AADE-11-NTCE-21

Lost Circulation Control and Wellbore Strengthening: Looking Beyond Particle Size Distribution

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Abstract

The application of particulate materials in lost circulation treatments designed to mitigate drilling fluid losses and strengthen the wellbore has been documented in several field applications. Ground marble with Resilient Graphitic Carbon (RGC) is reported to be one of the most successful combination for designing lost circulation treatments. The fluid loss control performance of the lost circulation material (LCM) is usually tested on a permeability plugging apparatus (PPA) with ceramic discs or straight slots. Particle size distribution is the most common criterion considered while designing the treatment, and other properties are neglected. In this paper we will evaluate the importance of other properties of LCM.

A hydraulic testing machine was used to measure the Crush Resistance and Resiliency of the LCM combinations. Experiments were performed at various loadings (2500 to 10000 psi), simulating the fracture closure stresses. A tapered slot (TS) physically resembling a wedge shaped fracture was designed for use in PPA testings. The tests performed on the hydraulic tester indicated that RGC is the only material that is resilient and that imparts resiliency when used in combinations. RGC also significantly increases the crush resistance of ground marble, which corroborates the successful field applications. The performance of the lost circulation treatments has been evaluated using TS and PPA in terms of the ability of the LCM to effectively plug the tapered slot with controlled fluid loss. Consideration of these properties while optimizing the LCM treatment will increase the success rates of drilling complex wells.

Introduction

With depletion of conventional hydrocarbon resources, drilling is gradually transferred to the layers of more depth and complexity. For these deeper reservoirs the safe drilling window (gap between pore pressure and fracture gradient) keeps decreasing. One of the main objectives in well construction is to maximize reservoir deliverability, reduce remedial jobs and minimize non productive time (NPT) during drilling. One of the major contributors to NPT is Loss Circulation. Lost Circulation is defined as the loss of whole mud (solids and liquid) into the formation. A severe lost-circulation event can cost a million dollars or more from delays and fluid losses and sometimes result in losing the well. It is clear that improved lost-circulation control capabilities can have a significant economic impact and is a key for reducing the drilling risks in such environments. Lost Circulation can occur naturally in formations that are cavernous, vugular, fractured, or unconsolidated or it can be the result of induced fractures (Kaageson-Loe et al, 2008). Controlling loss circulation during wellbore drilling is more than just selecting the proper type of lost circulation material (LCM). Fractured formations are being encountered which requires new technologies for controlling fluid losses and wellbore strengthening. Loss Circulation has been categorized as partial losses, seepage losses and no returns depending on loss rate (defined as bbl/hr). This categorization is only valid for losses through permeable formations. Loss Circulation can also occur through natural fractures or induced fractures. A natural fracture is defined as a macroscopic planar discontinuity resulting from stresses larger than the rupture strength of the rock (Soroush et al, 2006). Losses through pores start slowly and gradually increase whereas losses into fractures are associated with a rapid initiation followed by gradual decline with time (Majdi el al, 2008). Because of large opening size, there is no resistance for the flow to stop. In extreme circumstances, from tens to hundreds1 of barrels of drilling fluid can be flow through these fracture or vugs. From the drilling stand point, these fractures have a negative impact.

Numbers of solutions/methods have been developed to control lost circulation. Settable composition into a problematic zone to prevent or reduce the flow, or in an another method where placements of lost circulation material in the loss zone, or pumping of high yield stress fluid through the loss zone. Nie et.al (2010) discussed a special gel fluid for controlling severe loss circulation occurring below 90 ^{o}C. This special gel develops viscoelastic properties because of cross linking of polymers which cuts off the communication between the formation and wellbore. Kefi et al., (2010) discusses controlling losses using fibrous material in conjunction with LCM particles. Sander et al., (2010) developed a high fluid loss, high strength pill system for wide range of loss rate. Ramirez et al., (2005) discusses the application of using synthetic graphite to control losses by increasing fracturing pressure. Plugging capability of graphite was measured by performing experiments on 90 microns slots, however no experimental data on resiliency of the graphite was reported.

Song et al., (2006) applied a mixture of ground marble and resilient graphitic carbon to control losses by strengthening wellbore and reported an increase of 390 psi in fracturing pressure. Because of the lower permeability of shale formation, wellbore strengthening is considered to be difficult because of the inability of the formation to dissipate the pressure at the fracture tip. To address this issue, Aston et al., (2007) presented a blend of particulates and proprietary cross linked gelling polymers which will set in time. Wang et al., (2008) discusses the possible mechanism of strengthening a fractured wellbore with particulate LCM using a numerical method, and concluded that sealing the fracture leads to an increase in near wellbore effective tangential stress, which is an indicator of wellbore strengthening however in the calculations, no consideration was given to the physical properties of sealing particles.

Loss Circulation Control Mechanism

1. **Corrective:** In this method, once fluid loss has occurred/started, loss circulation control additives are added to the fluid system to control the loss. This could be attained by continuously adding engineered particles in active drilling fluid system to effectively plug/seal the permeable formation. Other very common technique is to run a curable pill. LCM is added to a small volume of active fluid system and pumped to treat the desired section in the formation.

2. **Preventive**: Objective of wellbore strengthening treatments is to increase the "hoop stress" (and thus the wellbore pressure containment ability) in the near wellbore region. While drilling, plugging the pores in permeable sand and plugging micro fractures that create well bore breathing accomplishes this dynamically. Once an interval has been drilled, a more robust treatment may be applied to significantly increase the wellbore strength. Though an over simplification, these treatments may be described as placing a designed particle size distribution particulate treating pill across an interval, and then performing an open hole formation integrity test up to the maximum ECD expected while drilling, casing and cementing that interval. A short fracture (or fractures) is initiated but is plugged immediately by the specially designed particulate treatment (Figure 1) that prevents further pressure and fluid transmission to the fracture tip, while at the same time mechanically propping the fracture to prevent closure. This action increases the hoop stresses around the wellbore, resulting in a strengthened wellbore that can contain a higher fluid pressure (ECD) as shown in **Figure 1**.

Loss Circulation Zones

Permeable formation: Most common thief zones are highly permeable formations. Because of higher permeability (because of large pore size), solids particles of drilling fluid do not forms a stable filter cake and loss of drilling fluid into formation initiates. Depending on loss rate, different kind of solutions could be applied, and most common amongst them is the use of particulate LCM. Properly sized LCM is added to the drilling fluid which plugs the pores of the permeable formation and arrests the losses. The ability for the carrier fluid of a lost circulation treatment to flow away from the fracture creates a higher solids loading and closer packing in the fracture. This improves the probability of a successful treatment. The reservoir is a subset of a permeable formation treatment with special requirements: it is preferable to use materials that may be removed once the well is completed. This is normally done by using acid soluble or breakable materials, but these materials are not always as effective as others to cure lost circulation. Even though not desirable, it is sometimes necessary to use non-acid soluble materials to treat lost circulation in the reservoir.

Natural Fractures/Vugs: The most difficult formations to treat for lost circulation are impermeable formations such as shale and vugular/naturally fractured carbonates. The lack of information on the actual fracture widths makes the particle size distribution design difficult. Standard particulate treatments are less effective for these cases. A measureable lost circulation rate may be treated with particulate material, however instances of total losses generally indicate to move beyond particulate based LCM solution.

Induced Fractures: In formations drilled with to high an equivalent circulating density, because of the wellbore pressure, fractures may be induced. Because of the induced fractures, a flow path opens from which loss circulation occurs. Induced fractures represent an even more complicated problem, as the shape and structure of induced formation fractures are always subject to the nature of the formation, drilling and mechanical effects, as well as geological influences over time. Induced fractures are generally small in size, however depending on wellbore pressure and fracture propagation pressure, the length and width of these fractures can change drastically. Very commonly particulate based LCM solutions will arrest the losses. However these induced fractures will have a propensity to open or close based on the variations in wellbore pressures.

LCM Properties-The Considered One

Particle Size Distribution: PSD of LCM is the most important criterion on which treatments are designed. The optimum size of the LCM combinations is selected based on several models like Abrams' Median Particle-Size Rule. According to this rule the median particle size of the bridging material should be equal to or slightly greater than 1/3 the median pore size of the formation. Tran et al., (2009) carried out experimental studies correlating plugging time and particle size to pore throat size as a function of particle volume fraction Reynolds number. Tran et al., (2009) concludes that very commonly used 1/3 plugging rule is valid for limited conditions and is not adequate for general applications.

$$D(50) = \frac{\lambda}{3} = \frac{Fracture\ opening\ size}{3}$$

IPT (Ideal packing theory) uses either pore size from thin section analyses or permeability information, combined with particle-size distributions of the bridging material, to determine the Ideal Packing Sequence (IPS). In the **Vickers Method**, PSD is selected covering a broad range of fracture widths to achieve minimal fluid loss into a reservoir. Insufficient information on formation pore size distribution and lack of understanding of proper filtration/screening mechanism under downhole conditions might lead to erroneous outcome.

LCM Properties – The Missing Links

Fluid Loss and LCM Evaluation Technique: Particle Plugging Apparatus (PPA) is a standard equipment to evaluate the performance of the lost circulation material. The ‘performance of the LCM’ is hereby defined as the ability to form an impermeable plug or bridge in the filtering media and arrest the mud loss. The set up consists of a 500 ml volume cell that has a movable piston at the bottom. At the top, the cell has an assembly for perfectly seal while testing. The cell is positioned with pressure applied from the bottom of the cell and the filtrate collected from the top. This prevents particles that settle during the static test from contributing to the performance of the LCM (as particles settle in the direction opposite to the filtration surface). The cell pressure is applied by a two stage hydraulic pump or using a nitrogen pressure line. Pressure is transferred to the drilling fluid through the floating piston in the cell. The filter media usually employed in the PPA is a ceramic disc available in different pore sizes or constant area slots available in different opening widths. But in order to study the performance of the LCM, as defined in the earlier section, the above two media may not be a proper choice. Ceramic disc only represents the formation but not the fracture. Design of LCM mixture for wellbore strengthening could be misleading. And the straight slots represent the face of the fracture. The LCM will tend to sit on the face of the slot and may get eroded by the shear stresses of the drilling fluid. Few tests were even performed on PPA using the straight slots, but most of the times the LCM particles were observed to be just sitting on the face of the slot opening and not inside the slot. **Figure 2** gives the schematic of the ceramic disc, constant area slots/ straight slots. Tapered Slot (TS) in which opening size of the slot tapers over a fixed length was fabricated and the performance of the LCM combinations were compared.

Crushing Resistance: It has been reported in many publications and field success stories that LCM like ground marble, resilient graphitic carbon (RGC) and ground nutshells performed better when used in combination. Particularly, ground marble and RGC combinations proved to be effective and hence the most used in many situations that demanded arresting lost circulation problems (Goud, 2006). Ground marble is brittle material that means the particles breaks in to smaller fragments at lower applied mechanical pressures, whereas LCM like ground nut shells are very ductile, even at very high pressure; instead of breaking they tend to elongate, and LCM like RGC are resilient in nature, once load is removed from the material, they revert back to a percentage of their compressed size. Adding RGC to ground marble decreases the crushing of the material as resiliency of the load bearing network increases significantly. Higher crushing resistance is always desirable for effective wellbore strengthening’, because once the fracture closes and stress gets transferred to the LCM particle inside the fracture, particle crushing will start. Lesser crushing of particles will lead to lesser deviation from the actual size maintaining the fracture width, which is the emphasis of wellbore strengthening.

Aspect Ratio: The aspect ratio of a shape is the ratio of its longer dimension to its shorter dimension. For a spherical particle, the aspect ratio will be equal to one. From a series of tests conducted (Arunesh, 2010), it was concluded that most of the commonly used LCM have similar aspect ratios. On the same note, on several occasions, flake type material has been used to arrest losses (**Gonzalez, 2003).** These flake type materials have higher aspect ratios and effective plugging of flow path take place. However, these particles have lower mechanical strength, and deteriorate rapidly in a drilling fluid and are not as suitable for wellbore strengthening applications.

Resiliency: Resiliency can be explained as the extent to which a material rebounds after compression when an applied load is removed. Commonly resiliency of a material is determined at 10000 psi. LCM combinations need to have sufficient resiliency to provide good crush resistance for arresting lost circulation as well as providing wellbore strengthening. Resilient Graphitic Carbon (RGC) is a material that has the unique property of Resiliency that helps in bearing the stresses without undergoing significant change in particle size. The reported resiliency of RGC is around 120 percent at 10,000 psi. Resiliency of RGC is given by the following equation,

$$\%\text{Resilieny} = \left(\frac{H_r}{H_c} - 1\right) * 100$$

where H_C is the height of the (compressed) sample at 10000 psi and H_r is the height of the sample after load has been removed. Comparing the resiliency with other petroleum products, RGC is the only product which exhibits higher resiliency (>60% at 10,000 psi) that may be utilized for wellbore strengthening. RGC are resilient, angular, dual-carbon based lost circulation materials. These unique resilient graphitic carbon (RGC) products allow tightly packed particles, under compression in pores and micro fractures, to compress and then expand without being dislodged by changes in differential pressure. The range in particle size allows RGC lost circulation material to act as bridging and sealing agents over a wide range of pore and fracture sizes where other materials might fail. RGC, when added with ground marble or ground nut shells, apart from improving their crushing resistance, also imparts resiliency to the mixture. Resiliency also plays an important role in wellbore strengthening where a variation in wellbore pressure may lead to fracture reopening; and then the resilient particles will rebound to close the fracture gap.

Concentration of LCM: Success rate in wellbore strengthening and lost circulation control in a newly drilled formation is significantly affected by the concentration of LCM in the fluid system. Fluids with lower concentration of LCM will not form an effective barrier inside the fracture, and consequently no increase in wellbore pressure containment will be observed. LCM blend is designed to minimize fluid loss and give pressure isolation. Similarly in porous formation, ability to plug the pores of the formation depends on both, concentration of LCM and particle size distribution. LCM concentration is also controlled by the equivalent circulating density as addition of LCM in drilling fluid increases the viscosity. Therefore for an application, LCM concentration should be optimized by considering ECD, fluid loss and fracture volume/porous zone length.

Experimental Results

Commonly it has been widely acclaimed that LCM particles should be large and uniform, so that it prevents mud leaks after being packed, yet does not significantly change mud properties and can be removed easily (and perhaps recycled). If the density of the LCM particle (if used alone or in mixture) is similar to base fluid density, then minimal phase separation or particle settling will take place. Products which are abrasive or easily crushable while drilling find negligible application for loss circulation control or wellbore strengthening.

Resilient graphitic carbon has been used for two decades to cure losses. Despite being angular in shape, RGC also provides lubricity to drilling fluid which enhances the ROP and decreases the torque and drag requirement. RGC has unique property of resiliency. Only those grades of graphitic carbon which exhibit minimum resiliency of 60% at 10000 psi can be called as Resilient Graphitic Carbon (RGC). Several different samples of graphitic carbon were procured and tested for resiliency following the procedure mentioned in the previous section. All graphitic carbon used in experiments have different particle size distribution and has been shown in **Figure 3**. Resiliency of different grades of graphitic carbon determined experimentally has been shown is **Figure 4**. Difference in the resiliency could be attributed to the structure of the graphitic carbon. The furnace process that produces RGC removes most of the impurities which results in some porosity in the carbon core. As the materials are ground to smaller particle sizes, some of the bulk porosity is lost – thus the resiliency trends down as the particle size decreases. Very often LCMs are used in combination with two different particles mixed together. Combination of ground marble and resilient graphitic carbon has been used very widely (Goud et al., 2006 and Song et al., 2006). Resiliency of the same combination was determined and has been reported in **Figure 5.** Ground marble is a non-resilient material. Addition of resilient graphitic carbon to ground marble imparts resiliency to the combination.

Resistance of LCM particles to undergo crushing is important for wellbore strengthening applications. Induced fractures tend to close, transferring the formation closure stress on the particles inside the fracture. Brittle particles will undergo instantaneous crushing and lesser success in wellbore strengthening will be observed.

Crushing resistance of various materials was experimentally determined. LCM particle were first sieved to determine the initial PSD. Then pressure at constant rate was applied till the desired loading. Once the desired limit of pressure was reached, pressure was released. A sample was collected and sieved again to determine the PSD. Based on initial and final PSD, change in PSD was calculated. Ground marble alone exhibited the highest change in mean particle size distribution because of its brittle nature. Addition of only 10 percent of graphitic carbon increases the crushing resistance significantly as shown in **Figure 6**. Addition of RGC in a low quantity also increases the applicability limit of ground marble for curing losses and wellbore strengthening. Crushing resistance of mixtures of ground marble and RGC for different sizes of RGC was also determined. With increasing size of the RGC, crushing resistance of the mixture increases as shown in **Figure 7**, because of the increase in contact area. Brittle particles like ground marble are protected by the RGC particles when load gets transferred to RGC without crushing the ground marble.

Effectiveness of these materials to control losses in a wellbore was determined using the PPA. Constant area slots and tapered slots were used to analyze the performance of the fluid based on their plugging capability and fluid loss. A test was carried out to determine the effectiveness of the tapered slots compared to constant area slots. Fluid loss test was carried out on 1016 µm, 1524 µm, 2032 µm and 2540 µm slots along with tapered slot (where slot size tapers from 2500 to 1000 µm). Fluid loss result has been reported in **Table 1**. Composition of the LCM used for comparing different filtration medium has been given in **Table 2**. In case of constant area slots, the face of the slot is plugged, with very minimal particle invasion inside the slot, where as in the case of a tapered slot plugging took place inside the slot. Because of the location where LCM particle plugs the slot, difference in the fluid loss value was observed. For tapered slot, fluid loss observed is 41.8 ml whereas for 1016 µm is 18.6 ml and 2504 µm is 71.6 ml. LCM combinations optimized using a tapered slot for plugging fracture along for wellbore strengthening will be more realistic and has been documented by Collins et al., 2010. Several more tests were done to establish the effectiveness of a tapered slot. From the crush test results, the concentration of RGC was kept at 20 percent in all the ground marble-RGC combinations. Different sizes of ground marble, like D (50) in the range of 150, 600 and 1200, were tested on the tapered slot to verify their ability to form an immobile mass of a bridge in the slot with minimum fluid loss. Particle size distribution of various combinations of particulate LCM and fluid loss results has been tabulated in **Table 3**. GM 1200 particles were able to plug the slot but didn't control the fluid loss. This was because the interstitial void in the plug was too large and continuous fluid loss occurred in spite of complete filling of the slot. This scenario is not desirable as permeable plug will not stop the pressure transmission from wellbore to the fracture and fracture tip will propagate continuously. Addition of RGC 400 (20 percent by volume) arrested the fluid loss. Ground nutshells – medium, always formed the bridge at the far end of the tapered slot with very small fluid loss. No significant improvement in the fluid loss was observed with the addition of 20 percent RGC 400 to ground nutshells medium. A few tests were also performed on tertiary combinations; nutshells, RGC and GM combinations, and found that the results were almost the same as that of binary mixtures

Conclusion

Different solutions need to be deployed for controlling losses occurring from different flow paths. Although in some instances the same material is being used for lost circulation control and wellbore strengthening, apart from particle size distribution additional properties should be investigated before deploying the treatment. Important conclusions that could be drawn from this study are**:**

1. Experimental technique: Experimental techniques which address the actual physics of the problem should be always practiced. Loss circulation treatment designed using a ceramic disc may fail completely when a natural fracture is encountered. Wellbore strengthening treatment design should always be carried out using a tapered slot, which more closely resembles an induced fracture.
2. Particle Size Distribution: Improper particle size distribution of LCM in treatment fluid, instead of controlling the losses could aggravate the problem.
3. Resiliency: Resiliency in a unique way is desirable for both controlling losses from permeable zones along with wellbore strengthening. Particles having ability to rebound or flex will respond in an intelligent way to any wellbore pressure change. Resilient particles also decrease the crushing of the particles.
4. Crushing resistance: For wellbore strengthening, it is imperative for the material to have higher crushing resistance. Significant crushing of LCM particles inside the fracture might lead to loss of stresses developed because of wellbore strengthening.

Considering the overlap between various properties (**Figure 8**) while designing the treatment for loss circulation control and wellbore strengthening will ensure best possible outcome and higher success rate.

Acknowledgement

The authors would like to thank Halliburton for allowing this work to be published. Special thanks to Dale Jamison, Robert Murphy, Dr Don Whitfill and Dr Matthew Miller for their valuable discussion and input.

Abbreviations

ECD	---	Equivalent circulation density
FCS	---	Fracture Closure Stress
GM	---	Ground Marble
LCM	---	Lost Circulation Material
PPA	---	Permeability plugging apparatus
PSD	---	Particle Size Distribution
RGC/GC	---	Resilient Graphitic Carbon/Graphitic Carbon
ROP	---	Rate of Penetration

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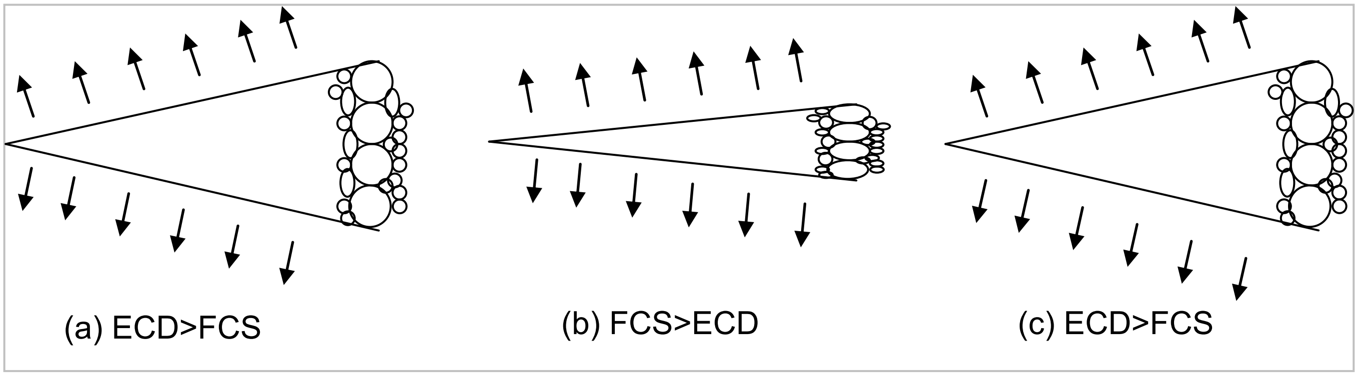

Figure 1: Formation of a bridge in fracture (a) When ECD>FCS, particles form a bridge inside the fracture near the throat (b) When FCS>ECD, fracture tries to close, transmitting the closure stress on the bridging particles (c) Again, when ECD>FCS, drilling resumes, fracture widens, particles forming the bridge should be capable of regaining its shape so that it can effectively isolate the fracture and control the total fluid loss.

Figure 2: Different filtration medium used for loss circulation treatment design for permeable section and fractures.

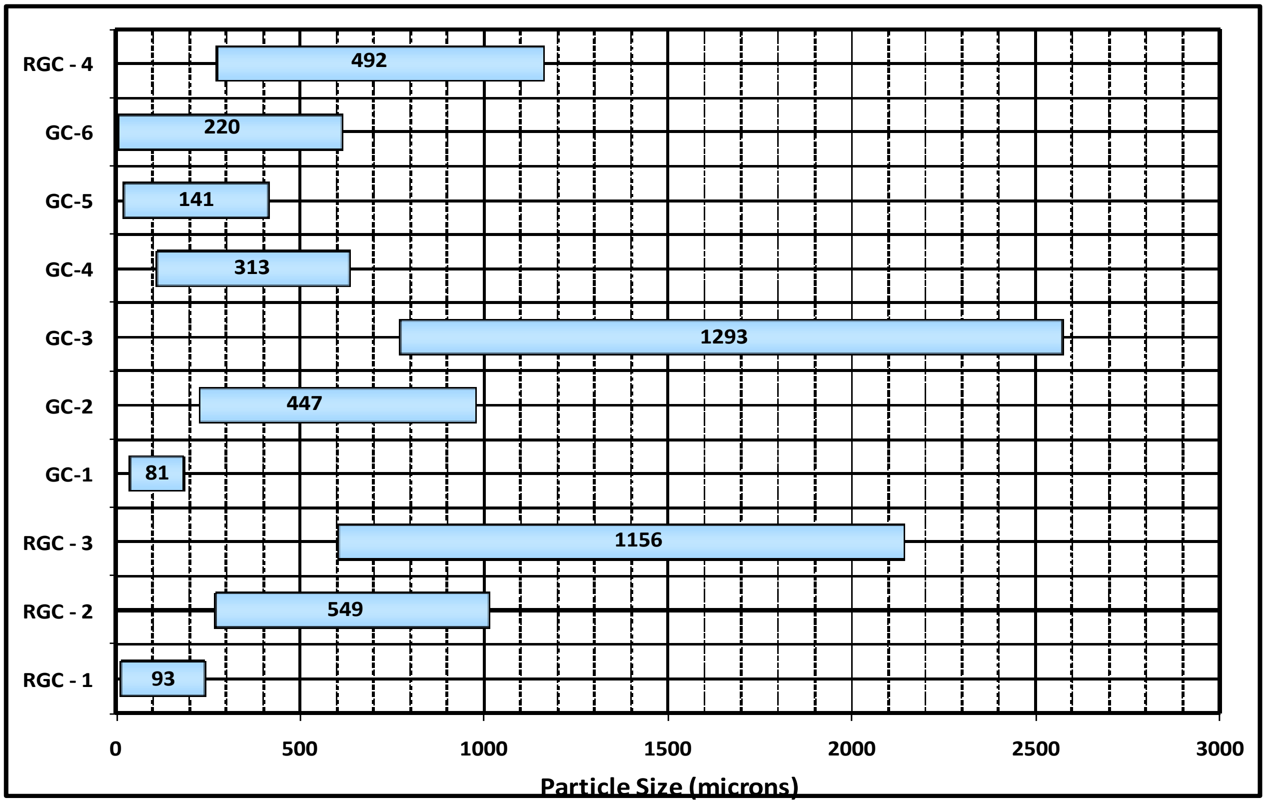

Figure 3: Particle Size distribution of different types of Graphitic Carbon

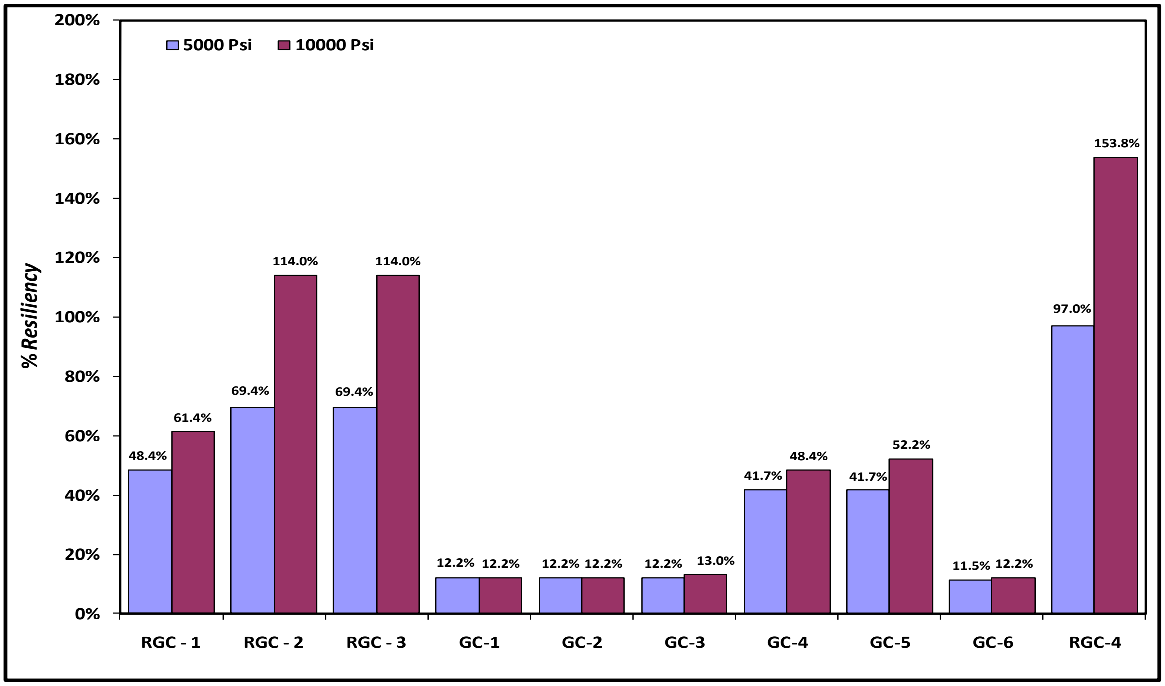

Figure 4: Percent Resiliency of different types of Graphitic Carbon

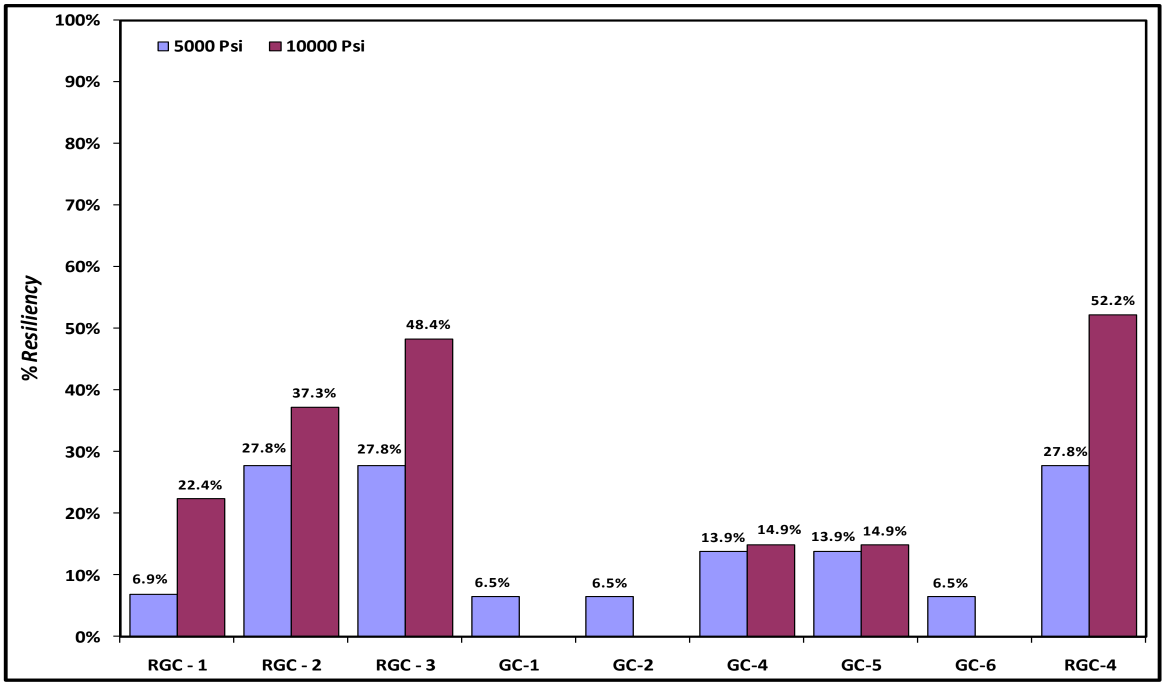

Figure 5: Percent Resiliency of 80/20 (Vol percent) combination of Ground Marble 600 and Graphitic Carbon

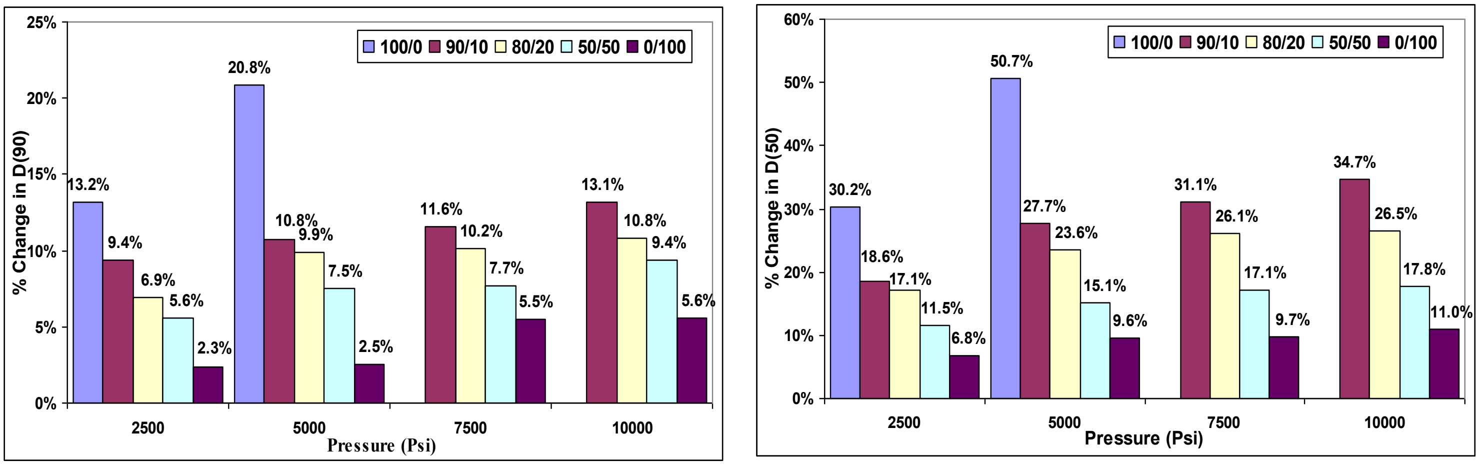

Figure 6: Percent Change in D (90) and D (50) for Different Ground Marble 600 /Resilient Graphitic Carbon 400 Combinations.

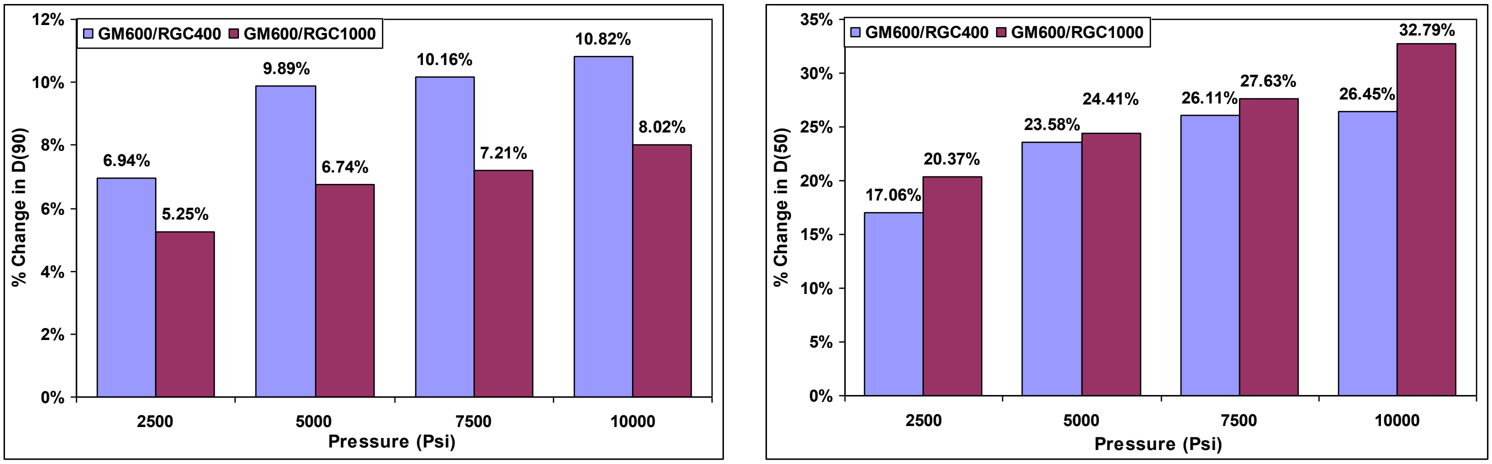

Figure 7: Percent Change in D (90) and D (50) for 80/20 (percent v/v) Ground Marble 600 /Resilient Graphitic Carbon.

Table 1: Comparison of constant area slots and tapered slots

	Fluid 1	Fluid 2	Fluid 3	Fluid 4	Fluid 5
Constant area slot (1016 micron)	18.67	37.18	25.85	4.48	10.35
Constant area slot (1524 micron)	24.51	47.88	8.85	6.87	13.27
Constant area slot (2032 micron)	19.05	47.35	7.24	7.53	9.11
Constant area slot (2540 micron)	71.65	86.55	73.6	68.97	66.16
Tapered Slot	41.85	38.2	81.11	48.53	14.92

Table 2: Composition of LCM used for comparing different slots

Material	lb/bbl
Nut Shell-1	7.5
Nut Shell-2	7.5
Ground Nut Shell- Medium	4
RGC 1000	5.5
RGC 400	8.25
RGC 100	8.25
Ground Marble 25	4.5
Ground Marble 5	4.5

Table 3: Particle size distribution and fluid loss data for different combinations of LCM. Fluid loss testing performed on Tapered slot

Sl No	Combination	Conc.	D (10) µm	D(50) µm	D(90) µm	Fluid Loss (ml)
1	GM600/ RGC 400	80/20	479	677	1230	20
2	GM600/ RGC 400	50/50	329	629	1159	70
3	GM1200	100	8	943	1489	No control over fluid loss
4	RGC 1000	100	604	1156	1539	20-30
5	GM1200/ RGC 400	80/20	11	847	1434	12
6	GM1200/ RGC 400	50/50	43	618	1307	5
7	GNS	100	243	1408	1935	5-7
8	GNS/ RGC 50	80/20	49	1278	1879	18-20
9	GNS/ RGC 400	80/20	250	1295	1888	10
10	GNS/ RGC 1000	80/20	274	1339	1887	10

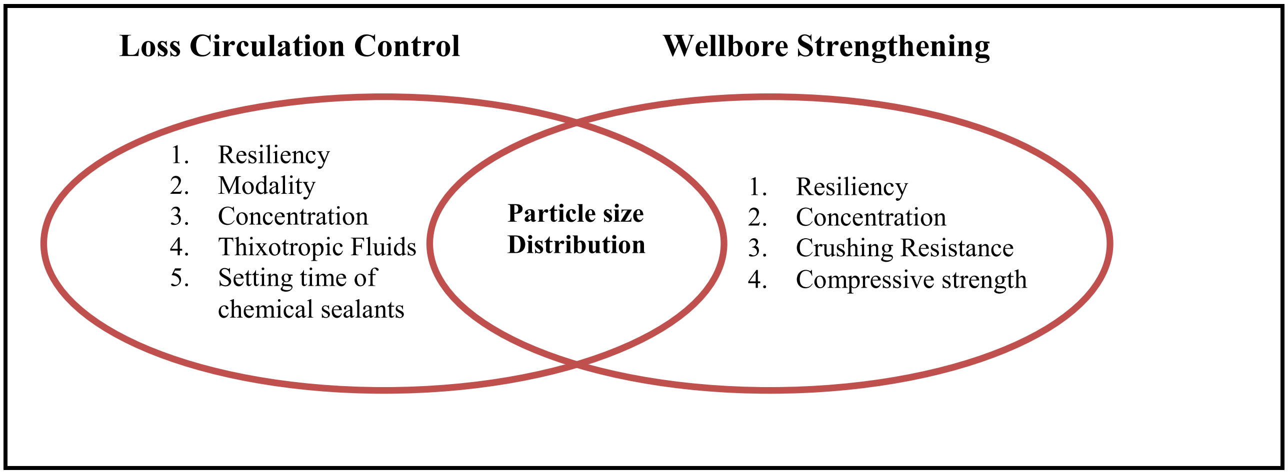

Figure 8: Overlap between properties of LCM used for loss circulation control and wellbore strengthening