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Can Particle Size Distribution of Lost Circulation Materials Affect the Fracture Gradient?

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Abstract

The purpose of preventive treatment of fluid losses, i.e. wellbore strengthening, is to deliberately enhance the fracture gradient by creating and curing fractures while drilling. The effectiveness of such treatments can be affected by the lost circulation material (LCM) type, size distribution, and the fracture width. This paper investigates if the particle size distribution of preventive LCMs can change the breakdown or re-opening pressure. Hydraulic fracturing experiments were performed on concrete cores as a proxy for impermeable rocks with a low-toxicity oil-based fluid and LCM blends with different particle size distributions. Two injection cycles were performed to measure the breakdown and fracture re-opening pressures. Microscopic analysis of the fractured cores was performed to estimate the fracture width. The fracture pressure and re-opening pressure were greatly increased by including LCMs in the fluid compared to the basic drilling fluid. The experimental results indicate that selecting fluids with LCM of certain range will enhance the fracture gradient and widen the available drilling fluid window.

Introduction

Lost circulation events, defined as the loss of drilling fluids into the formation, are challenging problems to prevent or mitigate while drilling[1]. Losses can occur when drilling through natural fractures, or into drilling induced fractures initiated when the drilling fluid pressure exceeds the formation breakdown pressure. Preventive lost circulation material (LCM) treatments can be used to cure losses on natural fractures before lost circulation occur or increase the breakdown pressure before drilling induced fracture is created. This preventive method will effectively widen the fluid weight window or in other words, enhance the fracture gradient. Experimental LCM performance studies have focused on reducing fluid loss[2] or increase fracture sealing pressure (i.e. fracture re-opening pressure) [3–7]. Fluid loss reduction is studied in high pressure high temperature (HPHT) filter press and plug particle apparatus (PPA) tests[2]. Creating a seal in fractures causing an increased sealing pressure has been experimentally studied on both permeable and impermeable fractures [3, 4, 6]. A broader distribution of particle sizes was recommended by [3] to get better fracture sealing efficiency (i.e. increased re-opening pressure) of drilling induced or natural fractures based on the results of permeable fracture test. Proposed procedure for wellbore strengthening fluid design by [4] focused on importance of particle sizes in bridging fracture aperture. According to [6], smaller sized particles and narrow particle size distribution (well sorted) gives a better fracture sealing efficiency. The results of the impermeable fracture tests showed that the particle size distribution should be a function of the type of formation to be strengthened. Using of slotted discs with different fracture aperture and fracture tip was one of the other methods used to evaluate LCM performance [8]. Based on the results of different LCM blends evaluation using a high pressure LCM testing apparatus, [8] observed that blends with a wide range of particle sizes exhibited the lowest fluid loss. Large scale fracturing experiments suggested large and uniform particle size of LCMs for a better sealing efficiency [9, 10]. Based on fracturing experiments, [11] concluded that coarser particles should be used for bridging the fracture mouth while smaller particles should prevent fluid loss through the bridge. According to fracturing experiment on shale cores using a block test set up with 5 in. rock cubes, [12] suggested particle size distribution and size of lost circulation materials should be selected based on fracture aperture. There are other studies which theoretically investigated the effect of LCM particle sizes[13-15]. The importance of the particle size distribution in improving sealing efficiency was emphasized by [13] without specifically addressing how to select the size distribution. According to [14], LCM particle sizes are relatively unimportant since any pill will develop into an immobile mass but particle sizes smaller than 100 microns should be used to block pore throats to stop matrix seepage and not as a LCM for minimizing fluid losses. [15] indicated that the design of particle sizes in wellbore strengthening pills is a function of fracture width while the effect of shearing at the bit face on particle size degradation should be considered.

The results from [3-15] show that particle size distribution is a critical parameter to effectively seal fracture either shown as reduced fluid losses, increased fracture breakdown or re-opening pressure. However, there are still limited published results on how particle size distribution could affect the performance of different LCM's. The majority of tests conducted have been with slotted/tapered discs, which do not simulate the process of inducing and propagation of fractures while drilling. The previous hydraulic fracturing experiments shows adding LCM increases the fracture gradient but no agreement has been achieved on how LCM strength, particle size, and size distribution affect the fracture sealing efficiency (i.e. strengthening).

The main objective of this paper is to investigate the effect of particle size distribution of conventional LCMs in enhancing the fracture gradient (fracture breakdown and re-opening pressure). Hydraulic fracturing experiments were carried out on concrete cores as a proxy for non-permeable rocks using low toxicity oil based fluid and LCM mixtures. These experiments were used a) to investigate the strengthening effect as a result of adding LCM to an oil based fluid, b) to investigate the effect of LCM particle sizes on enhancing fracture gradient (breakdown and re-opening pressure) c) find a relation between the particle sizes, the fracture size and the wellbore pressure.

Experimental Procedure

Hydraulic fracturing experiments were performed on nine concrete cores using nine different oil based drilling fluid formulations. Figure 1 shows a schematic drawing of the hydraulic fracturing apparatus. Two pumps are used to apply confining and injection pressure, while a hydraulic hand pump is used to apply overburden stress on the core sample. A metal accumulator was used to inject fluids into the core. Injection pressures was recorded using LabVIEW© software. Cement core samples were prepared using Portland cement (Class H) to simulate impermeable formations. Class H cement was mixed with API recommended water requirements of 38% by weight of cement in a large batch following the standard mixing procedures to ensure the same physical properties of the fractured cores. The cement mixture was poured into 5 7/8 inch (diameter) x 9 inch (height) molds and left to cure for at least 7 days. A ½ inch wellbore was drilled in the cement cores using a drill press, and then a steel cap were attached to the top and bottom of the cement cores using epoxy. The first test was conducted using EDC95-11 solid free clear base fluid used to prepare the pre-mixed drilling fluid. The second test was conducted with the pre-mixed oil based drilling fluid without LCM to serve as a control sample. Tests # 3, 4, and 5 were conducted using the oil based fluid mixed with 3 different LCM mixtures. The LCM mixtures were based on recommendations of previously published research. 20 ppb graphite and nutshells blend (G & NS) was used for test # 3 as suggested by [3]. 30 ppb graphite and sized calcium carbonate blend was investigated in test # 4 to follow the recommendations by [16]. 55 ppb graphite, sized calcium carbonate, and cellulosic fibers blend was used in test # 5 as recommended by [17]. Tests #6 to 9 were conducted using Graphite with different D50 of particle size distribution, 50, 100, 400, and 1000 microns respectively. A confining pressure of 100 psi and an overburden pressure of 400 psi were applied. An Injection rate of 5 ml/min was used to pressurize the wellbore until reaching the breakdown pressure where an increase in the confining pressure is observed due to fluid pushing against the rubber sleeve. The injection is stopped to allow for 10 minutes period before running the re-opening cycle. The test is stopped after the second cycle when an increase in the confining pressure is observed; indicating that the fluid has already propagated through the fracture. The retrieved fractured cores from the fracturing apparatus were examined under optical microscopy and fracture opening was measured perpendicular to the fracture side at several locations to estimate the range of fracture widths observed.

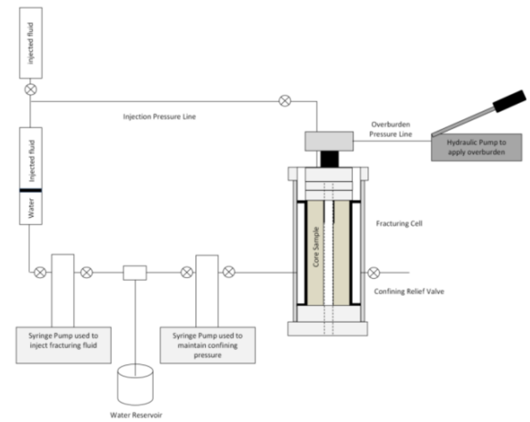

Figure 1. Schematic of the hydraulic fracturing apparatus

Results

Figure 2 shows the cross section of a concrete core for one of the test after the hydraulic fracturing experiment, a symmetric and bi-wing fracture created around the wellbore. Figure 3 shows micrographs of the actual fractures and the measured fracture width of the concrete cores for all tests. Figures 4-12 are the pressure versus time results from the hydraulic fracturing experiments. The blue line represents the first injection cycle, which is used to estimate the breakdown pressure. The red line represents the second injection cycle, which is used to estimate the re-opening pressure (after the 10 minutes fracture healing period). The peak pressure at first cycle shows the breakdown pressure and the peak pressure of the second cycle shows the fracture re-opening pressure.

Figure 2. Symmetric and bi-wing fracture created around the wellbore for Test #7

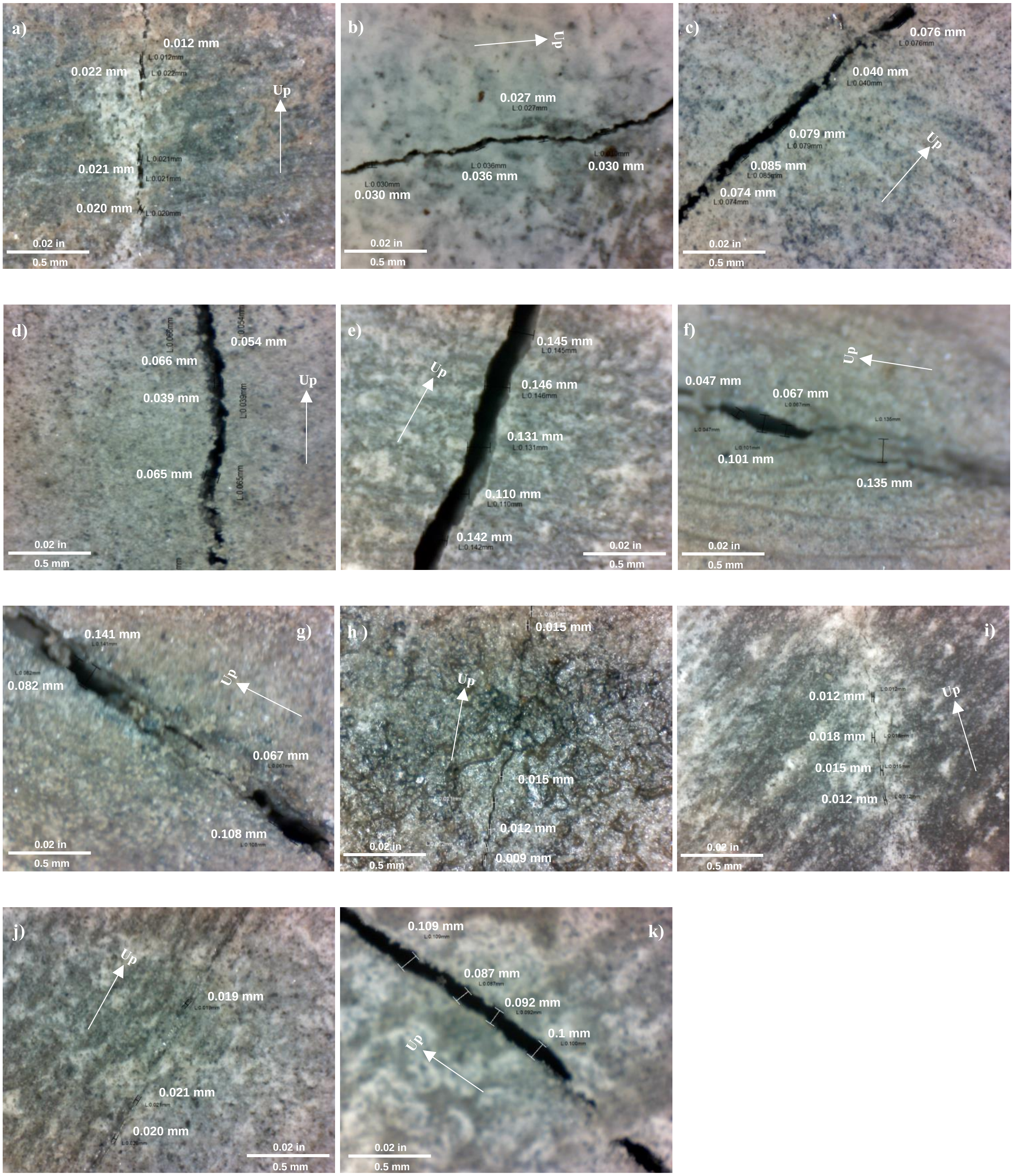

Figure 3. The fracture width for: **a)** Test #1 (15 – 22 microns), **b)** Test #2 (27 – 36 microns), **c)** Test #3 (40 – 85 microns), **d) & e)** Test #4 (40 – 145 microns), **f) & g)** Test #5 (50 – 145 microns), **h)** Test #6 (9 – 15 microns), **i)** Test #7 (12 – 18 microns) **j)** Test #8 (19 – 21 microns), **k)** Test #9 (92 – 109 microns)

The lowest breakdown and re-opening pressures (843 and 571 psi) were observed for the first test (Figure 4), which was conducted using EDC95-11 base fluid. The small size of fracture (15 to 22 microns) from microscopy image (Figure 3a) could be because of using clear fluid without solid content.

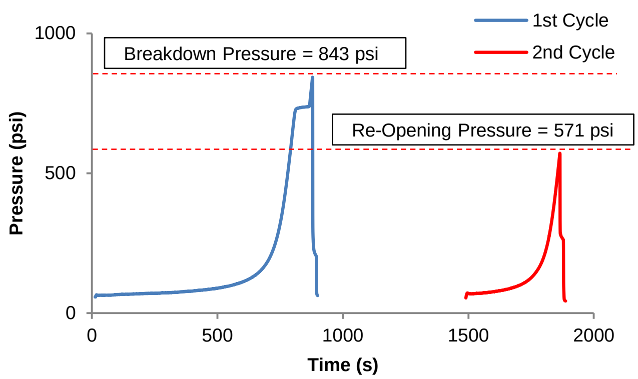

Figure 4. Pressure vs. Time for Test # 1

The results of the second test (Figure 5) with the pre-mixed OBM containing barite particles shows significant increase in breakdown pressure (From 843 psi to 2008 psi) compared to the results of the first test (Figure 4), however there is small difference between the fracture re-opening pressure for both test (Figures 4 &5). The measured range of fracture width for the second test (Figure 3b) (27 to 36 microns) is higher compared to the first test using the solid free fluid. Adding LCM blend of G &NS in test #3 increased the fracture re-opening about 125% (Figure 6) (From 592 psi to 1334 psi) compared to the results of test #2 with no LCM. Increasing of the breakdown pressure in test #3 (Figure 6) (From 2008 psi to 2199 psi) compared to the results of test #2 is not notable as the fracture re-opening pressure. The measured range of fracture width in Figure 3c (40 to 85 microns) shows broader range of measured fracture widths compared to the results test #1 and test #2 (Figures 3a & 3b).

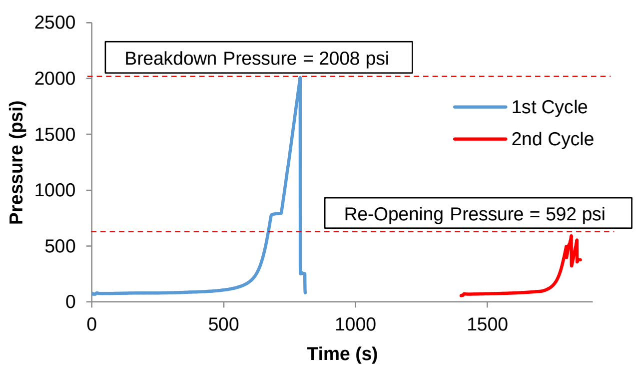

Figure 5. Pressure vs. Time for Test # 2

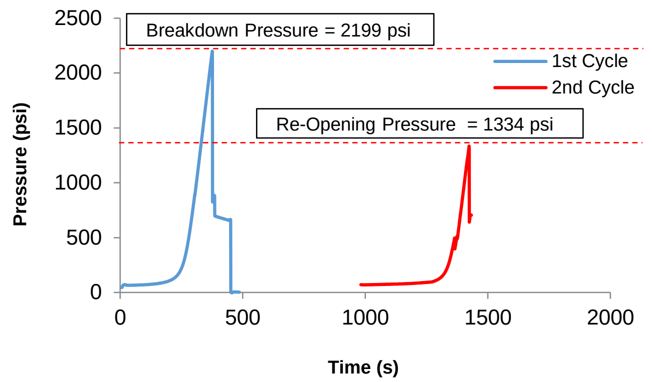

Figure 6. Pressure vs. Time for Test # 3

Replacing NS in LCM blend of test #4 with SCC and increasing concentration of LCM from 20 ppb to 30 ppb increased both the breakdown and the fracture re-opening pressure (Figure 7). Comparing the results of test #3 with the test #4, the fracture re-opening was increased form 1334 psi to 1834 psi. The increase of breakdown pressure is not remarkable as fracture re-opening pressure (Figures 3d & 3e) (From 2199 psi to 2309 psi).

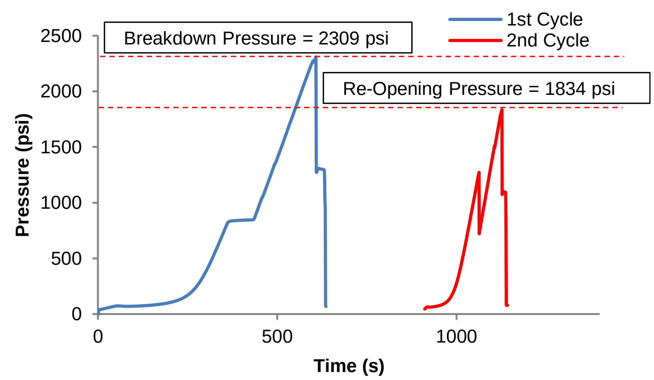

Figure 7. Pressure vs. Time for Test # 4

Test # 5 containing 55 ppb graphite, sized calcium carbonate, and cellulosic fiber resulted in highest breakdown pressure (2372 psi) (Figure 8) compared to the previous tests. However, the fracture re-opening pressure (1717 psi) is lower than the LCM blend used in test # 4. The range of the measured fracture width (Figure 4f & 4g) (50 to 145 microns) for test #5 is broader than previous tests (Figures 3a to 3e).

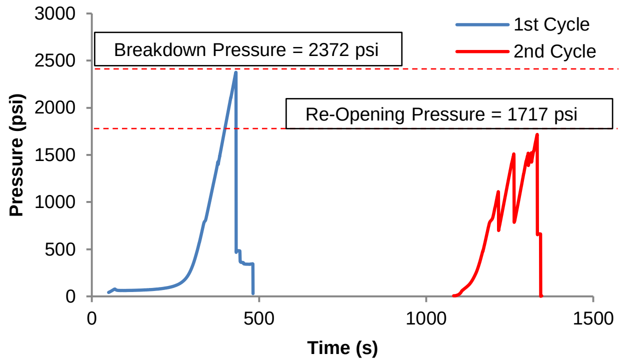

Figure 8. Pressure vs. Time for Test # 5

Second set of tests (Tests #6 to 9) were conducted with a single LCM (Graphite) with different particle sizes range. Using the same premixed OBM, Graphite with D50 values of 50, 100, 400, and 1000 microns were used.

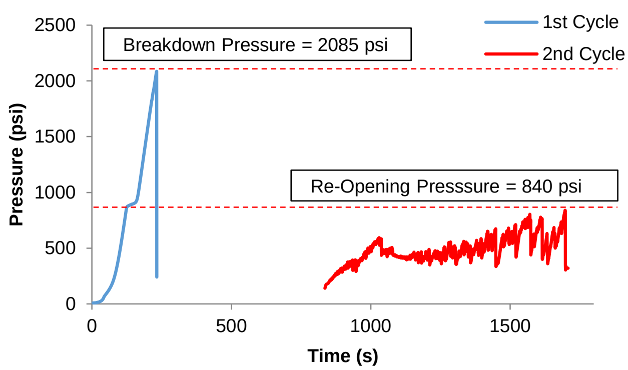

Figure 9. Pressure vs. Time for Test # 6 (D50: 50 microns)

According to the results of the second set of tests, increasing the D50 value of LCM (Graphite) particle size distribution from 50 microns to 100 microns increased both breakdown (From 2085 psi to 2725 psi) and fracture re-opening pressure (From 840 psi to 1292 psi) (Figures 9 &10). The wider fracture width (12 to 15 microns) was observed for test #7 (Figure 3i) compared to the measured fracture width (9 to 12 microns) of test #6 (Figure 3h). Increasing the D50 of the Graphite (test# 8 and 9) resulted in a lower breakdown and fracture re-opening pressure (Figure 11 and 12) compared to test #7 (Figure 10). For test #8 with D50 of 400 microns for Graphite particle sizes, the breakdown pressure (2004 psi) (Figure 11) is lower than the results of test #7 (2725 psi) with D50 of 100 microns for Graphite particle sizes. In the same situation, the fracture re-opening pressure for test #8 (1216 psi) (Figure 11) is lower than the fracture re-opening pressure for test #7 (1292 psi), but this difference is not significant breakdown pressure. The measured fracture width for test #7 (12 to 15 microns) (Figure 3i) with D50 of 100 microns for Graphite particle sizes is lower than the measured fracture width for test #8 (19 to 21 microns) (Figure 3j). Test #9 was conducted using larger particle sizes of Graphite with D50 of 1000 microns. The recorded breakdown pressure for test #9 (2415 psi) (Figure 12) is less than the results of test #7 (Figure 10) but higher than test #8 (Figure 11), however the fracture re-opening pressure for test #9 (1020 psi) (Figure 12) is lower than the fracture re-opening pressure for test # 7 &8 (Figures 10 & 11). The measured range of fracture width for test #9 (92 to 109 microns) (Figure 3k) is higher than the measured fracture width for tests #6, 7, and 8 (Figures 3h, 3i, & 3j).

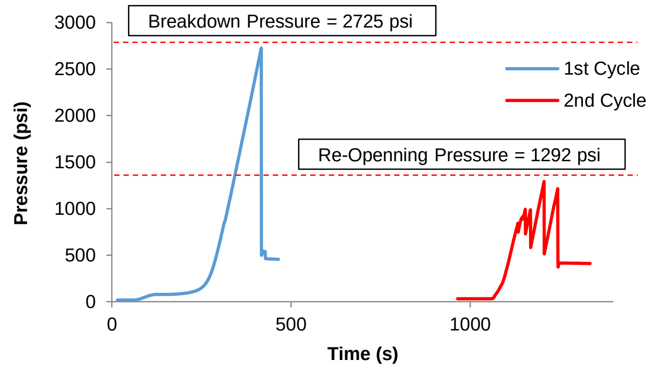

Figure 10. Pressure vs. Time for Test # 7 (D50: 100 microns)

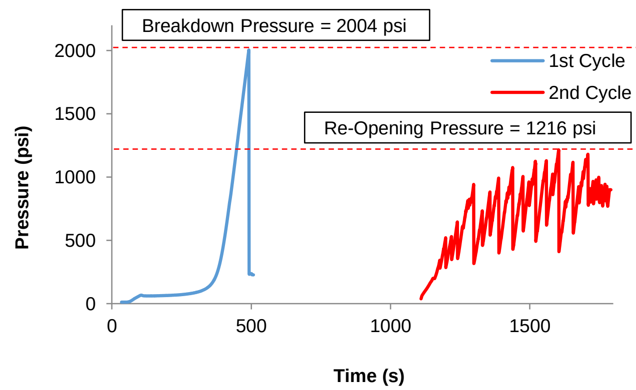

Figure 11. Pressure vs. Time for Test # 8 (D50: 400 microns)

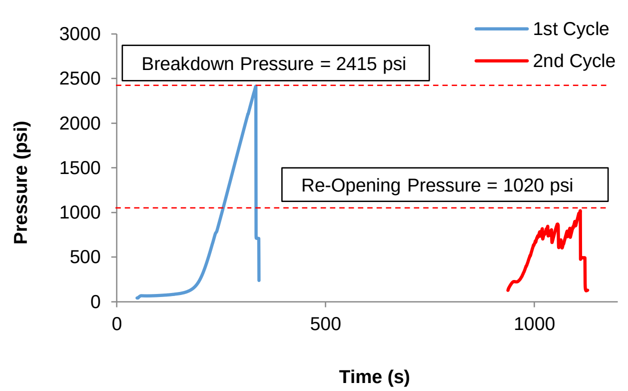

Figure 12. Pressure vs. Time for Test # 9 (D50: 1000 microns)

Discussions

Analysis of the results from the first set of tests (#1 to 5) (Table 1) showed that including LCM blend in fluid (Test #3, 4, &5) can enhance both breakdown and fracture re-opening pressure compared to solid free fluid (test #1) and also pre-mixed OBM (test #2) which only contained barite as weighting agent. The blend of G & SCC LCMs resulted in the highest fracture reopening pressure (1834 psi), while the highest breakdown pressure was observed with G, SCC, and CF blend of LCMs (Table 1). There is a significant difference in breakdown pressure of test #1 &2 but the fracture re-opening pressure is almost the same (Table1). The barite particles containing in the fluid of test #2 are able to block pore throats on the borehole wall which resulted in an increase in the breakdown pressure, however the small sizes of barite particles (Table 3) are not able of bridging the fracture aperture. The highest breakdown pressure resulted from the blend of G, SCC, &CF could be due to the same reason (Table 1). The blend of G, SCC, & CF in test #5 has smaller particle sizes compared to the LCM blends of test #3 &4, especially smaller range of particles (Table 3). These smaller particles could block pore throats and create a sealing that result in higher breakdown pressure (Table 1), however enhancing fracture re-opening pressure is a function of bridging the fracture aperture and also filling the fracture itself. Thus, broader range of particle sizes is required to reach higher fracture re-opening pressure.

Table 1. Summary of results for tests #1 to 5

Test #	Fluid Used	LCM Blend	Conc (ppb)	Breakdown Pressure (psi)	Re-Opening Pressure (psi)
1	EDC95-11	N/A	N/A	843	571
2	VERSATEC OBM	N/A	N/A	2008	592
3	VERSATEC OBM	G&NS	20	2199	1334
4	VERSATEC OBM	G & SCC	30	2309	1834
5	VERSATEC OBM	G, SCC, & CF	55	2375	1717

The second set of the tests (#6 to 9) was conducted using a single LCM with same concentration to specifically investigate how LCM particle sizes can enhance fracture gradient. Test #7 with D50 of 100 microns of Graphite particle size distribution resulted in the highest breakdown pressure among all other tests (Table #1 & 2) and also the highest fracture re-opening pressure among the second set of experiments (Table 2). Considering D10 of 25 microns and D90 of 210 microns (Table 3), LCM particles of test #7 were capable of blocking the pore throats, which increased the breakdown pressure and also the fracture aperture was sealed resulting in a higher fracture re-opening pressure (Table 2). The fine Graphite particle sizes, D50 of 50 microns, of test # 6 (Table 3) were not able to bridge the fracture aperture, causing the fracture re-opening pressure to be the lowest among the second set of tests (Table 2). The particle sizes of test #8 have a broader range compared to test #6 &7 (Table 3). The fracture re-opening from test #8 is not as high as the fracture re-opening in test #7 but much higher than test #6. Although the fracture aperture was bridged, the barrier was not strong enough as the particles barrier created in the test #7. This might be due to the lack of the presence of the finer particles as used in test #7. The particle sizes of test #9 are even broader than the test #9 (D50 of 1000 microns (Table 3)), the fracture re-opening pressure in this case is lower than the results of test #7 &8 since particles are not capable of bridging the fracture aperture and create a fluid barrier as particles in test #7 or 8 (Table 2).

Table 2. Summary of results for tests #6 to 9

Test #	Fluid Used	LCM	D50 (microns)	Conc (ppb)	Breakdown Pressure (psi)	Re-Opening Pressure (psi)
6	VERSATEC OBM	G	50	30	2080	840
7	VERSATEC OBM	G	100	30	2725	1292
8	VERSATEC OBM	G	400	30	2004	1216
9	VERSATEC OBM	G	1000	30	2415	1020

Table 3. LCMs particle size distributions

Particle Size Distribution (microns)				
Test #	LCM Blend	D10	D50	D90
2	Barite	3	21	64
3	G&NS	65	500	1900
4	G & SCC	80	460	1300
5	G, SCC, & CF	55	450	1200
6	G (50)	25	50	130
7	G (100)	35	100	210
8	G (400)	250	400	1000
9	G (1000)	300	1000	1700

The experimental analysis verified the importance of the particle sizes despite the conclusion of [14], which believed particle sizes are unimportant. Also, coarser particles and broader size distribution of LCMs recommended by [3] and [10] would not result in the highest sealing efficiency of the fracture, according to the results of this paper. Moreover, designing the LCM particle sizes to only bridge the fracture aperture as suggested by [4] and [12] do not cause high fracture sealing efficiency. Furthermore, small range of particle sizes [6] cannot effectively bridge the fracture aperture, so enhancement of fracture re-opening pressure would not be significant. Based on the results of this study, range of particle sizes which could effectively bridge the fracture aperture and also create a strong and impermeable seals within the fracture would result in the highest sealing efficiency, which agrees with [11] findings.

Conclusions

Two sets of hydraulic fracturing experiments were conducted with an oil based drilling fluid containing either a blend of LCMs or a single LCM with different particle size distributions. The results verified the effect of lost circulation material in enhancing fracture gradient of fracture wellbores however; the particle size distribution of lost circulation material has a significant effect on the sealing efficiency of fractured wellbores and also enhancing the breakdown pressure of intact wellbores. Smaller range of fine particles (<100 microns) were capable of blocking the pore throats and increasing the breakdown pressure; however they cannot create a strong barrier for enhancing the fracture re-opening pressure. Broad range of coarse particle sizes, in order of hundreds to thousands of microns, could bridge fracture aperture but the barrier would not be as strong toward fluid pressure. LCMs with particle sizes range of few hundred microns were capable of bridging the fracture aperture and creating a strong seal to enhance fracture re-opening pressure significantly. The measured range of fracture width increased by increasing the particle size distribution.

Nomenclature

LCM = *Lost Circulation Material*
G = *Graphite*
NS = *Nut Shells*
SCC = *Sized Calcium Carbonate*
CF = *Cellulosic Fiber*

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