Mixed Preformed Particle Gel System for Water Shutoff in Fractured Carbonate Reservoir

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Abstract / Water shutoff from a production well using particle type material is a great challenge, due to the complex pressure and flow distributions near the wellbore. A mixed preformed particle gel (ppg) system was developed to enhance the performance for water shutoff in fractured carbonate reservoirs. The ppg blocking behaviors in fractures and methods to improve the water flush tolerance were investigated. Effects of the ppg strength dominated the water shutoff performances in the fractures.

The ppg with medium to high strength showed a better performance than other samples, due to the well-adjusted properties in blocking and flush tolerance. For the selected ppg, a 30-mesh sample showed the best blocking performance among single mesh samples from 20 mesh to 80 mesh, in the fractured artificial metal plug. Using the 30-mesh sample as a base sample, the 30-mesh and 40-mesh mixture with a weight ratio 2:1, produced the highest pressure build-up in two size ppg mixtures.

By further increasing the particle size distribution by combining various particle size ppgs, the blocking performance was improved. An optimized combination of 30-mesh, 40-mesh, 50-mesh, and 60-mesh particles with a weight ratio of 4:2:1:0.25, respectively, was developed. In addition, a fiber material, added in the ppg, significantly improved the water flush tolerance of the ppg pack.

A particle size combination of ppgs, mixed with the fiber material, generated better blocking performances than the other combinations. This study provides insights on packing behavior of deformable gel particles in fractures with a practical ppg-based system for water shutoff treatments.

Introduction

Preformed particle gels (ppg) have been widely used in conformance control, water shutoff, and in-depth fluid diversion in heterogeneous reservoirs to control excessive water production[1-3]. The ppg is a polymeric gel particle material crushed from the bulk gel, in which the gelation reaction has finished before injection into the reservoir[4, 5]. The particle sizes of the ppg range from micro to centimeter. Compared with traditional in situ gel treatment, ppgs with a cross-linked network inside showed excellent chemical, thermal, and mechanical stabilities for various reservoir conditions[6, 7].

From the late 1990s, the ppg technology has been applied in thousands of wells for water management[8]. The main mechanism of ppg injection is to block high permeability zones or fractures by forming a gel pack during the migration in reservoirs. Different from inorganic particles, ppg particles are water swellable, and therefore, elastic and deformable. As such, the swollen ppg particles can pass through smaller pores due to their elasticity and deformability[7, 9].

The effects of fracture/particle size, ppg strength on ppg flow and blocking behaviors have been extensively investigated in both uniform and heterogeneous fractures[10]. The results showed ppg strength affected injectivity and blocking performance more dramatically than particle size[11, 12]. The reservoir heterogeneity affected the matching of ppg mesh size with the reservoir[13].

Different methods to improve ppg blocking performance were investigated, including mixing different ppg samples and with other materials. Alhuraishawy et al. (2017)[14] reported that combining two different ppg sizes produced higher plugging efficiency than uniform size ppg, and the residual resistance factor decreased as the flow rate increased. The optimum ppg size ratio is (1:1) 850 and 250 micrometers. Sun et al. (2019)[15] proposed to combine curable resin coated particles with ppg to control water production from fractured producers. The results showed the cured resin coated particles could generate immobile packs in fractures, and dramatically mitigate the ppg washout.

In this work, different ppg samples were evaluated and compared. The effects of ppg strengths and particle size combinations were studied. New methods were developed to improve ppg performance by adjusting particle size distribution and adding other materials into the ppg mixtures.

Experimental

PPG Samples

Four ppg samples with similar initial dry particle sizes were used in the tests. The strength of the four samples in injection water increased from 2,800 Pa to 13,900 Pa[16]. Accordingly, the swelling ratio decreased from 18.49 to 3.87.

Table 1 lists some of the basic information of the ppg samples used.

Brine

Synthetic injection water was used to prepare the ppg suspensions. The salinity — total dissolved solids (TDS) — was 2,425 mg/L. Table 2 lists the ion composition of the brine used.

Core Plugs

A cylindrical carbonate outcrop and artificial metal plugs were used to make fractures. Table 3 lists the basic properties of the two core plugs. The brine permeability of the outcrop core was around 35 mD. It was cut longitudinally along the axis to form an open fracture with a height of 2 mm. The artificial metal plug was composed of two halves with a thread end. A fracture with a height of 2 mm could be formed by resembling the two halves.

PPG Blocking Test

The ppg blocking tests were conducted by using the coreflooding method. The procedures followed are:

1. Prepare the ppg samples in injection water and allow them to fully swell overnight.
2. Put quantitative swollen ppg without free water on one side of the fractured core. Reassemble the other side with end plugs and O-rings to create an artificial fracture filling with ppg.
3. Load into the coreholder and set the confining pressure to 500 psi.
4. Inject the brine into the core at a flow rate of 0.5 mL/min, 1 mL/min, 2 mL/min, and 4 mL/min at a confining pressure of 500 psi at ambient and record the differential pressure.

Results and Discussion

Comparison of ppgs with Different Strength

The blocking abilities of four ppg samples with different strengths were tested by injecting water into a gel packed artificial open fracture. The ppgs were placed manually in the fracture to form a gel pack. The amount of the ppgs were 1.5 times the fracture volume (FV) in all tests. Table 4 lists a comparison of the four tests.

Table 1 *Some basic information of the ppg samples used.*

PPG Sample	Absorption Deionized Water (g/g)	Apparent Powder Density (g/mL)	Initial Particle Size (mm)	Strength in Injection Water (Pa)	Swelling Ratio in Injection Water
HOP-1	46.40	1	0.426	2,800	18.49
HOP-2	30.84	0.95	0.524	5,300	10.16
HOP-3	4.96	0.96	0.444	9,700	4.47
HOP-4	5.08	0.95	0.404	13,800	3.87

Table 2 *The composition of the brine used.*

Brine/Ion	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	HCO_3^- (mg/L)	SO_4^{2-} (mg/L)	TDS (mg/L)
Injection Water	442	262	80	760	199	682	2,425

Table 3 *The basic properties of the two core plugs.*

Core No.	Length (cm)	Diameter (cm)	Pore Volume (mL)	Gas Permeability (mD)	Brine Permeability (mD)
L55	7.07	3.81	10.34	48.11	~35
Artificial Metal Plug	7.00	3.81	—	—	—

Table 4 The comparison of ppgs with different strengths.

Test No.	PPG Sample	Swollen Particle Size (mm)	Fracture Height (mm)	Pack Volume (FV)	Stable Differential Pressure (psi)			
					0.5 mL/min	1 mL/min	2 mL/min	4 mL/min
1	HOP-1	2.4	2	1.5	3.75	5.72	—	—
2	HOP-2	2.2	2	1.5	6.61	9.84	15.41	—
3	HOP-3	1.1	2	1.5	5.48	9.80	17.21	29.87
4	HOP-4	1.1	2	1.5	3.81	6.97	12.78	23.51

Figures 1 and 2 show the results of the tests that used ppg samples HOP-1 and HOP-3, respectively. For HOP-1, with the lowest strength, the differential pressure first increased rapidly and then decreased to a stable value after the first two low injection rates. At a high flow rate of 2 mL/min, the gel pack was broken through with an unstable decreasing pressure. Subsequently, the differential pressures of HOP-3 were higher, and all were stable at the four flow rates. The stable differential pressure and breakthrough flow rate are listed in Table 4 for all four tests.

The HOP-2 ppg sample had a slightly high differential pressure than HOP-1. The breakthrough flow rate was 4 mL/min. Although the strength was the highest, HOP-4 did not perform as well as HOP-3 in both blocking and flush resistance. The medium to high strength HOP-3 produced the highest differential pressure among the four samples, and the gel pack was stable — even at high flow rates.

The reason for the differences came from the elastic nature of the ppgs. As listed in Table 1, the strength of the four samples decreased from 2,800 Pa to 13,800 Pa, respectively. For samples HOP-1 or HOP-2 with low strength, the pack was deformable and the interparticle pores were small due to the deformation. At the very beginning of the water injection, the pressure increased because the pores between the particles were small.

Meanwhile, the particles deformed with the pressure, and water was easy to breakthrough, resulting in a decrease of the pressure. The high flow rates made the deformation worse. For sample HOP-4 with high strength, the pack was permeable due to the large interparticle pores. This produced a stable but low pressure. The gel particles were more likely to move with water because of the lack of deformation at high flow rates. Sample HOP-3, with a median strength, balanced the blocking and flush tolerance. The proper deformability, on one hand, produced small interparticle pores for firm blocking, while on the other hand, it made the pack elastic so as to withstand the high flow rate flush.

Comparison between Single Size ppg and ppg Mixture

Using ppg sample HOP-3 as a base sample, the blocking abilities of single mesh ppg and ppg mixtures were compared. To exclude the effect of matrix permeability, the artificial fracture metal plug made of stainless steel was used. The fracture size was 7 cm × 2 cm × 0.2 cm (L×H×W). As mentioned before, the ppg blocking

Fig. 1 The differential pressure during water injection into the HOP-1 ppg sample packed fracture with a height of 2 mm.

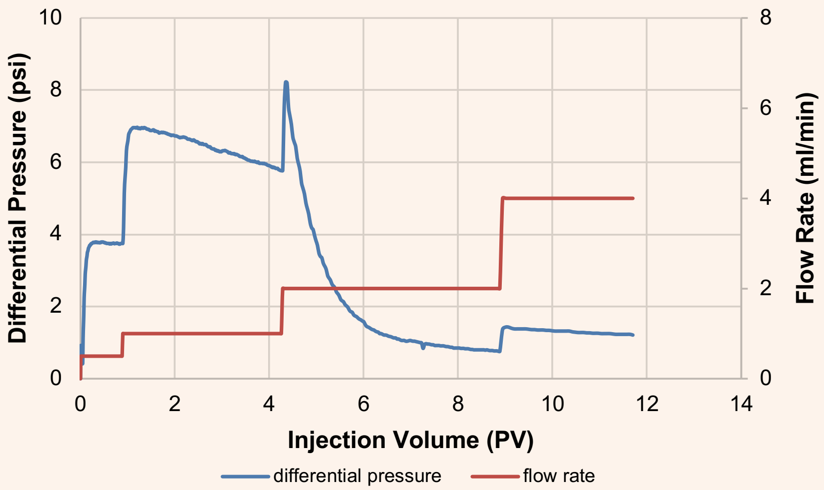
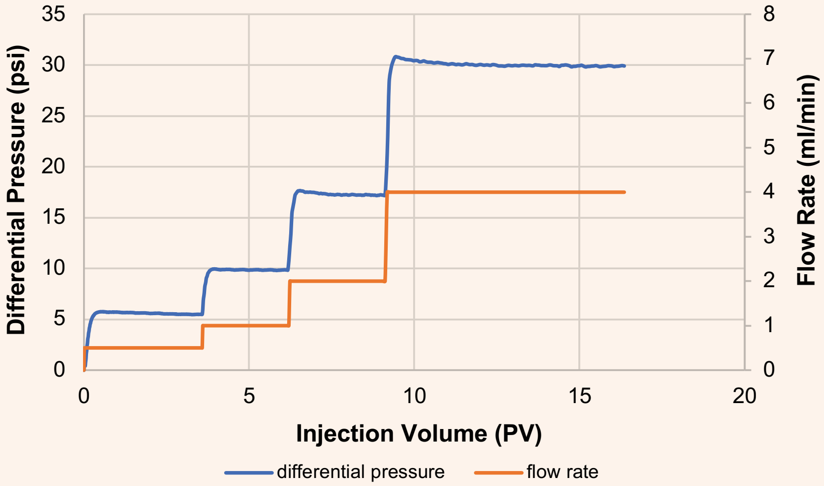


Fig. 2 The differential pressure during water injection into the HOP-3 ppg sample packed fracture with a height of 2 mm.



abilities were tested by injecting water into a gel packed artificial open fracture.

Two methods were used to get the quantitative ppg sample to pack in the fracture. The first method was through the weight of wet swollen ppgs without free water. Because the free water cannot be drained completely, the actual ppg weight was slightly different from sample to sample. To overcome this, a new method of using a dry ppg sample weight was used to confirm the results. The ppg samples with the same dry weight swelled in the brine, and were placed in the fracture to guarantee repeatability.

Figure 3 shows the differential pressure change during the water injection into a core plug with the fracture packed with a ppg mixture as an example. Table 5 lists all the tests conducted and summarizes the stable differential pressures.

The blocking abilities of the single size ppg samples were first evaluated in Test 1 to Test 6. The particle sizes of the ppgs ranged from 20 mesh to 80 mesh. Among the six samples, the ppg with 30 mesh produced the highest differential pressure at all the flow rates — from 0.5 mL/min to 8 mL/min. For the 20-mesh sample, the interparticle pores in the pack may be large due to the large particle size and the permeability to water was higher. For the smaller samples from 40 mesh to 80 mesh, the apparent volume was lower than the larger sample. The pack was not as firm as the 30-mesh sample at the same wet weight, therefore, the pressure buildup was lower.

To evaluate the blocking ability of the ppg mixture,

Fig. 3 The differential pressure during water injection into sample HOP-3 packed the fracture in Test 7.

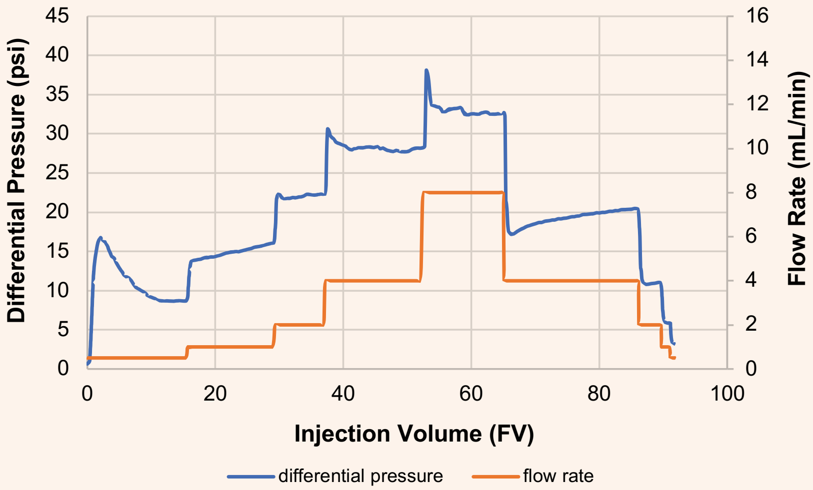


Table 5 The ppg blocking tests using single size ppg and ppg mixtures.

Test No.	Weight of Different Mesh Samples (g)							Method	Stable Pressure (psi)				
	20	30	40	50	60	80	100		0.5 mL/min	1 mL/min	2 mL/min	4 mL/min	8 mL/min
1	4.0094	—	—	—	—	—	—	Wet	0.76	1.60	3.34	6.18	11.81
2	—	4.0058	—	—	—	—	—	Wet	3.85	6.05	10.83	16.29	24.19
3	—	—	4.0099	—	—	—	—	Wet	3.28	4.68	7.92	12.71	20.28
4	—	—	—	4.0036	—	—	—	Wet	0.71	1.26	2.08	3.36	5.93
5	—	—	—	—	4.0049	—	—	Wet	0.93	1.59	1.81	3.35	6.83
6	—	—	—	—	—	4.0068	—	Wet	1.49	2.01	3.28	6.06	10.78
7	—	3.0028	1.0027	—	—	—	—	Wet	8.70	16.06	22.30	28.15	32.21
8	—	3.0049	—	—	1.0005	—	—	Wet	11.8	17.04	22.73	28.40	30.06
9	—	3.0043	—	—	—	1.0017	—	Wet	9.72	15.20	21.78	27.78	28.88
10	—	3.0058	—	—	—	—	1.0002	Wet	12.07	16.72	21.45	25.65	24.24
11	—	0.6009	—	—	0.2006	—	—	Dry	4.28	7.77	14.33	20.51	21.92
12	—	0.6007	—	—	—	—	0.2015	Dry	5.89	11.05	17.31	20.72	21.80
13	—	0.6604	—	—	0.2213	—	—	Dry	11.45	20.41	26.37	27.30	—
14	—	0.6602	—	—	—	—	0.2202	Dry	12.41	20.38	26.73	28.69	—
15	—	0.7204	—	—	0.2410	—	—	Dry	40.85	40.05	—	—	—
16	—	0.7208	—	—	—	—	0.2402	Dry	20.74	26.35	31.37	—	—
17	—	0.8806	—	—	—	—	—	Dry	7.36	14.13	21.34	30.19	32.82
18	—	—	—	—	0.8810	—	—	Dry	3.35	5.56	10.29	17.72	23.90

the 30-mesh sample was selected as the base sample to mix with other smaller samples at a weight ratio of 3:1. Four tests were conducted using 40-mesh, 60-mesh, 80-mesh, and 100-mesh samples in Test 7 to Test 10. The results showed that the ppg mixture produced a higher differential pressure than the single ppg sample, especially at a low flow rate. The results between different mixtures were not so comparable. A trend was found that the 30-mesh ppg, mixed with smaller samples, such as 80 mesh and 100 mesh, produced higher differential pressure at low flow rates, but lower differential pressure at high flow rates, than the relatively larger samples like 40 and 60 mesh.

To improve the repeatability, the ppg mixture was prepared using the dry samples instead of the swollen wet ones. Different pack densities were evaluated by adjusting the total weight from 0.8 g to 0.96 g. Two different ppg mixtures were compared, 30 mesh + 60 mesh and 30 mesh + 100 mesh, as in Test 11 to Test 16. Two more tests, Tests 17 and 18, were conducted to confirm the single ppg case. In the loose pack case, the results supported the previous results that the 30-mesh ppg mixed with a smaller sample produced a higher differential pressure than with the larger sample.

In the firm pack case, mixing with the larger sample seemed to perform better. In the tests using a single ppg sample of 30 mesh and 60 mesh, the single ppg sample showed much lower pressure buildup at a low flow rate, but good tolerance to water flush at a high flow rate compared with the ppg mixture in Tests 13 and 14, with the same sample weight.

Improvement by Widening Particle Size Combinations

Widening the particle size distribution is a common routine to get a firmer solid packing. Next, the wide particle size combinations, including three-particle size, four-particle size, and five-particle size were tested with the same total sample weight. Table 6 lists the ppg mixtures and weight ratios in different tests and summarizes the stable pressures.

The first five tests used the three-particle size combination to compare the base two-particle size weight ratios of 9:3 and 4:2. Test 3 and Test 4 used 4:2 as the base two-particle size weight ratio and showed a much better

Table 6 *The ppg blocking tests using a wider mixture with a different weight ratio.*

Test No.	Weight of Different Mesh Samples (g)					Weight Ratio	Stable Pressure (psi)			
	30	40	50	60	80		0.5 mL/min	1 mL/min	2 mL/min	4 mL/min
1	0.6092	0.2031	0.0677	—	—	9:3:1	28.18	30.92	95.55	200.00
2	0.6336	0.2112	0.0352	—	—	9:3:0.5	21.26	21.70	24.95	200.00
3	0.5029	0.2514	0.1257	—	—	4:2:1	23.20	28.24	149.62	129.54
4	0.5415	0.2708	0.0677	—	—	4:2:0.5	25.74	29.21	141.75	—
5	0.6465	0.2150	0.0179	—	—	9:3:0.25	21.88	29.17	52.92	220.68
6	0.4400	0.2200	0.1100	0.1100	—	4:2:1:1	19.10	25.83	26.18	164.46
7	0.4888	0.2444	0.1222	0.0244	—	4:2:1:0.2	19.68	22.89	23.20	22.36
8	0.4821	0.2410	0.1205	0.0361	—	4:2:1:0.3	18.24	25.92	26.03	68.19
9	0.4855	0.2427	0.1213	0.0303	—	4:2:1:0.25	25.63	33.53	34.56	66.43
10	0.4693	0.2346	0.1173	0.0586	—	4:2:1:0.5	22.12	28.55	27.58	70.12
11	0.4693	0.2346	0.1173	0.0293	0.0293	4:2:1:0.25:0.25	20.93	23.17	26.55	200.12

stable pressure performance than the 9:3 based particle size combination in Test 1 and Test 2. Test 5 used another 9:3 based ratio and confirmed that the performance was not as good as the 4:2 based tests. Comparing Test 3 and Test 4, a weight ratio of 4:2:1 showed a little higher pressure buildup and was used as the base weight ratio for the four- and five-particle size combination tests.

Test 6 to Test 10 used various four-particle size weight combinations. The pressure results did not vary much among all the tests and the pressure value seemed a little lower than the three-particle size combination, especially for the high flow rate region. This may be because the small particles were easily moved and even produced from the outlet at the water flush, causing the pack to be not as firm as in the beginning. Test 11, using a five-particle size combination, also showed lower pressures. Among Test 6 to Test 11, the weight ratio of 4:2:1:0.25 in Test 9 showed a little higher pressure build up in both the low and high flow rate region.

Improvement by Mixing with Additives

By widening the particle size distribution, the blocking ability of the ppg mixtures were improved at the low flow rate region by the closer packing. At a high flow rate, the ppg pack seemed not so stable, due to the particle migration. Two methods were tried to further improve the water flush tolerance, Table 7. In the first method, a fiber material was added into the mixture, in a very limited amount. In the second method, the dry ppg mixture absorbed brines containing a kind of organic crosslinker and placed in the fracture. A polymer solution was injected into the ppg pack containing a crosslinker to form gels.

Test 1 and Test 3 used the fiber method, where the pressure values at both a low and high flow rate region increased very significantly. The adding of fiber material improved the stability and water flush tolerance of the

Table 7 *The ppg blocking tests using ppg mixed with other material.*

Test No.	PPG Mixture	PPG Mixture Ratio	Additives	PPG/Additive Weight Ratio	Stable Pressure (psi)			
					0.5 mL/min	1 mL/min	2 mL/min	4 mL/min
1	HOP-3 30, 40, 50, 60 mesh	4:2:1:0.25	Fiber	0.25	36.04	186.67	225.54	345.77
2	HOP-3 30, 40, 50, 60 mesh	4:2:1:0.25	Crosslinker and polymer	0.5% and 0.2%	0.60	0.88	1.26	1.82
3	HOP-4 40, 60, 80, 100 mesh	9:3:1:0.25	Fiber	0.25	40.93	184.46	273.05	153.66

ppg pack. Test 2 used the second method. The swelling ratio of the ppg in the brine containing a crosslinker was much lower than the case without a crosslinker. This made the pressure much lower, even with the polymer injection.

Conclusions

This work evaluated and compared different ppg samples with the effects of ppg strength, ppg pack density, and particle size. New methods, by adjusting particle size distribution and adding other materials into the ppg mixtures, were developed to improve ppg performance.

1. The strength of the ppg samples affected the ppg blocking performance significantly. The sample with medium to high strength showed better performance than other samples, due to the well-adjusted properties in blocking and flush tolerance.
2. For the selected sample, sample HOP-3, the 30-mesh sample showed the best blocking performance among samples from 20 mesh to 80 mesh. The base sample, 30 mesh mixed with a sample 40 mesh, produced the highest pressure buildup in the open fracture.
3. By widening the particle size distribution, the tightness and blocking ability of the ppg pack was improved, especially at the low flow rate region. The weight ratio 4:2:1:0.25 was selected for the 30-mesh, 40-mesh, 50-mesh, and 60-mesh combination of sample HOP-3.
4. By adding fiber material into the mixture, the ppg pack stability and water flush tolerance were significantly improved. Adding a crosslinker and polymer material did not perform as well as fiber.

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