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A Wellbore Strengthening Comparison between Conventional and Highly Resilient Synthetic Graphite: New Data to Support the Utility of Low Resilience Graphite as a more Effective LCM

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Abstract

The use of high resilient graphite in wellbore strengthening applications is growing annually thus putting a strain on the availability of the raw material globally. In this study, test results are generated using a modified particle plugging apparatus (PPA) equipped with parallel slotted plates comparing carbon and graphite based loss-control materials (LCM). The formation and mechanical stabilization of the fracture seal is described and a practical hypothesis of fracture seal initiation presented. Carbon/graphite particle resiliency is compared and the measurement methodology of resiliency described and questioned. PPA test results show that low to moderately resilient carbon and graphite LCM prove more effective as fracture sealing materials than highly resilient carbonaceous materials. Mixtures containing added calcium carbonate were also evaluated to a limited extent.

Introduction

Resilient graphitic carbon has been utilized as a wellbore strengthening and lost circulation material for many years. These products have been promoted because of their ability to withstand wellbore pressures, protecting the stability of the seal in a fracture in under and over balance situations.

Recently, the lack of availability and increased cost of highly resilient carbon has prompted the industry to validate whether or not high resilient carbon provides the performance claimed. The purpose of this paper is to determine the validity of that assertion: Due to the fact that first, the resiliency measurement is suspect, and second, based on slot test measurements, a highly resilient particle does not actually provide additional integrity to a fracture seal compared to lower resilient graphitic material.

Lost Circulation Background

Lost circulation is considered as partial and total losses of drilling fluid to the formation due to many factors (Messenger 1981). This can include fluid lost while drilling into a permeable formation, natural faults, natural fractures and induced fractures where the weights of the drilling column are higher than the formation pressure. There are two distinguishable differences between natural and induced fractures based on the leak-off (Wang et al. 2005). Natural lost circulation occurs with fluid loss to large pores, faults, vugular formations, and fractures, etc. Induced fractures occur when the weight of the drilling column surpasses the formation allowable pressures. Lost circulation can be a great expense to the drilling industry in lost drilling fluid and non-productive time. Sometimes, the well bore may be sidetracked, bypassed, or completely lost due to these issues. These situations can be more prevalent today as more easy to find oil reservoirs are less abundant and more difficult wells are being drilled. The events of lost circulation could be due to depleted reservoirs, extended reach drilling and narrow mud windows. Over the past, specific particle size distribution of LCM has been recommended for stopping or aiding in ending these losses. No matter the type of fluid loss, natural or induced, the particles are mixed as a pill or run continuously through the system in order to mitigate these losses.

Wellbore Strengthening and Stress Cage

In order to keep induced fractures from occurring the mud weight should always be between the pore pressure and fracturing pressure. This is easy on a formation that does not have faulting and folding which are natural occurrences in the earth's crust. Sometimes these issues lead to a narrowing of these windows or require that they be ignored. During these occurrences and when drilling into depleted zones, extended reach and deviated wellbores will have very narrow mud weight windows. When this happens, the effective circulating density (ECD) will overcome the fracture pressure of the formation and induced fractures will occur thus leading to lost circulation. In order to arrest these occurrences, LCM is to be applied to stop the fluid loss. If the particles can stay inside the fracture mouth, the additional mass of particles can contribute to well bore strengthening as the additional mass in the particular area has increased and thus isolating the fracture tip (DuPriest 2005). If this is the case, higher mud weights can be used to drill that section of formation hopefully without further mud losses.

Stress Cage Theory

Stress cage theory provides insight into the fact that having more particles in the fracture mouth will allow for additional mass to collect in the near wellbore volume. This configuration provides for higher mud weights to be drilled because more volume of material needs to be overcome for a breakdown. The different types of stresses are shown in the Figure 1. (Kumar 2010) states that *minimum horizontal stresses* (S_h) also called far field stresses, are inherent to the formation and cannot be changed. Effective tangential stresses (σ_Θ) are the near well bore stresses acting on the outside of the well bore, creating by drilling.

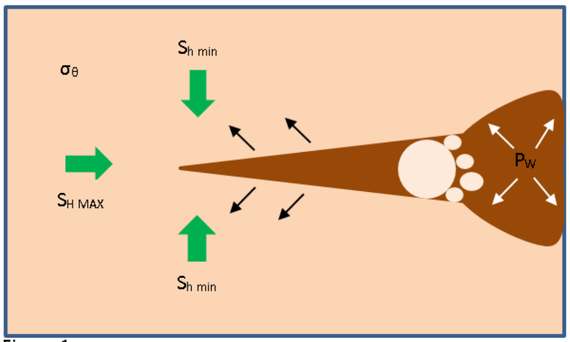

Figure 1.

Stress cage theory is modeled for induced and permeable formations only as LCM near to the face of the induced fractures will act as a proppant to isolate fluid pressure from the fracture tip (Kumar 2010). The fluid stopped to the fracture tip will lead to pressure loss inside the fracture beyond the seal or bridge. If fractures are induced, then the formation at the wellbore will be compressed, and the material in the fracture mouth will increase the effective tangential stress. This method is proposed through Stress cage Theory (Alberty et al. 2004). The wellbore strengthening effect is calculated as (Whitfill2008):

$$\Delta p = \frac{\pi}{8} * \frac{w}{R} * \frac{E}{\left(1-\upsilon^2\right)}$$

Rules and Theories to cure Lost Circulation and Strengthen the Wellbore

To this day, most lost circulation treatments for well bore strengthening selected via particle size distribution (PSD). Many models have been utilized to create a successful treatment based on PSD in order to seal the fracture or pore to keep fluid loss at a minimum and withstand high well bore pressures. They Include:

1. **Abrams' Median Particle-Size Rule** (Abrams 1977): The median particle size of the particulate bridging material should be equal to or slightly greater than 1/3 the median pore size of the formation where λ is the pore throat size. This rule is generally meant for sealing pore throats in the formation and not fractures.

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

2. **IPT (Ideal Packing Theory)** (Dick 2000): In this theory, the permeability data or pore size is joined with PSD of the bridging material to determine Ideal Packing Sequence.

3. **The Vickers Method** (Vickers 2006): In this method, target fractions are used to aid in bridging effectiveness in the IPT method. The criteria for this method are as follows:

   D (90) = largest pore throat
   D (75) < 2/3 of largest pore throat
   D (50) +/- 1/3 of the mean pore throat
   D (25) 1/7 of the mean pore throat
   D (10) > smallest pore throat

4. **Halliburton Method** (Whitfill 2008): The d50 of the particle blend is to equal the estimated fracture size in order to allow for error in estimation. This way both particles larger and smaller than the estimated fracture size are included in the distribution to seal fractures that can be both larger and smaller than anticipated.

There are many other characteristics that come into play besides particle size as not all materials of a specific size would be an effective wellbore strengthening material. Physical properties such as hardness, sphericity, convexity, and aspect ratio also need to be examined before choosing an effective bridging material. Particles must be capable of withstanding fracture closure stress (FCS) *without undergoing significant size reduction.* Particles must also be capable of withstanding large changes in ECD without re-establishing lost circulation or continued fracture propagation may occur (Kumar 2010).

Previous papers on resiliency have concluded that the higher the crush strength and resiliency of LCM combinations, the better the control of mud losses and strengthening of the wellbore. This claim is illustrated in Figure 2 and states that a seal will be created near the wellbore of an induced fracture and the high resilient products of the LCM will act like a buffer and keep the harder less crush resistant material from breaking when the fracture closure stress (FCS) is more than the equivalent circulating density (ECD). When the ECD is then once again greater than the FCS the high resilient particles will rebound and return to normal size sealing the fracture. The difficulty with this theory is that in the figure depicting this claim, the fracture is sealed at the fracture mouth with many small particles which is not physically possible. For example, if the fracture mouth was 1mm wide in this figure, it portrays four particles of 250 µm in size, stacking on top of each other in the fracture mouth. What mechanism would cause these four particles to seal inside the fracture mouth without any downstream support against the applied fluid pressure? There is nothing to keep the particles from continuing to flow inside the fracture. Attempting to seal a 1mm fracture with bridged and unsupported 250 µm particles seems illogical.

Figure 3, illustrates the hypothesis, that to seal a fracture efficiently, a large particle, slightly smaller than the fracture opening will be needed to begin the sealing process. This does not allow for smaller particles to act as a buffer between this particle and the fracture walls since the large particles will be wedged in the fracture mouth. The primary large particle must be influenced directly by the formation inside the fracture when the FCS>ECD. Proof of this theory is affirmed when choosing a lost circulation treatment with particle sizes being near the projected fracture size. In addition, lab tests show that when sealing a particular fracture it is necessary to have particle sizes similar in size of the slot width.

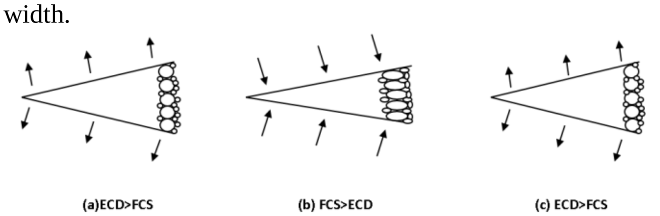

Figure 2- Previously printed formation of a bridge in a fracture: (a) When ECD>FCS the large particle begins the bridging across the fracture mouth with smaller particles filling in the voids; (b) When FCS>ECD, the fracture tries to close, transmitting closure stress on the bridging particles; (c) When drilling resumes, the ECD>FCS, the fracture widens, the belief is that the particles will regain its shape to seal off the fracture tip and control fluid loss. Why should this be questioned? What is going to allow for small particles to accumulate at the fracture mouth? These particles are small enough to continue flowing into the fracture, not sealing off the fracture mouth at all.

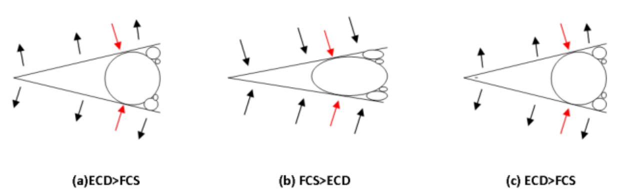

Figure 3- Actual Formation of a bridge in a fracture: (a) When ECD>FCS the large particle begins the bridging across the fracture mouth with smaller particles filling in the voids; (b) When FCS>ECD, the fracture tries to close, transmitting closure stress on the bridging particles; (c) When drilling resumes, the ECD>FCS, the fracture widens, the belief is that the particles will regain its shape to seal off the fracture tip and control fluid loss. The red arrows show that the large initial bridging particle must have direct contact with the formation in order to create a bridge or seal across the fracture mouth. This particle would have to have the resiliency needed in order to do this. Question is how much resiliency is needed and if the resiliency is high, it will be readily compressible and not seal the fracture mouth as when it undergoes pressure from the well bore it will compress and move further into the fracture. A particle such as CaCO3 has a low crush strength and would fracture when the FCS>ECD, so this particle is not recommended. A particle with a high crush strength and some resiliency would be best, not so much that the particle will squeeze into the fracture when ECD>FCS.

In the drilling industry, resiliency (Figure 4) is measured by putting a certain amount of material into a sample holder and applying pressures up to 10,000psi, measuring how much the sample compacts under applied pressure and finally how it rebounds to its original size when the pressure is released. The resiliency or spring back measurement is then determined by the calculation:

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

Where:

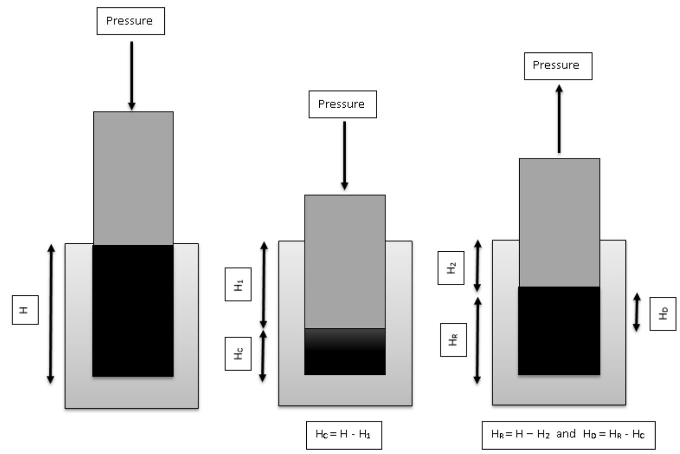

Figure 4 -% Resiliency = [H_R/H_C-1]*100 or %Resiliency = H_D/H_C*100

In summary, the % Resiliency= rebound distance from measurement at 10,000psi/ compressed sample height from bottom of the sample apparatus. Thus, the more the material compresses the more likely a high resilience is possible. This is how resiliency can be higher than 100%. In the above figure the graphics illustrate a material with a resiliency of 100%. The original height of the sample column is 1.0. Under 10,000psi, the column height is 0.35. The rebound height is 0.7. According to the equation (0.7-0.35)/ 0.35*100= 100%.

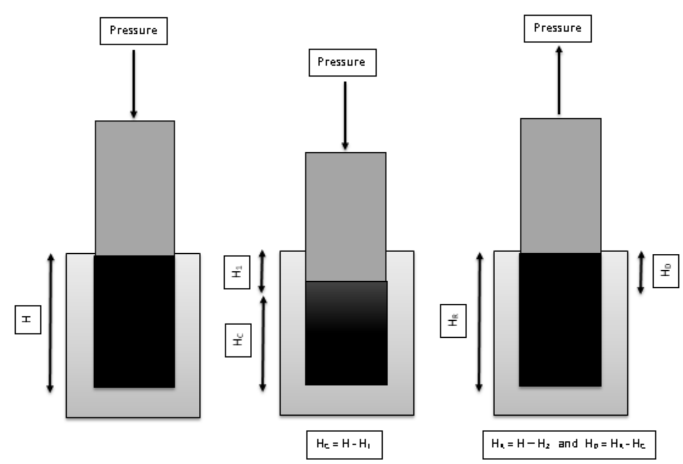

Figure 5- % Resiliency = [H_R/H_C-1]*100 or %Resiliency = H_D/H_C*100

Figure 5 is a graphical illustration of a potentially low resiliency material. In this case, the original size sample column height of 1.0. After application of 10,000psi, the sample column height is 0.8. After release of the applied pressure the rebound size is 1.0. According to the equation (1.0-0.8)/ 0.8*100= 25%. This example is to show how the measurement can be misleading and does not provide complete insight into the material's resiliency. The rebounded sample can actually reach its original size and still be measured as a lower resilient material than the material that returns to 70% of its original size. Actual measurements of different resiliencies are compiled in Table D and plotted on Figure 9 and show the different initial compression of each material when the pressure is low (500psi) and high (10,000psi). These measurements were used to calculate the resiliency values.

In all resiliency measurements, the rebound size never exceeds 70% of the original size, no matter what the resiliency %. The resiliency measurement is actually a strong function of compression. (Kumar 2010) notes that for efficient well bore strengthening, the LCM plug must be able to withstand the fracture closure *stresses without undergoing significant size reduction* and must also withstand large changes in ECD without re-establishing the lost circulation. Therefore, because of the compressible nature of high resiliency particles, these materials are actually undergoing a significant size reduction and as a result are not expected to be effective LCM plug materials. This statement is consistent with the hypothesis that the primary fracture plugging materials have to be similar in size to the fracture mouth. Because it takes one large particle to begin a seal at the fracture mouth, it cannot be inferred that smaller RGC particles are cushioning this particle, or protecting this particle from fracture stresses when the FCS>ECD. If this configuration were possible for the condition when the ECD>FCS, the most this particle can rebound is 70% of its original height, which would allow for continued fracture propagation as the seal would be compromised. If the RGC is the largest material in the fracture mouth, the large compression ratio of the material also causes the LCM plug to compress significantly when the FCS>ECD. During drilling when the ECD>FCS, the large compression of high resilient particles allows for the material to compact and actually push further into the fracture therefore not aiding in wellbore strengthening, which needs to take place at the fracture mouth.

Present Work

In order to prove that there is minimal difference between a high resiliency material and a low resiliency material in induced fracture sealing or wellbore strengthening, a modified particle plugging apparatus (PPA) was used with parallel slots in order to model sealing near the fracture mouth. Some studies have preferred to use tapered slots since they mimic the shape of a fracture. However, the problem with tapered slots is that it is difficult to pinpoint where in the slot the sealing is occurring and it may result in mounding of material as sealing off flow through the slot progresses (Figure 6). This is inefficient as the "mound" may be close to an inch in length or longer if the material is present outside the slot. Once the fracture is sealed the "mound" will quit growing as no more fluid can carry particles on to the static "mound" surface.

Tapered slots are used primarily to model natural fractures or small vugular formations where well bore strengthening is not possible. The use of parallel slots allows the investigator to know exactly what size fracture is being sealed. Also, if "mounding" is taking place it indicates to the investigatory that the seal is poor. If a mound is outside the region modeled by the slot and projecting into the wellbore, fluid force and rotating pipe would constantly be breaking apart this mound, which would prohibit good seal formation.

Figure 6- Picture on the left shows a tapered slot with "mounding" occurring. Where is the sealing taking place? The "mound" will also be subject to forces within a well bore such as turbulent or laminar flow of the fluid as well as drilling equipment such as drill pipe. The picture on the right shows a parallel slot that seals directly in the fracture mouth without a "mound". This is much more efficient and will not be subjected to the wellbore influences caused by fluid flow and drill pipe.

The PPA cell is modified by enlarging the fluid exit hole to allow for large particles to exit the apparatus. The hole has and o.d. of ¾". A spacer the width of an aloxite disk (1/4") is placed on the top of the slot in order to allow the entire fracture/slot to have full flow of the test fluid through it. The objective of the tests is to measure:

- The maximum pressure the LCM plug can withstand
- The fluid loss associated with the initial seal
- The total fluid loss if the LCM plug can withstand the maximum pressure of the PPA cell (3500psi).

Methodology of the Experimental Methods:

A water based fluid was selected as the primary carrier of the LCM particles as this will not influence the performance of the particles in the slot. For a lab barrel equivalent, 1ppb viscosifier and 20ppb bentonite clay were added for each test and thoroughly sheared to ensure that the LCM particles will not move or settle and remain homogenous throughout testing. A slot size of 750µm was selected due to the particle size of the graphitic material, as this size should allow for sealing, but should not in all occasions seal to the maximum pressure of the apparatus (3500psi).

How It Works

Lost circulation material is mixed homogenously into drilling fluid or a standard fluid which has enough viscosity that the particles will not rise or sink within the fluid. This "pill" is then poured into a piston driven slot test cell. The appropriate slot is inserted on top of the fluid and an end cap is placed to seal the cell. The cell is placed in a rigid holding device and a syringe pump is attached at the bottom of the cell to drive the piston.

Once the test is ready to begin, the pressure is increased by a syringe pump that is connected to the piston that forces the fluid towards the slot. If the material in the pill seals the slot, an increase in pressure on the pill will occur. The pump can control these pressures. In most cases investigators using this device will apply pressure increases on the seal in 250psi increments. During this pressurization period, the material sealing the slot will realign, compress, or fail, which causes the material as well as fluid to be discharged out of the top of the test cell. Plots of how much pressure can be maintained by the seals or at what pressure the seals are not strong enough to hold are of interest to the investigators. Data on the fluid volume that is pumped by the syringe pump is also of interest. Samples of the data generated on a slot test device are presented in Figure 7 and 8.

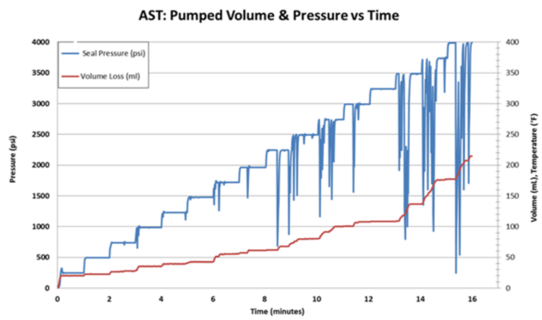

Figure 7 - Example plot of a slot test. This "pill" required a pump volume of 20mL to initially seal at 250psi. Sealed relatively well to 2000psi (60mL). At this point each increase of pressure causes seals to fail and reform and fail again. Notice that the test will reach 4000psi, but with considerable fluid pumped (220mL).

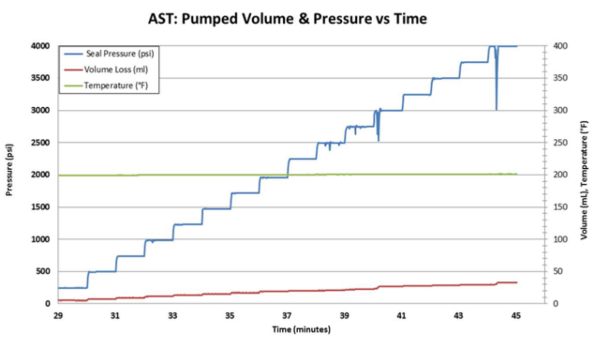

Figure 8 - Example plot of a second slot test. This "pill" required very little fluid to reach 250psi (10ml). Test had minor instabilities to 2500-3000psi. Seal then strongly re-establishes to 4000psi. Total fluid pumped to 4000psi= 35mL.

Results

For this set of tests a generic water based mud was utilized in order to ensure that the particles would be homogenous when mixed, and would not settle before the testing commenced (Table A).

Table A - Generic Mud Mix

Material	s.g.	Amount
Water	1.0	341.8g
Viscosifier	1.0	1.0g
Clay	2.6	20g
Caustic	1.3	As needed

The graphitic material was sieved according to Chart B below in order to achieve similar particle size distributions, thereby reducing particle size related test variation. In the initial round of tests the amount of each in grams or ppb are tabulated in the far right column of the table. For each subsequent test, the amount of material of each size is noted in the title of the test.

Table B- Sieve Sizes in Testing

Sieve Number	Diameter (mm)	Grams
18	1.0	0
30	0.6	3.00
60	0.25	3.00
200	0.075	3.00
Pan	0.00001	3.00

Each material will be designated by the following in the results (Table C) and corresponding resiliency measurements (Table D):

Table C- Graphitic Material Type

Material Designation Type	Material Type	True Density
A	100% Resilient Carbon	2.18
B*	80% Resilient Carbon	2.22
C**	20% Resilient Parent Carbon of B	2.04
D	50% Resilient Synthetic	2.23
E	Mined CaCO3	2.75

Note: *Sample B was manufactured by a graphitizing heat treatment of a petroleum coke specifically for testing purposes.
** Petroleum coke parent carbon from which Sample B was synthesized.

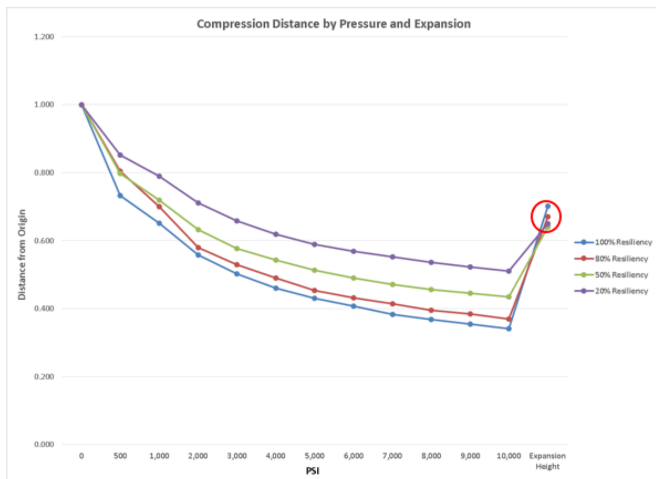

Figure 9- Graph of compression versus original size. Note that all return to almost the same height when pressure is released.

Table D- Resiliency Measurements by Carbon Type

Carbon Type	100% Resiliency	80% Resiliency	50% Resiliency	20% Parent Resiliency
Material Designation	A	B	D	C
Start	1.0	1.0	1.0	1.0
500psi	0.73	0.81	0.80	0.87
500psi Compression	27%	19%	20%	13%
10000psi	0.34	0.37	0.43	0.53
10000psi Compression	66%	57%	57%	47%
Pressure Release Size	0.70	0.67	0.64	0.65
Difference from Start	-30%	-33%	-36%	-35%
Resiliency	105.8%	81.0%	48.8%	22.6%

Results by carbon and calcium carbonate material with no combination of LCM materials:

3ppb of each sieve from Table B above run on a

750µm slot:

Table E-

Test	Material	Fluid loss at 250psi	Max Pressure Sealed
1	A	85mL	500psi
2	B	71mL	750psi
3	C	24mL	2250psi
4	D	170mL	500psi
5	E	105mL	1000psi
6	Equal Vol. E	74mL	1500psi

Table E presents the slot test device results for samples A thru E (see Table C for sample ID). At 250 psi, sample A sealed with a fluid loss of 85mL. In contrast, at the same pressure Sample B showed a fluid loss of 170mL. This may be due to the rough, granular nature of the 100% resilient material (Sample A) which may aid in the sealing properties at such a low pressure. The rough surface texture may also provide a mechanism that allows the particles to stick together better. Figure 10 shows SEM images of the subject carbons.

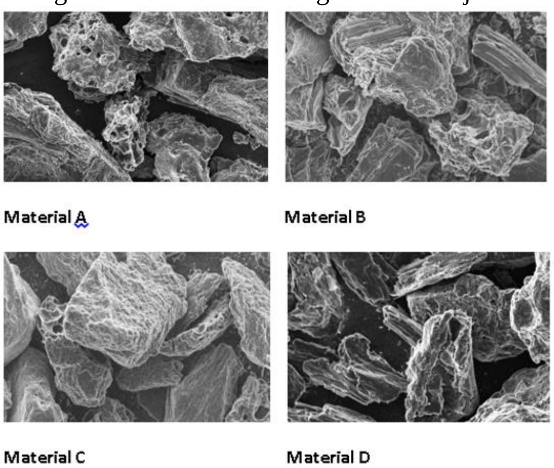

Figure 10- SEM photos at magnification of 50x on the different types of carbon. The convexity appears to decrease from Material A to D in sequence.

The 20% resilient material (Sample C) sealed much better than all the resilient carbons tested (2250psi and 24mL initial fluid loss). A conventional granular calcium carbonate (Sample E) was also tested to compare the performance since it will be used as a blend item in additional tests noted below.

Results by carbon material when combined with larger sized mined CaCO3

Many previous papers have utilized a combination of mined calcium carbonate and the higher resilient carbon (100%) in an 80:20 ratio. For continuity this same mix ratio was used in this study. In this test set calcium carbonate is the larger particles used on the 750µm slot (Table F).

Table F

Test	Blend	Fluid loss at 250psi	Max Pressure
7	6ppb E Each 30,60mesh, 1ppb E Each 60, 200,-200mesh	31mL	1000psi
8	6ppb E Each 30,60mesh , 1ppb A Each 60, 200,-200mesh	37mL	2500psi
9	6ppb E Each 30,60mesh , 1ppb B Each 60, 200,-200mesh	57mL	2500psi
10	6ppb E Each 30,60mesh , 1ppb C Each 60, 200,-200mesh	33mL	2500psi
11	6ppb E Each 30,60mesh , 1ppb D Each 60, 200,-200mesh	37mL	2500psi

Results show that combining the large calcium carbonate particles with the smaller particles of each carbon has close to the same fluid loss at 250psi. All the carbons held a maximum pressure of 2500psi when mixed with larger calcium carbonate particles.

Results by carbon material when combined with smaller sized mined CaCO3

For this phase of testing, the importance of the resiliency of the large carbon particles is considered. In this case, the carbon material represents the large particle fraction of the blend, and the conventional calcium carbonate takes the place of the smaller particle component of the mixture. In this test set the same 80:20 CaCO3 to carbon ratio is utilized.

Table G

Test	Blend	Fluid loss at 250psi	Max Pressure
12	1.5ppb A Each 30, 60mesh, 4ppb E Each 60, 200,-200mesh	uncontrolled	
13	1.5ppb B Each 30, 60mesh, 4ppb E Each 60, 200,-200mesh	109mL	1000PSI
14	1.5ppb C Each 30, 60mesh, 4ppb E Each 60, 200,-200mesh	45mL	1750psi
15	1.5ppb D Each 30, 60mesh, 4ppb E Each 60, 200,-200mesh	uncontrolled	
16	1.5ppb E Each 30, 60mesh, 4ppb E Each 60, 200,-200mesh	124mL	500psi

In this trial, only the medium resilient carbon was able to seal when combined with smaller CaCO3 particles. The initial fluid loss and P_{max} were similar to the former test set in which larger carbonate particles were utilized. This result raises the questions; is the resiliency the most important factor in fracture sealing with carbons, and is particle spericity and convexity (surface roughness) more important on high resilient carbons?

SEM images were taken of each material and based on interpretation of these images the porosity or convexity appear to be high on the 100% and 80% resiliency carbons, and low on the 50% resiliency carbon. The parent material also exhibited a low surface roughness, and performed better than the other materials tested. This behavior may be explained by the relationship between resiliency and convexity: The higher the resiliency the more important high convexity becomes. For a low resilient carbon particle, convexity may not be important. Would the high resilient carbon perform much worse than synthetic graphite because of its higher compressibility if not for correspondingly higher convexity than the lower resilient synthetic graphite?

Is convexity important to enable high resilient carbon materials to seal properly? In other words, is convexity a more important attribute to high resilient carbons than to those that have a lower resiliency? These answers will require further investigation.

Conclusions

- For effective well bore strengthening near the fracture mouth, particles close in size to the fracture opening are necessary in order for a seal to begin forming. These particles should not be highly compressive and should be slightly smaller than the fracture size at the mouth. Undersized particles will push into the fracture until the particle is met by fracture side walls. This causes the fracture to make contact with the large particles and thus is immediately subject to wellbore pressure increases and decreases when the FCS is greater, equal to, and less than ECD.

- The smaller particles in the sealing bridge have no effect in keeping the large particles from compressing or breaking when ECD pressures are changing. Smaller particles do not prevent large particles from touching the fracture walls.
- The resiliency measurement is completely dependent on the applied test pressure and resultant compression of the material. A material can compress a short distance, rebound to its original size, and be considered a low resiliency material. In contrast, a material may be highly compressive, but does not spring back to the original size during rebound. All carbon materials tested did not exhibit more than about 70% rebound after being subjected to a 10,000psi compaction pressure. A compression ratio including more information about starting and finishing sample volumes, morphological features, etc., may be necessary to improve the meaning and understanding of the so-called resiliency values reported for carbonaceous materials.
- For sealing of induced fractures, and where wellbore strengthening is required, there is really no difference between synthetic graphite and high resiliency carbon particles effectiveness in slot testing when combined with $CaCO_3$.
- Particle resiliency combined with spericity and convexity may be as or more important than resiliency values: This hypothesis will require further exploration.

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Nomenclature

CaCO3 = Calcium Carbonate
ECD = Effective Circulation Density
FCS = Fracture Closure Stress
IPT= Ideal Packing Theory
LCM = Lost Circulation Material
LRG = Low Resilience Graphite
PPA = Permeability Plugging Apparatus
ppb = Pounds per Barrel
PSD= Particle Size Distribution
RGC = Resilient Graphitic Carbon
SEM = Scanning Electron Microscope

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