions

With the study of the experiments in this paper, following conclusions can be drawn:

(1) According to the results of degradation experiment, both the JRS-1 fiber TPA and QXD-1 granular TPA have appropriate degradability for temporary plugging technology. At ground temperature, the TPAs will not be degraded. They will be degraded less than 5% at construction temperature after 2 h, which does not affect the using effect. And the TPAs can be degraded more than 95% at high temperature condition to recover the flow conductivity of original fracture.

(2) According to the results of temporary plugging experiment: JRS-1 fiber TPA, QXD-1 granular TPA, and composite TPAs can block the stimulated fracture. When the ratio of granular TPA is 55–65 wt%, and the ratio of fiber TPA is 35–45 wt%, the composite TPA has better plugging effect than that of the fiber and

granular TPA used alone. And the plugging effect of the composite TPA with 60 wt% granule and 40 wt% fiber is the best.

(3) According to the results of pressure-bearing experiment, composite temporary plugging layer (60 wt% granule and 40 wt% fiber) can withstand the pressure of 7.1 MPa., it is much higher than the fiber or granular temporary plugging layer. It means that the composite TPA (60 wt% granule and 40 wt% fiber) has excellent plugging performance and can meet the requirements of the blocking and steering of the general reservoir.

**Acknowledgements.** This work is partially funded by the National Natural Science Foundation of China (Grant No. 51674278) and the National Science and Technology Major Project of China (Grant No. 2016ZX05034001-007 and 2017ZX005030005).

## References

1. Wang H, Zhang S. Numerical calculation method for hydraulic fracturing design. 1st edn. Petroleum Industry Press, 1998.
2. Economides MJ, Nolte KG. Reservoir stimulation. 3rd edn. Wiley & Sons, Inc, 2003.
3. Li S, Zhang D, Li X. A new approach to the modeling of hydraulic-fracturing treatments in naturally fractured reservoirs. SPE J. 2017;22(4):1064–81.
4. Wen Q, Wang S, Duan X, Li Y, Wang F, Jin X. Experimental investigation of proppant settling in complex hydraulic natural fracture system in shale reservoirs. J Nat Gas Sci Eng. 2016;33:70–80.
5. Harrison AL, Jew AD, Dustin MK, Thomas DL, Joe-Wong CM, Bargar JR, Maher K. Element release and reaction-induced porosity alteration during shale-hydraulic fracturing fluid interactions. Appl Geochem. 2017;82:47–62.
6. Li Y, Yao F, Weng D, Yi X, Yu Y, Jiang X. Progress and prospect of repeated fracturing technology. J Oil Gas Technol. 2005;27(5):789–91.
7. Wang D, Zhou F, Ding W, Ge H, Jia X, Shi Y, Wang X, Yan X. A numerical simulation study of fracture reorientation with a degradable fiber-diverting agent. J Nat Gas Sci Eng. 2015;25:215–25.
8. Leal Jauregui JA, Malik AR, Nunez Garcia W, Solares JR, Bukovac T, Sinosic BV, Gurmen MN. Successful application of novel fiber laden self-diverting acid system during fracturing operations of naturally fractured carbonates in Saudi Arabia. In: SPE Middle East oil and gas show and conference. society of petroleum engineers, Manama, Bahrain, 25–28 January 2011.
9. Shi Y, Zhou F, Yang X, Liu X, Lian S, Li X. Laboratory study and filed application of fiber-based fracture reorientation technology. In: International petroleum technology conference. Beijing, China, 26–28 March 2013.
10. Cohen CE, Tardy PMJ, Lesko TM, Lecerf BH, Pavlova S, Voropaev, SV, Mchaweh A. Understanding diversion with a novel fiber-laden acid system for matrix acidizing of carbonate formations. In: SPE annual technical conference and exhibition. society of petroleum engineers, Florence, Italy, 19–22 Sept 2010.
11. Droger N, Eliseeva K, Todd L, Ellis C, Salih O, Silko N, Fu D, Meyer A, Bermudez R, Degradable fiber pill for lost circulation in fractured reservoir sections. In: IADC/SPE drilling conference and exhibition. society of petroleum engineers, Fort Worth, Texas, USA, 4–6 March 2014.

12. Sau R, Shuchart C, Clancey B, Lecerf B, Pavlova S. Qualification and optimization of degradable fibers for re-stimulation of carbonate reservoirs. In: International petroleum technology conference. Doha, Qatar, 6–9 Dec 2015.
13. Wang D, Zhou F, Ge H, Shi Y, Yi X, Xiong C, Liu X, Wu Y, Li Y. An experimental study on the mechanism of degradable fiber-assisted diverting fracturing and its influencing factors. J. Nat Gas Sci Eng. 2015;27:260–73.
14. Gomaa AM, Nino-Penaloza A, McCartney E, Mayor J. In: Engineering solid particulate diverter to control fracture complexity: experimental study. In: SPE hydraulic fracturing technology conference. Society of Petroleum Engineers, The Woodlands, Texas, USA, 9–11 Feb 2016.