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Washout of Cr(III)-Acetate-HPAM Gels from Fractures

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Abstract

This paper investigates washout of mature Cr(III)-acetate-HPAM gels from fractures. After gel placement, the pressure gradient for gel washout during brine or oil flow was similar to the pressure gradient observed during gel placement. The mechanism of gel failure involved the displacement of relatively mobile gel from wormholes. Generally, only a small fraction of the gel (<5%) was displaced during the washout process. Resistance to washout can be increased by injecting a more concentrated gel. However, this approach exhibits significantly higher pressure gradients during gel placement.

The presence of a constriction in a fracture inhibited gel washout during the first pulse of brine flow after gel placement. However, during subsequent brine flow, gel erosion occurred upstream of the constriction to the same extent as downstream. The extrusion, leakoff, and washout behavior in fractures in strongly oil-wet polyethylene cores were similar to those in strongly water-wet Berea sandstone.

Gel washout can be reduced by controlling gel placement rate. A Cr(III)-acetate-HPAM gel placed in a 0.04-in. wide fracture at 826 ft/d was about five times more resistant to washout than a gel placed at 4,130 ft/d. Gel washout can also be reduced using secondary crosslinking reactions. Post-placement reaction with Cr(III) acetate increased resistance to washout for a resorcinol-formaldehyde-HPAM gel by a factor from two to three.

During steady state flow after first breaching the gel, a Cr(III)-acetate-HPAM gel reduced permeability to water (within the fracture) moderately more (2.5 to 4.7 times) than that to oil. Disproportionate permeability reduction in fractures was most evident at low flow rates.

Introduction

In many field applications, gel treatments were less effective than expected in reducing water production from fractured wells. Concern exists about the resistance of gels to washout after placement. This paper examines several issues regarding washout of mature Cr(III)-acetate-HPAM gels from fractures. In particular, we investigate how gel washout is affected by the applied pressure gradient, fracture width, gel composition, presence of a constriction in the fracture, nature of the fracture surfaces, and flow of oil versus brine. We also consider two promising new methods to reduce gel washout—rate control during gel placement and use of secondary reactions.

Review of Gel Behavior in Fractures

Gel compositions used for conformance control usually contain more than 90% water—and frequently more than 99% water. For example, much of our research focused on an aqueous gel that contained 0.5% Ciba Alcoflood 935™ HPAM (molecular weight ≈$5x10^6$ daltons; degree of hydrolysis 5% to 10%), 0.0417% Cr(III) acetate, 1% NaCl, and 0.1% $CaCl_2$. The gelation time for this formulation is about 5 hours at 41°C. In this paper, this formulation (after aging 24 hours) is called our standard 1X Cr(III)-acetate-HPAM gel.

Gels can be placed in fractures either as gelants[1] or formed gels.[2,3] Gelants (the fluid solution of crosslinker and polymer that exists before gelation) flow readily into fractures and medium to high permeability rock, exhibiting relatively low pressure gradients during placement. However, gelants often experience problems with gravity segregation in fractures.[4] Also, when gelants contact reservoir fluids or rock minerals, compositional changes can occur that interfere with gelation.[1,5] Alternatively, formed gels (i.e., the crosslinked product of gelation) can be extruded into fractures during the placement process. Formed gels have significantly fewer problems with gravity segregation and chemical interference than gelants. However, formed gels exhibit water loss and higher pressure gradients during placement that may affect their distance of propagation along a fracture or into a fracture system.[2,3]

During extrusion through fractures, formed gels dehydrate—i.e., water (or brine) leaves the gel and leaks off through the fracture faces into the porous rock.[2,3] The crosslinked polymer remains behind in the fracture, becoming increasingly concentrated with time and gel throughput (i.e., crosslinked polymers do not flow through porous rock after gelation). Dehydrated gel usually becomes immobile at the point in the fracture where dehydration occurs. During placement, the only gel that generally moves through the fracture has basically the same composition, appearance, and properties as the injected gel.[2,3] However, small bits of the dehydrated gel can erode to join the flowing gel.

The pressure gradients required to extrude gels through fractures are greater than those for gelant flow. Depending on conditions, the effective viscosity of formed gels in fractures are typically 10^3 to 10^6 times greater than those for gelants.[2-4] However, useful gels do not show progressive plugging during extrusion through fractures. A minimum pressure gradient is required to extrude a given gel through a fracture. Once this minimum pressure gradient is exceeded, the pressure gradient during gel extrusion is insensitive to the flow rate.[2]

The rate of gel front propagation increases significantly with increasing injection rate.[2] Gel has less time to dehydrate as the injection rate increases. With a lower level of dehydration (concentration), the gel propagates a greater distance for a given total volume of gel injection. This result has important consequences for field applications. It suggests that gels should be injected at the highest practical rate in order to maximize penetration into the fracture system. On the other hand, in wide fractures or near the end of gel injection, gel dehydration may be desirable to form rigid gels that are less likely to washout after placement. In these applications, reduced injection rates may be appropriate.[2]

For a Cr(III)-acetate-HPAM gel, the pressure gradient required for extrusion varys inversely with the square of fracture width (**Fig. 1**). In contrast, a force balance predicts that the pressure gradient should vary inversely with fracture width.[6] Although the origin of this behavior has not been definitively identified, it is directly linked to the extremely strong apparent shear-thinning behavior during extrusion.[6] Note from Fig. 1 that the pressure gradient for gel extrusion is not sensitive to the permeability of the porous medium that contains the fracture (i.e., from 1.5 to 10,000 md).

A new model was developed to describe water leakoff from gels during extrusion through fractures.[3] The rate of gel dehydration varies inversely with the square root of time**.** Fresh (mobile) gel wormholes through concentrated gel.[2,3] Early in the process of gel injection, the wormhole pattern is very branched, with a significant fraction of the fracture area contacted by the wormholes. As additional gel volumes are injected, the wormholes become less branched, and a diminished fraction of the fracture area is contacted by the wormholes. This behavior is not surprising since the dehydrated gel becomes increasingly concentrated and less mobile and the mobility ratio (mobility of fresh gel divided by mobility of concentrated gel) increases with gel throughput.

The leakoff behavior and pressure gradients during gel extrusion are not sensitive to temperature from 20°C to 80°C.[3] Elastic modulus is also insensitive to temperature.[6] In contrast, the viscosity of water decreases by a factor of approximately three as temperature rises from 20°C to 80°C.

For gel compositions between 1X and 3X, the leakoff behavior is not sensitive to polymer concentration.[3] (The "X" multiplier refers to the HPAM and chromium concentrations relative to those in our standard 1X gel. The HPAM/Cr(III)-acetate ratio was fixed at 12/1.) In these experiments, the gels were aged for one day at 41°C before injection at 4,130 ft/d into 6-in.-long, 1.5-in.-diameter Berea cores that each contained a 0.04-in.-wide fracture. Pressure gradients during gel extrusion increase approximately with the square of polymer content in the gel.[3] This behavior parallels that for measurements of elastic modulus versus gel composition.[6] However, based on force balance considerations, the pressure gradients during gel extrusion through fractures are much greater (i.e., 87 times greater) than expected from measurements of elastic modulus.[6]

Ganguly *et al.*[1] studied gel rupture in tubes. Their gel was placed as gelant in 0.094-in. to 0.30-in. diameter plastic tubes. The gel contained 0.75% Alcoflood 935 HPAM, 0.0417% Cr(III) acetate, 1% NaCl and was aged for 6-8 days at room temperature. During brine injection after gel formation, the pressure required to rupture the gel varied almost linearly with the ratio of tube length to inner tube diameter.[1] Stated another way: the pressure gradient for gel rupture varied inversely with the tube diameter. This result was expected based on a simple force balance.[6] In fact, given that the elastic modulus of the gel was 17.6 Pa (0.0025 psi)[3,6], the experimental data of Ganguly *et al.* were quantitatively consistent with predictions from a simple force balance. A key difference exists between placement with gelants (i.e., as in Ganguly's work) versus placement with formed gels. With gelant placement, the entire fracture cross-section (ideally) is filled with a low-concentration, homogeneous gel. In contrast, with placement of formed gels, most of the fracture cross-section is filled with concentrated immobile gel. Only small wormholes contain the low-concentration gel that can be readily mobilized.

Experimental Procedures

To characterize gel washout, many experiments were performed where brine was injected at various rates after gel extrusion into fractured cores. In most cases, the core material was 700-md Berea sandstone, with a fracture placed lengthwise down the middle of each core. Unless stated otherwise, the fractures had lengths of 4 ft (122 cm) and heights of 1.5 in. (3.8 cm). The cross-sectional area of each core was 2.25 in.^{2} (14.5 cm^2). Each core contained four equally spaced internal pressure taps along the fracture—separating the core and fracture into five sections of equal length (9.6 in. or 24.4 cm). In each fractured core, 3,700 cm^3 of one-day-old Cr(III)-acetate-HPAM gel (i.e., a formed gel) were injected—typically using a rate of 2,000 cm^3/hr. After gel placement, the core was shut in for one day. (All experiments were performed at 41°C. Details can be found in Ref. 7.) Next, brine was injected at a low rate (e.g., 100 cm^3/hr). A steady state was established, and the pressure gradient was recorded. Then the brine injection rate was doubled, and the measurements were repeated. This process was repeated in stages up to a final brine flow rate of 16,000 cm^3/hr. Then the rate was decreased in stages.

Washout during First Brine Flow after Gel Placement

Representative results were obtained using our standard 1X Cr(III)-acetate-HPAM gel in a fracture with a width of 0.04 in. (1 mm). The solid line in **Fig. 2** shows the average pressure gradient (9.9 psi/ft) during gel injection (at 4,130 ft/d effective velocity in the fracture or 2,000 cm^3/hr). After 80 fracture volumes of gel, brine was injected at 206 ft/d (100 cm^3/hr). The symbols in Fig. 2 show the pressure gradients in the five fracture sections during this first brine injection. In the first fracture section, the pressure gradient peaked at 10.5 psi/ft after 0.30 fracture volumes of brine. Pressure gradient peaks in the other four fracture sections occurred within the next 0.2 fracture volumes. The peaks indicate the time associated with gel failure and washout in each of the sections. In Sections 1, 4, and 5, the pressure gradient peaks (10.5, 11.1, and 9.1 psi/ft, respectively) were similar to the average pressure gradient during gel placement (9.9 psi/ft). Interestingly, in Sections 2 and 3, the peaks occurred at 13.0 and 20.3 psi/ft, respectively. These anomalies reveal that a degree of variability exists—perhaps associated with temporary screen outs for gel within the fracture. This variability is also reflected in the pressure gradients during gel extrusion through fractures of a given width (see Fig. 1). However, to a first approximation, the pressure gradient for washout was similar to the pressure gradient during gel placement.

After each peak, the pressure gradient dropped sharply, averaging between 1 and 1.6 psi/ft in four of the five fracture sections after one fracture volume of brine. In Section 5, the pressure gradient was 3.4 after one fracture volume. This difference also points to variations in gel movement and washout. Further evidence of variation is provided by the small pressure gradient peaks near 0.75 fracture volumes (Fig. 2). This variation may have been caused by a gel piece mobilizing in the upstream sections of the fracture and ultimately becoming trapped in Section 5.

As mentioned, during placement, mobile gel forms wormholes through concentrated immobile gel. Presumably, the gel in the wormholes provided the point of failure during brine injection. Several observations support this suggestion. First, during brine injection, the pressure gradient peaks occurred within 0.2 fracture volumes of each other, indicating that the pathway that opened within the gel (i.e., the wormholes) was significantly smaller than one fracture volume in size. Second, after the peaks, the stabilized pressure gradients (i.e., 1 to 3.4 psi/ft) were substantially greater than the values expected for brine flow through an open 0.04-in. wide fracture. Standard calculations for laminar flow of brine in tubes or slits[8] (coupled with the brine pressure gradients and flow rates) suggested that less than 1% of the gel washed out during brine injection. In contrast, if the entire gel mass had washed out, the brine pressure gradients should have been lower by a factor of 4,000. Finally, at the end of the experiment (i.e., after the rate studies described below), the fracture was opened—revealing wormholes and showing that most of the fracture was filled with concentrated gel.

Washout at Higher Rates

The pressure gradients during brine injection at other rates are shown in **Fig. 3**. The open triangles show the maximum pressure gradients (at a given rate), when the rates were increased in stages. Note that the maximum pressure gradient decreased for the first two rates in the sequence, and then the pressure gradients consistently rose for the higher rates. Presumably, brine displaced gel in the wormholes during brine injection at the lowest rate (Fig. 2). For subsequent rate increases, gel erosion was less significant, although some probably occurred. During brine injection at 4,130 ft/d (2,000 cm^3/hr), the maximum pressure gradient was about the same as the average pressure gradient during gel injection at the same rate (solid square in Fig. 3).

In Fig. 3, the solid triangles show the maximum pressure gradients when the rates were decreased in stages. The open circles show the average pressure gradients when the rates were increased in stages, while the solid circles show the average pressure gradients when the rates were decreased in stages. As expected, for these curves, the pressure gradients increased monotonically with increased rate. Exposure to the increasing/decreasing rate cycle caused the average pressure gradient at 206 ft/d (100 cm^3/hr) to decrease by a factor of 10 (from 1.7 to 0.17 psi/ft).

Figs. 2 and 3 suggest that the greatest damage to the gel occurred during the first exposure to the pressure gradient experienced during gel injection. Certainly, exposure to larger flow rates and pressure gradients caused additional damage to the gel. However, the incremental damage was less severe than that after the first large pressure pulse (Fig. 2). The greatest discrepancy between the average and maximum pressure gradients occurred during the first brine injection stage (i.e., 206 ft/d). This behavior is consistent with gel of the original composition being washed out from wormholes. Presumably, larger pressure gradients were required to erode the more concentrated gel from the sides of the wormholes.

A regression indicated that the average pressure gradient for the increasing rate sequence varied with rate raised to a power around 0.4. In constrast, for the decreasing rate sequence, the average pressure gradient varied directly with rate. The latter correlation suggested that little additional gel washout occurred during the decreasing rate sequence.

The data from Fig. 3 can be used to calculate an effective average diameter for a wormhole through the gel.[8] This analysis helps to visualize and quantify the gel erosion process. In the simplest case, brine is assumed to flow through a single wormhole, with the remainder of the fracture being filled with an impermeable gel. **Fig. 4** plots these calculated wormhole diameters relative to the width of the fracture. For the lowest brine injection rate (i.e., the stabilized rate after the peak in Fig. 2), the estimated wormhole diameter was about 40% of the width of the fracture. As the brine injection rate increased, the wormhole diameter increased, reaching about 90% of the fracture width at the highest rate. Even at the highest rate, this analysis suggested that brine occupied less than 2% of the fracture volume (the remainder being occupied by gel).

Effect of Fracture Width

Experiments were performed (using the 1X Cr(III)-acetate-HPAM gel) to examine how gel washout was affected by fracture width, using widths of 0.02, 0.04, 0.08, and 0.16 in. These fractures were 4-ft long and 1.5-in. high in 4-ft long Berea cores with a 1.5x1.5-in. cross-section. **Fig. 5** shows the results. In this figure, the *y*-axis plots the final core permeability relative to the permeability of an unfractured core. If no damage was caused to the matrix, a *y*-value of unity meant that the gel "healed" the fracture. As the *y*-value increased above unity, the fracture became more open or conductive—indicating a greater degree of gel washout. For *y*-values below unity, the fracture may have been plugged, and the gel caused some damage to the matrix. The *x*-axis plots the maximum pressure gradient observed during brine injection at a particular rate (i.e., using the brine injection sequence described in Fig. 3). As expected, the gel's resistance to washout increased with decreased fracture width. The pressure gradients where dramatic increases in permeability occurred (i.e., washout) were generally similar to or less than the pressure gradients observed during gel placement (Fig. 1).[2] The average pressure gradients (averaged over the middle three fracture sections) during gel placement were 20.9, 9.9, 4.0, and 2.4 psi/ft for fracture widths of 0.02, 0.04, 0.08, and 0.16 in., respectively.

Effect of Gel Concentration

In a 4-ft long, 0.04-in. wide fracture, gel washout was less severe for a 2X Cr(III)-acetate-HPAM gel (i.e., a gel with twice the Cr and twice the HPAM) than for a 1X gel (see **Fig. 6**). However, the pressure gradient required for placement was significantly greater for the 2X gel than for the 1X gel (i.e., 35.6 versus 9.9 psi/ft). The pressure gradient for gel washout was generally similar to the pressure gradient for gel placement. This observation is consistent with our earlier findings in shorter (6-in. long) fractured cores.[3]

Effect of a Constriction in the Fracture

In the experiments described to this point, the fractures had relatively uniform widths throughout their lengths. Would gel washout be less severe if a significant constriction occurred within the fracture? To address this question, an experiment was performed using a 48-in. long fracture where the fracture width was 0.08 in. (2 mm) in the first 16-in. (41-cm) long section, 0.02 in. (0.5 mm) in the second 16-in. long section, and 0.08 in. in the final 16-in. long section. The cross-sectional area of the Berea sandstone core that contained the fracture was about 1.5 in. x 1.5 in. Gel placement and subsequent brine injection were performed as described earlier.

During gel injection, the pressure gradient quickly stabilized at values of 5.0 psi/ft in the first fracture section and 4.9 psi/ft in the third fracture section (see **Fig. 7**). Thus, the pressure gradients during gel extrusion were similar in the two 0.08-in. wide sections, even though they were separated by a 0.02-in. wide fracture section. In the 0.02-in. wide section of the fracture, the pressure gradient averaged 19.5 psi/ft. As expected,[2] the pressure gradient for gel extrusion increased with decreased fracture width.

Fig. 8 shows the peak pressure gradients during the first brine injection (at 100 cm^3/hr) after gel placement. In the first fracture section, the pressure gradient rose rapidly to 9.6 psi/ft (within 0.15 fracture volumes of brine injection), followed by a rapid decrease to 0.6 psi/ft. The peak pressure gradients were 6.9 psi/ft in the second fracture section and 3.2 psi/ft in the third section. It is interesting that the primary pressure peaks diminished in magnitude by about 3 psi/ft sequentially through the three sections. One might have expected the largest pressure peak in the second (and most narrow) section. For the three sections, the primary pressure peaks occurred at about the same time (i.e., 0.15 to 0.18 fracture volumes—see Fig. 8). This result indicates that gel failure occurred simultaneously in all three fracture sections.

For the first fracture section, the peak pressure gradient during brine injection (9.6 psi/ft) was almost twice the average pressure gradient during gel injection (5 psi/ft). In contrast, the pressure gradient for gel mobilization during brine injection was expected to be about the same as that during gel injection. Thus, the constriction associated with the middle fracture section may have inhibited gel washout during the first phase of brine injection. Interestingly, however, in the second fracture section, the peak brine pressure gradient was only about one-third of the average pressure gradient during gel injection (6.9 versus 19.5 psi/ft).

During gel placement, mobile gel (with the same composition as the injected gel) forms wormholes through a much more concentrated immobile (dehydrated) gel in the fracture.[2,3] Presumably, during brine injection after gel placement, the gel in these wormholes provided the point of failure. This presumption was qualitatively consistent with the pressure gradients noted near the end of brine injection. Standard calculations for laminar flow of brine in tubes or slits[8] (coupled with the brine pressure gradients and flow rates) suggested that less than 2% of the gel washed out during brine injection. In contrast, if the entire gel mass had washed out, the brine pressure gradients should have been lower by at least a factor of 300 in the 0.02-in. (0.5-mm) wide section of the fracture and at least a factor of 10,000 in the 0.08-in. (2-mm) wide sections. Also, at the end of the experiment (i.e., after the rate studies described below), the fracture was opened—revealing that most of the fracture was filled with concentrated gel.

The average pressure gradients during brine injection at other rates are shown in **Fig. 9**. The behavior in the third fracture section closely tracked that in the first section—indicating that the degree of gel washout was similar in both 0.08-in. wide fracture sections. In the above discussion, the constriction associated with the middle fracture section was suggested to have inhibited gel washout during the first phase of brine injection. Evidently, during the subsequent phases of brine injection (at higher rates), the constriction did not inhibit gel erosion or washout in the upstream fracture section any more than in the downstream section.

In all fracture sections, the pressure gradients consistently increased with increased brine injection rate. If the brine flow paths (i.e., the open wormholes) were of fixed size, the pressure gradient should be directly proportional to the brine injection rate. For the increasing rate sequence in the middle section (solid symbols in Fig. 9), the pressure gradient varied with rate raised to the 0.5 power. Since the rate exponent was less than unity, the flow paths became progressively more open with increased rate. For comparison, in the first and third fracture sections (open symbols in Fig. 9), pressure gradients varied with rate raised to the 0.25 power. These results revealed that increased brine rates widened the flow openings to a proportionately greater extent in the 0.08-in. wide fractures then in the 0.02-in. wide fracture.

For all fracture sections, when the rates were decreased in stages, pressure gradients varied with rate raised approximately to the first power. This result indicated no further erosion of the wormhole pathways when subjected to diminishing brine injection rates.

During brine injection after gel placement, if all flow occurs through a single cylindrical wormhole, the diameter of that flow path can be estimated using pressure drops and rates.[8] For the middle fracture section, the calculated wormhole diameter rose from 0.007 in. (0.18 mm) at the lowest rate to 0.014 in. (0.36 mm) at the highest rate. Thus, the effective wormhole width remained less than the fracture width (0.02 in. or 0.5 mm). For comparison, in the 0.08-in. (2-mm) wide fracture sections, the calculated wormhole diameters were about the same at the lowest rate (100 cm^3/hr) as that in the 0.02-in. wide section (i.e., 0.008 in. versus 0.007 in.). However, as the brine injection rate increased in the 0.08-in. wide sections, the wormhole diameters increased proportionately more—from 0.008 in. (0.2 mm) at the lowest rate to 0.023 in. (0.58 mm) at the highest rate.

In summary, the pressure gradients during gel extrusion were similar in two 0.08-in. wide fracture sections, even though they were separated by a 0.02-in. wide fracture section. The constriction associated with the middle fracture section may have inhibited gel washout during the first pulse of brine injection after gel placement. However, during subsequent phases of brine injection, the constriction did not inhibit gel erosion or washout in the upstream fracture section any more than in the downstream section.

Effect of Rock Surface

From earlier work, the pressure gradient and the degree of dehydration during gel extrusion were not sensitive to the permeability of the rock that contained the fracture.[2] Also, when the rock was Berea sandstone, the extrusion behavior was the same if the fracture faces were smooth surfaces that were generated by cutting the cores with a diamond saw or were jagged surfaces that were generated by cracking the core open. We were asked whether the extrusion and washout behavior depends on the wetting character of the fracture surface. Some speculated that gel slippage on a strongly oil-wet plastic surface might be different than on a water-wet sandstone surface. In contrast, our current concept of how gels propagate through fractures leads to a different expectation. Specifically, since the washout pathway is expected to follow the mobile gel in the wormholes, the point of failure during washout should be at the mobile gel/immobile gel interface—not at the gel/fracture wall interface. Thus, gel washout from fractures should not be sensitive to the porous medium that borders the fracture.

To address this issue, two fractured cores were prepared from 10-darcy polyethylene cores. These cores were 31-in. (78-cm) long and 1.5-in (3.8-cm) in diameter. The fractures were created by cutting the cores in half lengthwise. One fracture was 0.02-in. (0.5-mm) wide while the other was 0.04-in. (1-mm) wide. Our standard 1X Cr(III)-acetate-HPAM gel was injected using 2,000 cm^3/hr (41°C). During gel extrusion, the pressure gradients were 7.7 psi/ft in the 0.04-in. wide fracture and 10.7 psi/ft in the 0.02-in. wide fracture. These values (solid circles in Fig. 1) were consistent with those observed during extrusion of the same gel through fractures in Berea sandstone and Indiana limestone. The leakoff rates during extrusion through the fractured polyethylene cores were consistent with predictions from our new leakoff model—which in turn were consistent with leakoff results in the fractured Berea cores.[3,7]

After gel placement, brine was injected at various rates to assess washout. **Fig. 10** compares the washout results in the fractured polyethylene cores versus in a new set of fractured Berea cores. For both fracture widths, the polyethylene data followed the Berea trends, although the polyethylene results generally were associated with lower pressure gradients. The lower pressure gradients for polyethylene were not surprising since those cores were much more permeable than the Berea cores (10 darcys versus 0.7 darcys). In other words, for a given total brine rate, the polyethylene matrix had a greater flow capacity than the Berea matrix.

The main conclusion from this study was that the extrusion, leakoff, and washout behavior in fractures contained by strongly oil-wet polyethylene cores were not significantly different than those in strongly water-wet Berea sandstone.

Use of Particulates to Reduce Washout

Earlier work[7] explored how incorporation of particulate matter into the gel affects mobilization. Gel extrusion and washout experiments were performed using our 1X Cr(III)-acetate-HPAM gel that was prepared with and without 0.1-0.2% suspended fiberglass insulation. Gel with 0.1-0.2% fiberglass significantly increased the pressure gradient for washout in 0.04-in and 0.08-in. wide fractures. However, the pressure gradients for gel placement were quite high (e.g., 220 psi/ft in a 0.04-in. wide fracture). In both cases, the pressure gradient for washout was less than or equal to the pressure gradient during gel placement. Also, in 0.16-in. wide fractures, the washout behavior of Cr(III)-acetate-HPAM gel was no better with fiberglass than without fiberglass. For gels containing 0.2-0.5% shredded polypropylene, the pressure gradients during washout were significantly lower than during gel placement.[7] These studies should be regarded as preliminary since many operators noted positive results by incorporating particulates into gelants and gels. Also, a wide range of particulates and conditions remain to be investigated.

Rate Control

For the above work, the pressure gradient for washout was generally less than or equal to the pressure gradient during gel placement. Ideally, the pressure gradient for washout should be much higher than the pressure gradient required for gel placement. We investigated whether washout could be reduced by controlling gel injection rate to form concentrated gels during placement. Maximizing gel injection rate minimizes water loss and maximizes the distance of gel propagation along a fracture.[2,3] In contrast, as injection rate decreases, the concentration increases for the gel deposited in the fracture. This gel should be increasingly resistant to washout as it becomes more concentrated.

A key difference exists between this idea and the case where a concentrated gel was placed by injecting a 2X gel. The pressure gradient for gel extrusion increased significantly with increased concentration of the injected gel (see Fig. 6). Thus, pressure gradients can be very high when injecting a 2X gel. In the new concept, the injected gel would have a relatively low polymer concentration (e.g., a 1X gel). For a given fracture width and composition of the injected gel, the pressure gradient is insensitive to injection rate.[2] Therefore, by lowering the injection rate, a concentrated gel can be placed in the fracture without resorting to high pressure gradients.

To test this idea, three corefloods were performed that were identical except for the gel placement rate. These floods used the same procedures as those described earlier, but using gel placement rates of 400, 2,000 or 16,000 cm^3/hr (effective fluxes of 826, 4,130, or 33,100 ft/d). Pressure gradients during gel placement averaged 7.1, 9.9, and 16.7 psi/ft, respectively. Consistent with earlier findings,[2] the pressure gradient was fairly insensitive to rate, considering the 40-fold difference in placement rates.

Interestingly, the washout behavior during brine injection was fairly similar for the gels placed at 4,130 and 33,100 ft/d (**Fig. 11**). However, gel placement at the lowest rate (826 ft/d) showed a greater resistance to washout. The washout curve for the low placement rate occurred at pressure gradients roughly five times greater than those for the other two rates. Consequently, adjustment of gel placement rates is a promising method to control gel washout. Depending on the gel and fracture width, one may wish to first inject gel at a high rate to maximize penetration into the fracture. Near the end of the treatment, gel injection at low rates should form concentrated gels to better resist washout for high, near-wellbore pressure gradients.

The composition was determined for the concentrated gel in the fracture at the end of each of the three experiments. On average, the gel concentration in the fracture was 17X, 3X, and 1X relative to the concentration of the injected gel for placement rates of 826, 4,130, or 33,100 ft/d, respectively.

Use of Secondary Reactions

Another method to control gel washout involves use of secondary gelation reactions. The concept is to inject a gel that undergoes two separate crosslinking reactions. The first (primary) reaction is timed to take place before entry into the fracture. The second crosslinking reaction occurs after the gel has been placed. The first reaction forms a crosslinked polymer that will not enter the porous rock but will be sufficiently fluid to exhibit relatively low pressure gradients during extrusion. The second reaction strengthens the gel and significantly increases the gel's resistance to washout. The crosslinker for the second reaction should not gel with any component that leaks off into the porous rock. In this way, damage to the porous rock is minimized.

In a test of this concept, the primary reaction involved 0.5% Alcoflood 935 HPAM crosslinked with 0.5% formaldehyde and 0.5% resorcinol. (The gel also contained 1% NaCl and 0.1% $CaCl_2$. Gel injection occurred at 2,000 cm^3/hr or 4,130 ft/d.) During a baseline experiment, 80 fracture volumes (3,700 cm^3) of this formed gel showed a pressure gradient of 20.9 psi/ft during extrusion through a 4-ft long, 0.04-in. wide fracture.

The same volume of the same gel was injected into a second 0.04-in. (1-mm) wide fracture. An additional 5 fracture volumes of the same formed gel was injected that included 0.0417% Cr(III) acetate. The Cr(III)-acetate crosslinker was mixed with the formed resorcinol-formaldehyde-HPAM gel and injected into the fracture before the secondary crosslinker had time to react. The pressure gradient during gel injection also averaged 20.9 psi/ft. **Fig. 12** shows that the secondary reaction with 0.0417% Cr(III) acetate significantly increased the gel's resistance to washout. This washout curve occurred at pressure gradients 2 to 3 times greater than those where no secondary reaction was used. Thus, the use of secondary reactions is a promising method to reduce washout.

Effect of Oil Flow

The washout experiments described to this point used brine. Is the washout behavior different if oil is used instead of brine? This question is especially relevant to gel treatments in production wells. Ideally, gel in the fracture should washout more easily during oil flow than during brine flow.

To address this issue, three extrusion experiments were performed in 4-ft long Berea cores—with fracture widths of 0.04 in. (1 mm) for one core and 0.02 in. (0.5 mm) for the other two cores. During injection of our standard 1X Cr(III)-acetate-HPAM gel at 2,000 cm^3/hr, the pressure gradient was 10.2 psi/ft in the 0.04-in. wide fracture versus 26.6 and 28.8 psi/ft in the 0.02-in. wide fractures. These pressure gradients were similar to those from extrusion experiments in fractures with comparable widths (see Fig. 1).

Sequential Injection of Oil and Water Banks. After gel placement in one of the 0.02-in. wide fractures, 80 fracture volumes of Soltrol 130™ oil (1.05 cp at 41°C) were injected at 2,000 cm^3/hr (8,260 ft/d in 0.02-in. wide fractures). The solid circles in **Fig. 13** show that the pressure gradients during the first oil injection peaked at 22.6 psi/ft—roughly similar to the 28.8 psi/ft associated with gel placement (open squares in Fig. 13). As with brine injection, the pressure gradient for gel washout was about the same as that for gel placement. After the peak, pressure gradients dropped and approached 0.87 psi/ft after 80 fracture volumes of oil.

Next, sequential banks of brine, oil, and brine (80 fracture volumes each) were injected at 2,000 cm^3/hr (8,260 ft/d). For these three banks, a prominent peak, like that associated with the first oil bank, was not observed. After 80 fracture volumes, the final pressure gradients were 0.87 psi/ft for the first oil bank, 2.6 psi/ft for the first brine bank, 1.2 for the second oil bank, and 1.9 psi/ft for the second brine bank. Since the oil viscosity was 1.05 cp, brine viscosity was 0.67 cp, and depending on which pair of oil and water pressure gradients were chosen, the ratio of water permeability reduction to oil permeability reduction ranged from 2.5 to 4.7 [i.e., (1.9x1.05)/(1.2x0.67)=2.5 to (2.6x1.05)/(0.87x0.67)=4.7]. Thus, the gel showed a moderate disproportionate permeability reduction. However, one could argue that this effect was of minor importance, considering that the pressure gradient for the first gel failure (i.e., in the wormholes) was the same for oil and brine flow.

Oil Injection at Different Rates. For the other two fractured cores, oil was injected using the same sequence of rates described earlier for brine. **Fig. 14** compares these results with analogous results from brine injection experiments. In both fractures, the final permeability to oil was much higher than that for brine. Interestingly, as the applied pressure gradient increased, the relative permeability to oil remained fairly constant at 5 times the matrix permeability in the 0.02-in. wide fracture and at 33 times the matrix permeability in the 0.04-in. wide fracture. Evidently, the oil opened a relatively large pathway upon first breaching the gel bank, but that pathway did not increase in size with increased oil flow rate. In contrast, the relative permeability to brine increased dramatically as the applied pressure gradient increased—suggesting significant gel erosion with increased brine rate.

These results are plotted in a different form in **Fig. 15**. For a given fracture width, the average pressure gradients during oil injection at low rates were 10 to 20 times less than those during water injection. At high rates, the differences between water and oil pressure gradients became less pronounced—especially in the 0.02-in. wide fracture. These results indicate that disproportionate permeability reduction in fractures was most evident at low flow rates. Prior to this study, the presence of a porous medium was thought necessary to observe disproportionate permeability reduction.[9]

Conclusions

The following conclusions were reached during a study of mature Cr(III)-acetate-HPAM gel washout from fractures at 41°C:

1. After gel placement, the pressure gradient for gel washout during brine injection was similar to the pressure gradient observed during gel placement. The mechanism of gel failure involved the displacement of relatively mobile gel from wormholes. Generally, only a small fraction of the gel (<5%) was displaced during the washout process.
2. Resistance to washout can be increased by injecting a more concentrated gel. However, this approach is accompanied by significantly higher pressure gradients during gel placement.
3. The presence of a constriction in a fracture inhibited washout during the first pulse of brine flow after gel placement. However, during subsequent brine flow, gel erosion occurred upstream of the constriction to the same extent as downstream.
4. The extrusion, leakoff, and washout behavior in fractures in strongly oil-wet polyethylene cores were similar to those in strongly water-wet Berea sandstone.
5. Gel washout can be reduced by controlling gel placement rate. A Cr(III)-acetate-HPAM gel placed in a 0.04-in. wide fracture at 826 ft/d was about five times more resistant to washout than a gel placed at 4,130 ft/d.
6. Gel washout can be reduced using secondary crosslinking reactions. Post-placement reaction with Cr(III) acetate increased resistance to washout for a resorcinol-formaldehyde-HPAM gel by a factor from two to three.
7. For both brine and oil, the pressure gradient for first gel mobilization or washout (i.e., from wormholes) was about the same as the pressure gradient during gel placement.
8. During steady state flow after first breaching the gel, the Cr(III)-acetate-HPAM gel reduced permeability to water moderately more (2.5 to 4.7 times) than that to oil.
9. Disproportionate permeability reduction in fractures was most evident at low flow rates.

Acknowledgments

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Nomenclature

h_f = fracture height, ft [m]
k_f = fracture permeability, darcys [μm^2]
L_f = fracture length, ft [m]
dp/dl = pressure gradient, psi/ft [kPa/m]
w_f = fracture width, ft [m]

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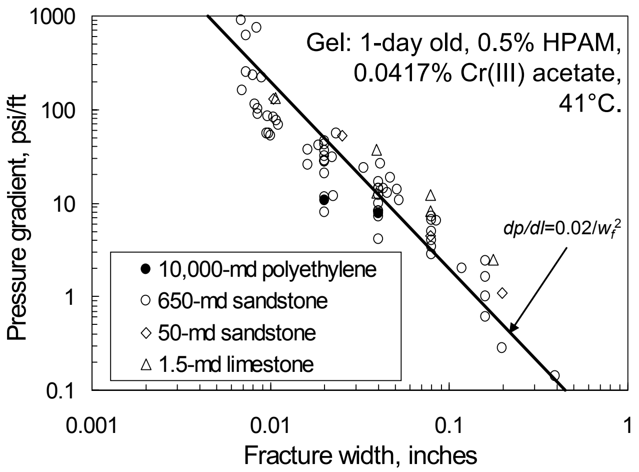

Fig. 1—Pressure gradients required for gel extrusion.

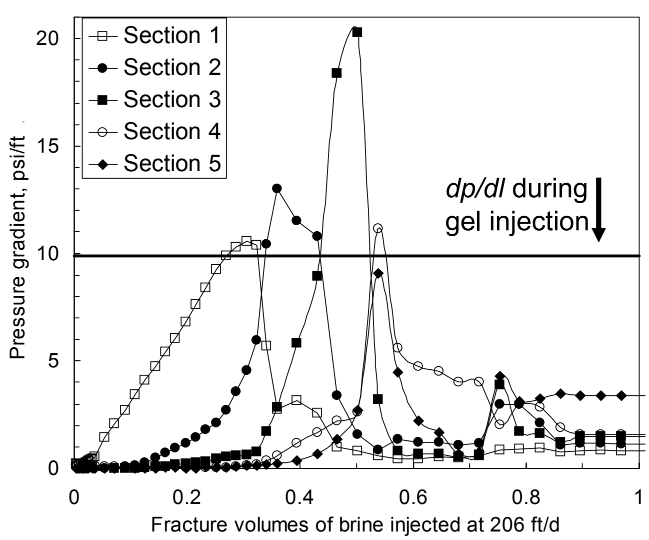

Fig. 2—Pressure gradients during first brine injection.

SI Metric Conversion Factors

cp x 1.0*	E-03	= Pa·s
ft x 3.048*	E-01	= m
in. x 2.54*	E+00	= cm
md x 9.869 233	E-04	= μm^2
psi x 6.894 757	E+00	= kPa

*Conversion is exact.

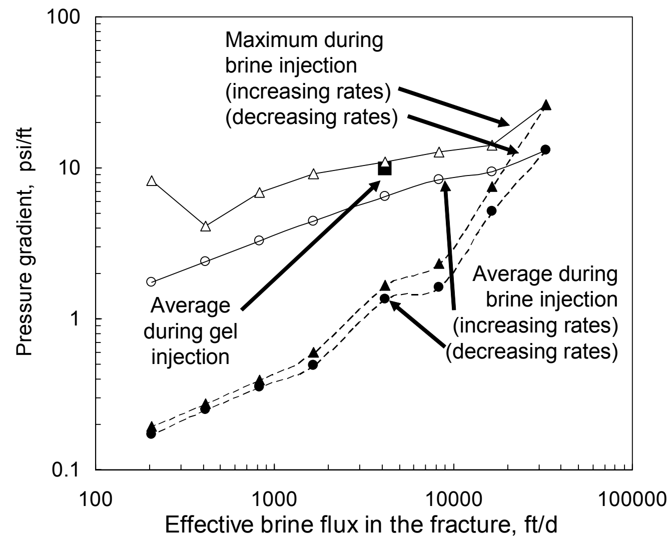

Fig. 3—Pressure gradients versus brine flux.

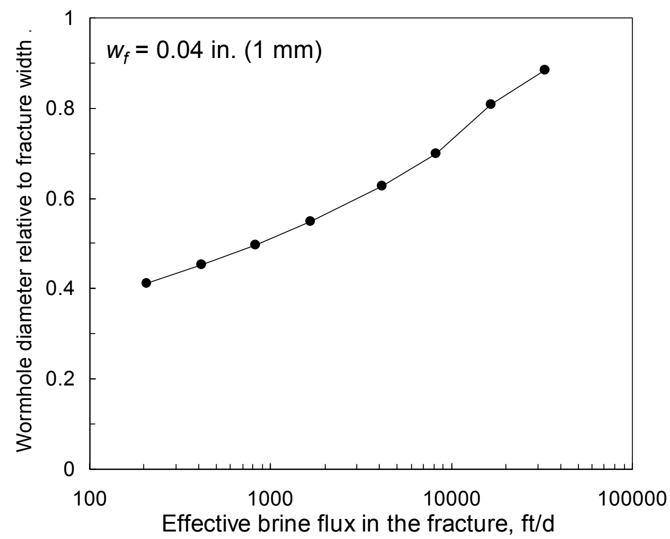

Fig. 4—Effective wormhole sizes versus brine flux.

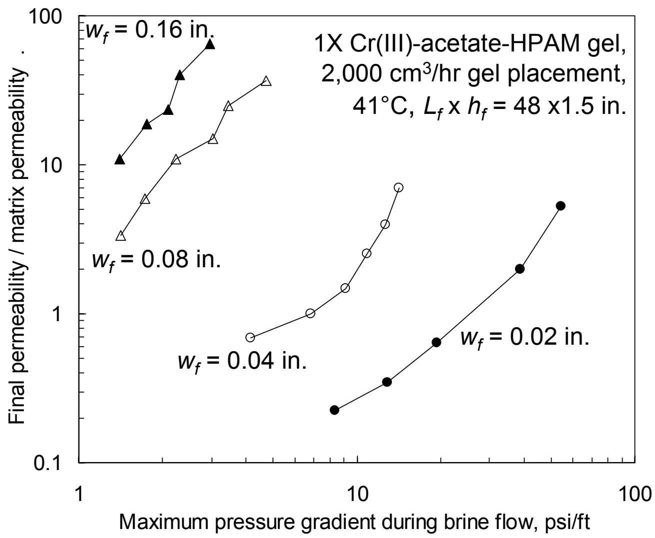

Fig. 5—Effect of fracture width on washout.

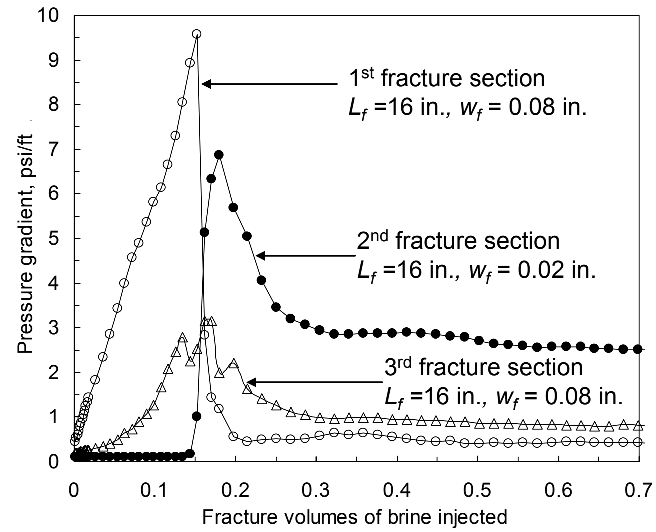

Fig. 8—First brine injection into a constricted fracture.

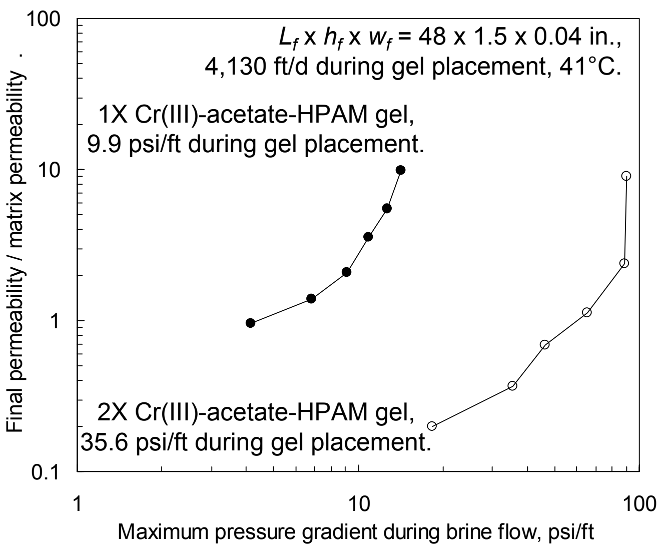

Fig. 6—Effect of injected gel composition on washout.

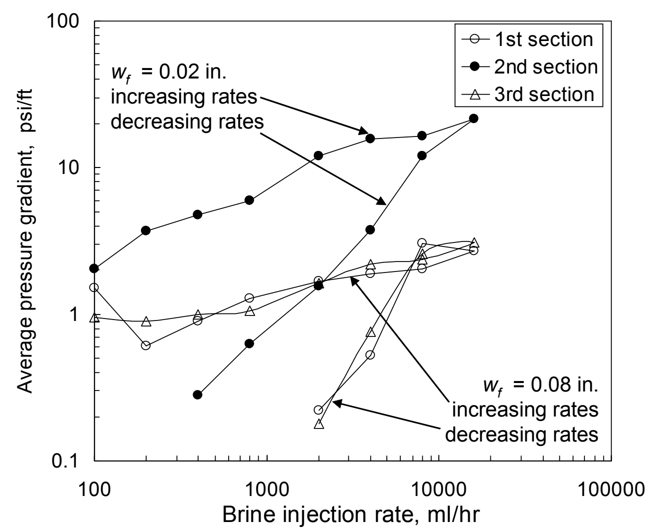

Fig. 9—Washout versus rate in a constricted fracture.

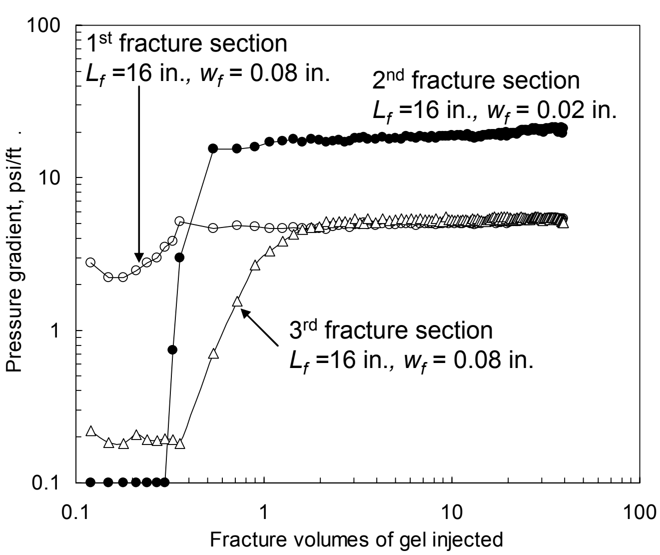

Fig. 7—Gel injection into a fracture with a constricted section.

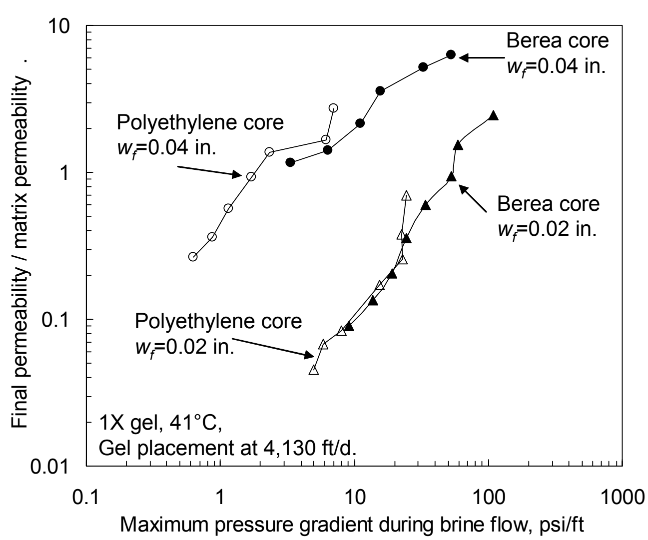

Fig. 10—Gel washout in fractured polyethylene versus Berea.

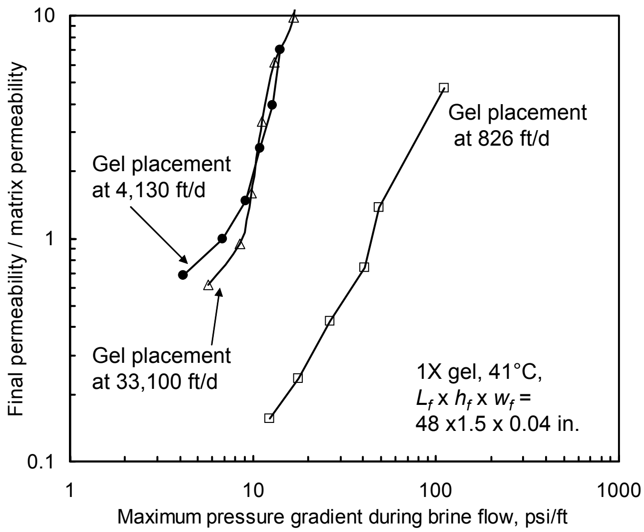

Fig. 11—Using gel placement rate to reduce washout.

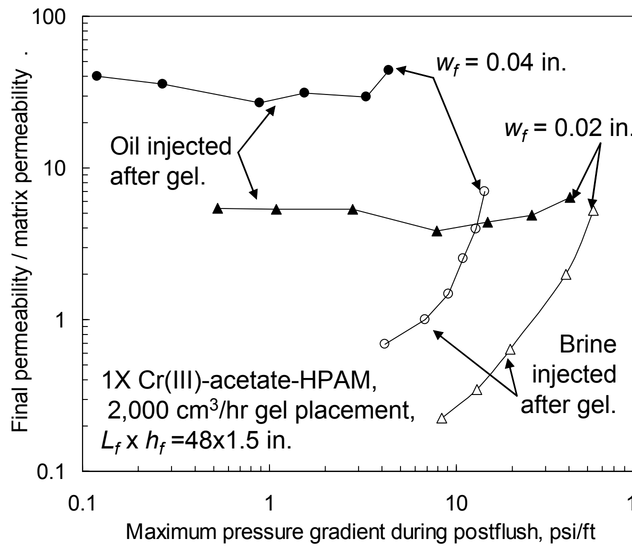

Fig. 14—Gel washout using oil versus brine.

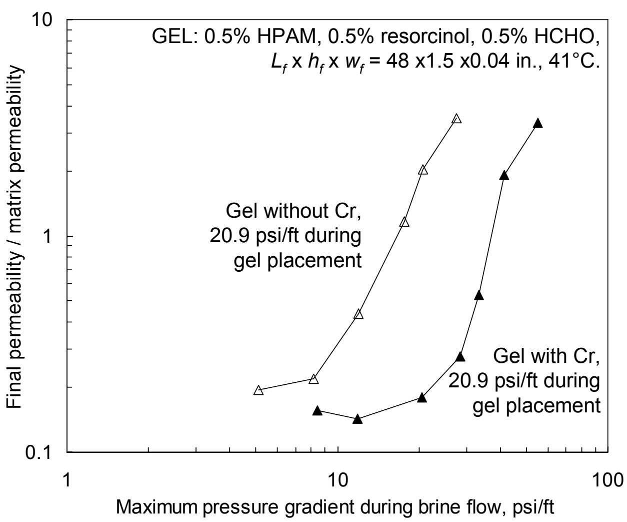

Fig. 12—Using secondary reactions to reduce washout.

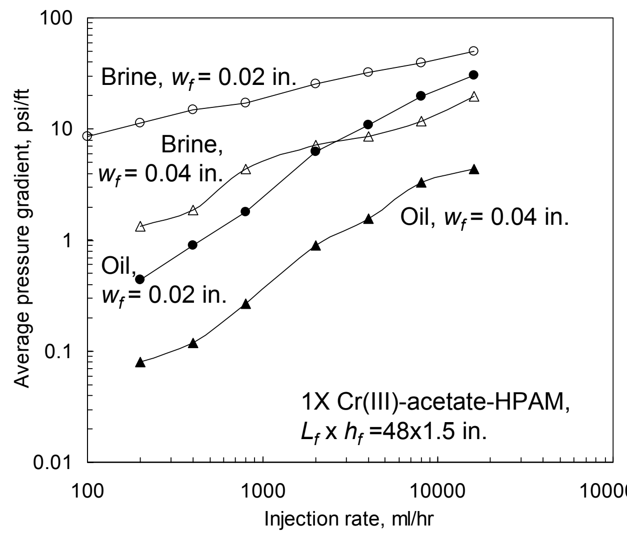

Fig. 15—Gel washout using oil versus brine at various rates.

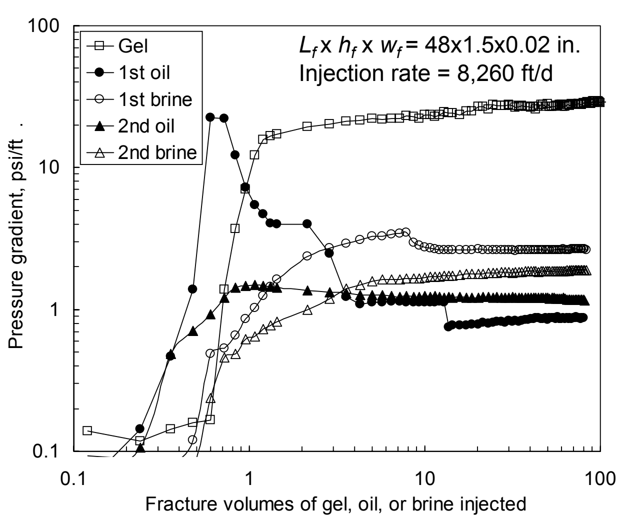

Fig. 13—Gel washout during oil/brine/oil/brine sequence.