# CHRONIC HOLE ENLARGEMENT IN UNCONSOLIDATED SANDSTONES CAN BE PREVENTED

A Thesis

by

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# ABSTRACT

Low-cost engineering design and operational practices are presented that prevent significant enlargement in shallow, unconsolidated sands while drilling. The methodology includes a combination of fluid design, geomechanical design, drilling practices, and a progressive road map that can be followed to achieve gauge hole. The performance incentive is large, including gains in rates of penetration, reduction in cement volumes, elimination of control drilling due to poor cuttings transport, reduced cuttings disposal costs, and reduction in circulating and tripping times.

Operators who do utilize low fluid loss muds use API fluid loss (FL) or HTHP tests to determine the filtration rate. These tests measure the filter cake's effectiveness against very low permeability filter paper. Fluids with very low values in standard API FL tests may have uncontrolled loss rates in multi-Darcy sands. The common filtration testing methods are also misleading because the initial downhole cake will be composed almost entirely of the sand being drilled and will be highly permeable regardless of the fluid design used.

The changes needed in practice are to use a slightly modified API FL testing apparatus to design fluids that enable cake formation on multi-Darcy formations, to use stability mud weight which is usually relatively low in shallow formations, and to use stabilizers to shear and condition the initial high permeability filter cake.

The research presented provides quantitative insight into these processes. The lab research on the effects of reaming on cake morphology is particularly unique, with implications for elimination of other operational issues, such as stuck pipe. The hidden cost of enlarged shallow sands is greater than generally recognized, while the investment required to drill a near-gauge hole is quite small. The product of this study is an overview of the steps one can follow to develop a fluid design and a field implementation workflow that will reliably reduce wellbore enlargement.

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# NOMENCLATURE

| | |
|---|---|
| API FL | American Petroleum Institute Fluid Loss Test |
| bbl | Barrel, 42 gallon equivalent |
| $cm^3$ | Cubic centimeters |
| cp | Centipoise |
| $D_{50}$ | Median particle diameter |
| fps | Feet per second |
| lbs | Pounds |
| mL | Milliliter |
| mm | Millimeter |
| MW | Mud weight |
| ppg | Pounds per gallon |
| PSI | Pounds per square Inch |
| µm | Microns, micrometer |

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# 1. INTRODUCTION

## 1.1 Wellbore Enlargement

Wellbore enlargement, commonly referred to as “washout” is a significant, yet largely misunderstood problem for the oil and gas industry. Hydraulic washout does occur, but only if the nozzle velocity creates hydraulic shear strength greater than rock strength. This requires unusually high velocity (>400 fps or approximately 100 times less than a typical surface interval fluid velocity) and low rock strength (<1500 psi). This does not account for the enlargement the industry is referring to with the term washout. In shallow unconsolidated sandstone intervals, the nozzle velocity is usually an order of magnitude lower than 400 fps. Hydraulic enlargement is limited to less than an inch (Chemerinski et al., 1995) due to the drop in fluid velocity as the flow expands into greater annulus area. The common fix to “washout” as described above is to reduce flow rates. In unconsolidated sands, a decrease in flow rate does not lead to a better gauge hole. Decreasing flow rate reduces the nozzle velocity, hydraulic impact, and in turn, the hydraulic horsepower at the nozzles (Chemerinski et al., 1995). Decreasing either of these in the name of reducing hole enlargement will likely only lead to more problems.

Now that the phrase “washout” is understood as mythical, the true problem should be identified. In shallow, unconsolidated sandstones, the formation is under confining overburden stress and acts similar to formations at any depth. The wellbore has a force known as “hoop stress” acting on it. Hoop stress is a circumferential stress acting in the tangential direction of the wellbore (Kirsch, 1898), as shown in **Fig. 1** (Dupriest, 2016).

The circumference can be shrunk or expanded as the internal pressure changes (Duffadar et al., 2013). If the hoop stress acting on the rock is greater than that formation's strength, breakout and enlargement will occur. While the strength of the rock cannot be changed, the hoop stress acting on it can.

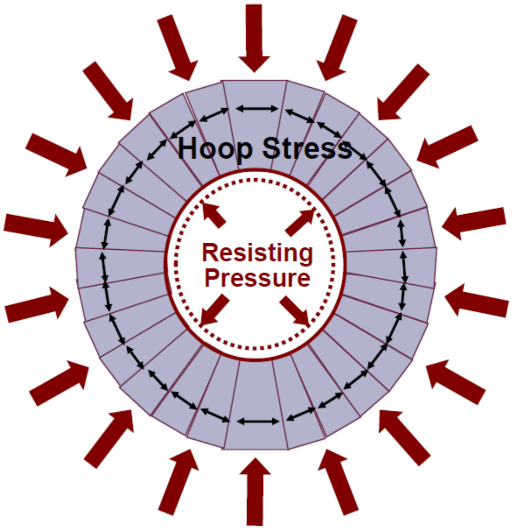


**Fig. 1 - Representation of hoop stress with internal resisting pressure caused by hydraulic forces.**

Pressurization of the pore spaces in the formation near the wellbore are of great concern when considering hoop stress. This pressurization will reduce the effective stress and formation shear strength. Sands at shallow depths do not have much strength to begin with due to low overburden. Pressurization rates differ with permeability and any other factors preventing fluid from leaking off such as deep formation damage. Pressurization does not occur if the filtrate loss rate is reduced below the rate at which it can escape to the far field (Zeilinger et al., 2010). If this is achieved, the native state of the interval is unaltered and the expected stability mud weight will suffice.

Many problems in the wellbore are caused by wellbore enlargement. As the wellbore gets larger, the velocity of fluid flow is reduced and hole cleaning is affected negatively. The fluid velocity can fall below the slip velocity of the solids causing excess buildup of cuttings, increasing bottom hole pressure which can lead to lost circulation and/or lower drilling rates. Stuck pipe can also be an issue due to increased buildup of cuttings. Cement will often not fill large washout intervals because the volume needed is unknown. The resulting low quality cement jobs can cause leaks behind the casing. In intervals with extreme cases of hole enlargement, the quality of open hole logs are greatly reduced and become difficult to interpret. With enlargement, more cuttings are brought to the surface and this leads to greater disposal costs of cuttings and drill fluids (Chemerinski et al., 1995). In producing zones, filtrate invasion can reduce permeability by blocking or plugging pore spaces, reducing the potential flow of hydrocarbons. However, in unconsolidated sandstones, the effect of filtrate invasion results in wellbore enlargement.

Reducing or eliminating wellbore enlargement can significantly lower well costs in many places. Reduced cement volume requirements alone can typically pay for the additional bridging materials proposed. Rates of penetration can be increased due to increased hole cleaning capacities, thus reducing rig time and length of time to reach TD. Trouble time and non-productive time can be reduced dramatically as wellbore enlargement can lead to bridging and/or stuck pipe. Increases in efficiency by drilling a gauge wellbore will also reduce hidden non-productive time. Drilling a near-gauge hole will allow for less risk downhole, less trouble time, a higher quality wellbore and cement job, faster completion to TD, and reduced costs.

The solution to reducing wellbore enlargement is to reduce the hoop stress. This can be achieved by increasing mud weight. However, a low permeability filter cake is needed especially in shallow unconsolidated sandstones to stop filtrate and solids from penetrating the formation. Stabilizers can play a role in conditioning the filter cakes to reduce permeability and cake thickness. A testing method has been developed and will be discussed in this paper.

### 1.2 Filter Cakes

The method proposed to reduce the hoop stress to acceptable levels and allow enlargement to be reduced dramatically or eliminated altogether is to build a low permeability filter cake on the wellbore. A filter cake is a low permeability film that accumulates on the wellbore. An efficient filter cake will reduce filtrate invasion and utilize the hydraulic forces to reduce hoop stress below the rock's strength, allowing a uniform gauge wellbore. An illustration of this can be seen in **Fig. 2**. A critical factor to building a good filter cake is to obtain surface bridging on the formation face while maintaining minimum solids penetration into the producing zone. Proper selection of bridging particles that are based on the formation's pore sizes can make this possible (Mahajan and Barron, 1980). Larger particles form the skeleton of the cake and smaller particles deposit within the porous filter cake (Elkatatny et al., 2011). Thicker filter cakes can lead to excessive torque, drag, swab and surge pressures, and sticking of tubular. The filter cake has no structural strength but is rather supported by the formation wall as long as overbalanced conditions are maintained. When the well is swabbed or returned to production, there is a mechanical breakdown of the filter cake and the carbonate particles are flushed from the pores. This can only occur when the filter cake is thin and solids penetration is minimized (Mahajan and Barron, 1980).

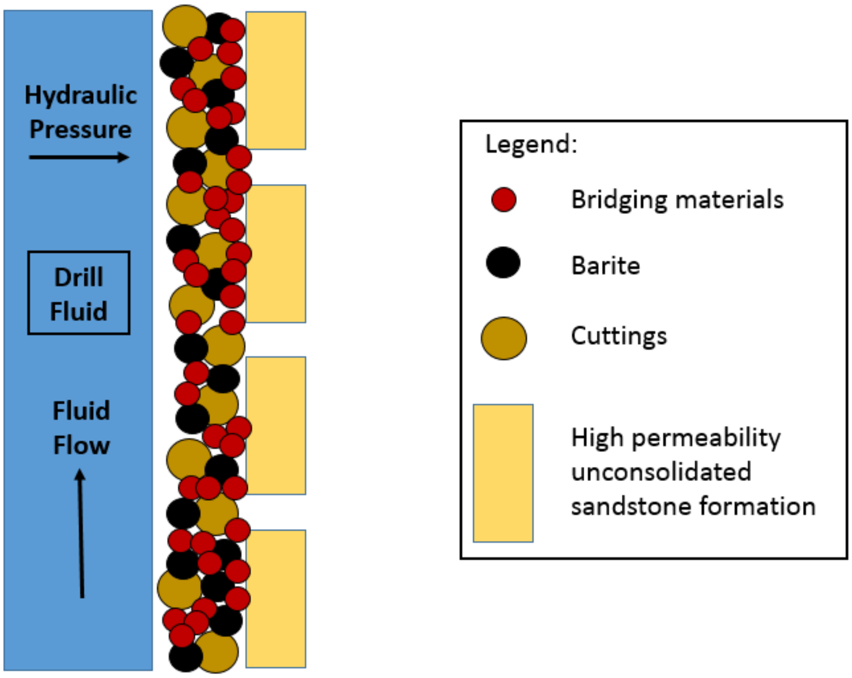


**Fig. 2 - Example of a filter cake constructed on a wellbore.**

An unrecognized problem in the oil and gas industry which leads to poor filter cake design is the use of the standard API Fluid Loss procedures for testing filtrate volumes and the creation of a filter cake for a given drill fluid (American Petroleum Institute, 2009). The procedures recommend using a filter paper as the filtrate medium. Filter paper does not resemble unconsolidated sandstones at all. Filter papers on average have a permeability of 3 mD (Fann Instrument Company, 2007), and the formations in which enlargement is of primary concern have a permeability on the order of 2-5 Darcys. Filter paper is also thin, while the ceramic discs are 0.25 inches thick. This will provide a more realistic representation of the formation. To get a more accurate response to how the drill fluids will invade the formation, the use of a ceramic disc will provide much more realistic results. Ceramic discs can be manufactured in a variety of pore throat sizes and correlations can help us to select a disc that more closely matches unconsolidated sandstones. Using the ceramic discs instead of filter paper in the API Fluid Loss test is part of the method employed in this work to test how effective the newly formulated drill fluids are.

## 1.3 Bridging Materials

Selection of the bridging materials is a crucial aspect to constructing a near gauge hole. Variations in geologic properties will require different grain size distributions of bridging materials to effectively bridge the pores. A variety of methods to select bridging agents have been proposed and they each have advantages and disadvantages. Some of the primary methods of bridging material selection are Abrams' method (Abrams, 1977), the Ideal Packing Theory (Dick et al., 2000), and Vickers' Method (Vickers et al., 2006). When using these methods, calcium carbonate bridging particles are most commonly used for bridging material because they are acid soluble and can easily be removed when the well is ready to be returned to production. They are also low-cost and available in a wide variety of particle sizes. (Mahajan and Barron, 1980).

The Abrams method is a widely known and utilized method for selection of bridging materials. It simply states that the median particle size of bridging material should be at least 1/3 of the median pore size (Abrams, 1977). Vickers' method takes into account many points on the particle size distribution plot and creates a tighter fit (Vickers et al., 2006). However, since this is a more complex process, software is usually required. The experiments presented in this paper utilized the Ideal Packing Theory because it is more accurate than the Abrams method, yet not as complex as the Vickers method and can be conducted in the field quickly and easily.

The Ideal Packing Theory is a graphical approach that states that ideal packing occurs when a straight line can be formed when plotting the cumulative percentage finer of the particle size distribution versus the square root of the particle diameter. It is based on an estimation of the median pore size by taking the square root of the permeability and setting this value to the $D_{50}$ (50% finer point) value of the ideal mixture. An example of this can be seen in **Fig. 3**.

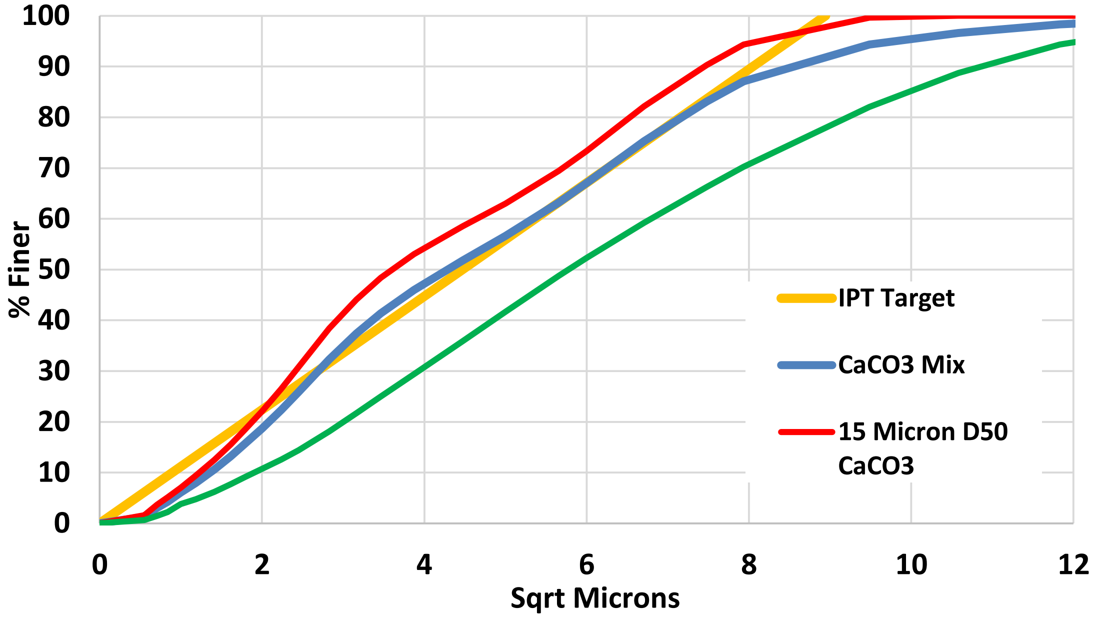


**Fig. 3 - Optimization of particles by use of Ideal Packing Theory. Target line is defined by the theory and the $CaCO_3$ particle size distributions are provided by suppliers. The $CaCO_3$ mix consists of 70% 15 micron $CaCO_3$ and 30% 50 micron $CaCO_3$.**

No single bridging agent perfectly matches the optimum target line. Blending two or more agents however can form a more ideal formulation. The optimum blend should remain slightly below the optimum target line (Dick et al., 2000). This method is also used often because it takes into account grain size distributions of the bridging particles and correlates them to a formation. A number of different bridging materials can be mixed together to formulate an optimum drill fluid. Laboratory studies have shown that blending more than three varieties of calcium carbonate solids shows no further improvements. Also, when the particle size of coarse particles is four to five times larger than that of very fine particles, a higher packing efficiency can be achieved (Jienian et al., 2006). One of the disadvantages of the Ideal Packing Theory is that the pore throat size distributions in a reservoir are not linear so there are some inaccuracies with this method (Dick et al., 2000).

# 2. METHODOLOGY

## 2.1 Drill Fluid

The first requirement was to develop a drilling mud to use. The drill fluid used was comparable to one that would be used in drilling surface holes of unconsolidated sandstones. Experimentation was conducted with many different concentrations and types of additives that gave similar values of pH, mud weight, and viscous properties to those which are used in the field. Properties of the ideal base fluid used are shown in **Table 1**.

| | |
|---|---|
| Lime (lbs/bbl) | 0.14 |
| Bentonite (lbs/bbl) | 11.5 |
| Calcium Carbonate ($D_{50}$ - 15 µm) (lbs/bbl) | 7.0 |
| Calcium Carbonate ($D_{50}$ - 50 µm) (lbs/bbl) | 3.0 |
| Barite (lbs/bbl) | 24.5 |
| 3 rpm Viscometer Reading (cp) | 3 |
| 6 rpm Viscometer Reading (cp) | 4 |
| 100 rpm Viscometer Reading (cp) | 6 |
| 200 rpm Viscometer Reading (cp) | 8 |
| 300 rpm Viscometer Reading (cp) | 10 |
| 600 rpm Viscometer Reading (cp) | 14 |
| MW (ppg) | 9 |
| pH | 9 |
| Marsh Funnel Test (seconds) | 34 |

**Table 1 - Mud mix and properties for ideal base fluid.**

It must be noted the fluid used was not intended to be the ideal drilling fluid. It was developed with input from several services companies and operators and is intended to be representative of the current typical surface interval drilling fluid. The authors recognize that many surface holes are drilled with less than ideal drilling fluid which further increases the importance of this work. The grain size distribution of the drill solids used in this series of tests is shown in **Fig. 4.**

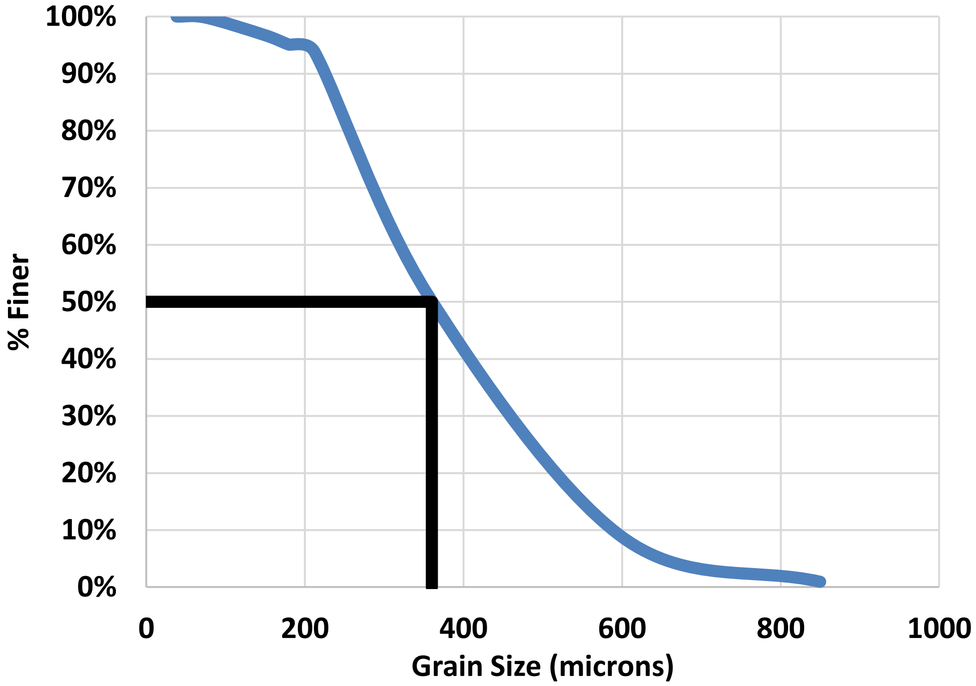


**Fig. 4 - Drill solids sieve analysis shows $D_{50}$ of 360 microns.**

### 2.2 Filter Cell and Ceramic Disc

The next step was preparing the filter cell for the test. The API FL tests include a filter cell, which is a steel cylinder that holds the filtrate medium – in this case a ceramic disc – and drill fluids. Since API FL tests typically utilize filter paper, a filter cell had to be modified and machined to be able to accommodate the ceramic disc.

The ceramic discs utilized in this project have a mean pore size of 20 µm and a permeability of 3 Darcys. These discs are most similar to some of the shallow, unconsolidated sandstones of concern.

### 2.3 Replicating Stabilizer Effect

As previously mentioned, the presence of stabilizers is an important factor in the filter cake formation. The API FL test does not account for stabilizers so a method to simulate stabilizers was created. The stabilizer effect was simulated by conducting a normal fluid loss test for 15 minutes, then opening the cell, emptying the drill fluids remaining in the filter cell, and manually scraping the filter cake with a piece of high strength monofilament. Because the cake was scraped at atmospheric pressure, there was no confining strength. When trying to perform the scrape with stabilizer-like objects, the cake would be pushed and not scraped. This pushing resulting in an unrealistic peeling effect. The monofilament sliced the cake and was used to replicate the rebuild and recapture effect seen downhole with confining pressure and stabilizer blades. The cake thickness was measured before and after the scraping so that the total thickness scraped off could be determined. In theory, the stabilizers would remove the larger sand particles off the cake so that the filter cake can capture bridging particles that fit the remaining gaps more closely. After each scrape, the particle sizes on the filter cake decline and the gaps in the filter cake decline, thus the particles that fit into those gaps decline, creating a thin, low permeability filter cake. After thicknesses were measured, the filter cell was put back together, fresh drill fluid was added and the fluid loss test was repeated. Overall, this procedure was repeated so that the disc was run in the fluid loss test four times and the disc was scraped three times.

## 2.4 Experiments

A number of tests are to be run. A test with the most optimal calcium carbonate mix obtainable was conducted first. Utilization of an excel spreadsheet helped optimize the mixing of more than one calcium carbonate type to follow the Ideal Packing Theory. Its formulation and mud properties are shown in **Table 1**. This test was utilized to see what minimum filtrate loss and filter cake thicknesses could be obtained.

A variety of mud types were experimented with to show the effect of each additional fluid additive on the fluid loss. The fluid types used in these tests can be seen in **Table 2**. Each test will be conducted using a new ceramic disc and a single API fluid loss test.

| | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 | Test 6 | Test 7 |
|---|---|---|---|---|---|---|---|
| **Description** | Water Only | Add Bentonite, Lime | Add Barite | Add $CaCO_3$ | Add PHPA/Drill Solids | Run same disc again with new mud | Remove $CaCO_3$ |
| **Water (mL)** | 250 | 250 | 250 | 250 | 250 | 250 | 250 |
| **Lime (gr)** | | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| **Bentonite (gr)** | | 8.2 | 8.2 | 8.2 | 8.2 | 8.2 | 8.2 |
| **Barite (gr)** | | | 17.5 | 17.5 | 17.5 | 17.5 | 17.5 |
| **15μm $CaCO_3$ (gr)** | | | | 5 | 5 | 5 | |
| **50μm $CaCO_3$ (gr)** | | | | 2.2 | 2.2 | 2.2 | |
| **PHPA (gr)** | | | | | 0.14 | 0.14 | 0.14 |
| **Drill Solids (gr)** | | | | | 12.5 | 12.5 | 12.5 |

**Table 2 - Overview of fluid additive analysis testing.**

The steps in the next series of tests are outlined in **Fig. 6.** This test was used to identify the effect of stabilizer conditioning on the total filtrate loss. The first part of these experiments included running a base case with no scraping of the disc. An API FL test was conducted with a given drill fluid. After the test is complete, the used drill fluid was removed, the filter cake thickness was measured, new drill fluid was added, and the API FL test was repeated three times. This testing procedure can also be explained visually by looking at the right half of **Fig. 6**.

The next part of the experiment is describe on the left half of **Fig. 6**. After running the initial API FL test, the filter cell will be emptied, the filter cake thickness will be measured and scraped to a predetermined height. Then, new drill fluid will be added, and the process will be repeated until four total API fluid loss tests have been conducted. **Table 3** and **Table 4** show the fluid formulation and properties, respectively.

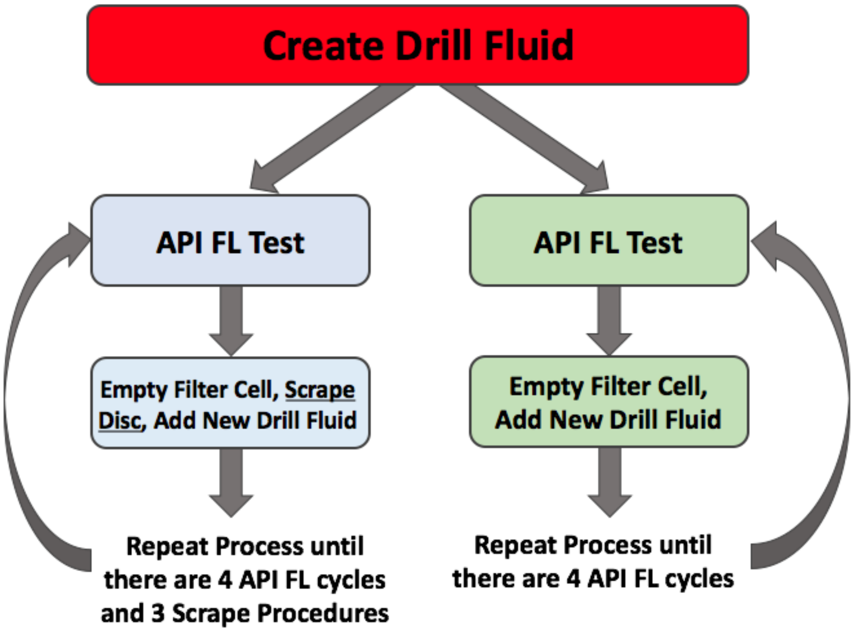


**Fig. 5 - Outline of stabilizer simulation tests.**

| | |
|---|---|
| **Water (mL)** | 250 |
| **Lime (gr)** | 0.1 |
| **Bentonite (gr)** | 8.2 |
| **Barite (gr)** | 17.5 |
| **15µm $CaCO_3$ (gr)** | 0 |
| **50µm $CaCO_3$ (gr)** | 7.2 |
| **PHPA (gr)** | 0.14 |
| **Drill Solids (gr)** | 12.5 |

**Table 3 - Scrape test fluid formulation.**

| **MUD PROPERTIES** | |
|---|---|
| **3 rpm** | 3 |
| **6 rpm** | 4 |
| **100 rpm** | 6 |
| **200 rpm** | 8 |
| **300 rpm** | 10 |
| **600 rpm** | 14 |
| **MW (ppg)** | 9 |
| **pH** | 9 |
| **Funnel (seconds)** | 34 |

**Table 4 - Scrape test fluid properties.**

# 3. RESULTS

## 3.1 Optimum Bridging Material Tests

The first test included the best selection and concentration of bridging solids. This test was utilized a disc that has an average pore throat size of 20 microns and a permeability of 3 Darcy's. This is closest to the unconsolidated sandstones that are of concern. The mud used contained bentonite, lime, PHPA, barite, calcium carbonates (2 types), and drill solids. The fluid properties were shown in **Table 1** and the bridging selection spreadsheet using the Ideal Packing Theory was shown in **Fig. 3.** It was found that the best formulation of bridging solids consisted of 70% of a calcium carbonate mix that contained a median particle diameter of 15 microns. The other 30% was also calcium carbonate but it contained a median particle diameter of 50 microns. As expected, the result was a very low spurt loss and filtrate volume (**Fig. 6)**.

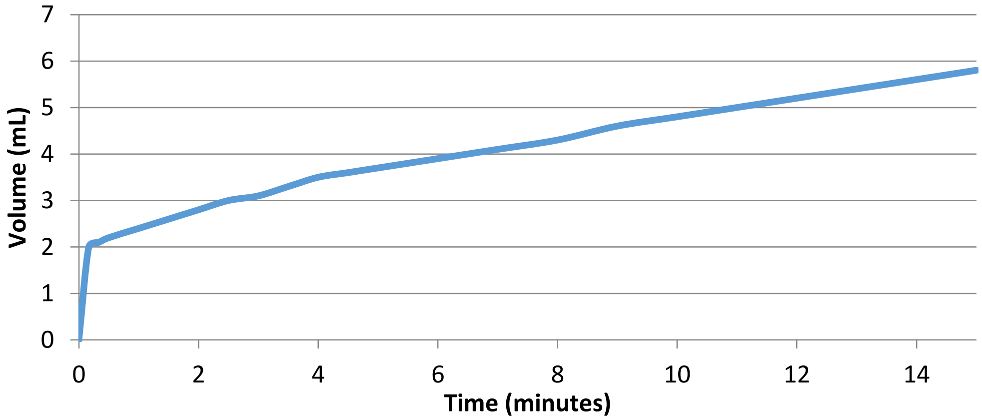


**Fig. 6 - Filtrate volume over time for fluid with optimal bridging particles over time with short spurt time and linear filtrate volume observed.**

A picture of the graduated cylinder after completion of the test is shown in **Fig. 7**. When looking at the graduated cylinder, the spurt loss and filtrate can be easily identified. The spurt loss is a murky, muddy color indicating that a filter cake has not yet been established and the fine solids of the drill fluids are making their way through the disc. The spurt loss, containing barite, is also heavier than the filtrate. The filtrate is almost clear and shows the effects of a quality filter cake. Another test, which was conducted for 3 hours had similar results with the clarity changing noticeably over time. **Fig. 8** shows the three cylinders that were used to hold all of the fluid loss over this extended time frame.

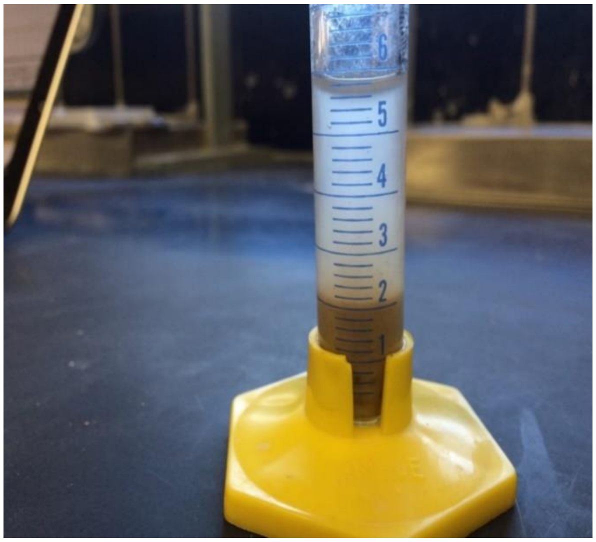


**Fig. 7 - Graduated cylinder after test with optimal bridging selection.**

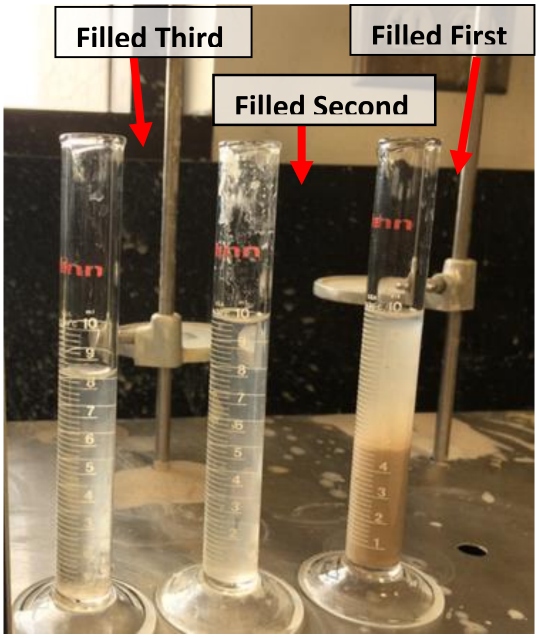


**Fig. 8 - Total fluid losses after extended API fluid loss test (3 hours), shows change in clarity indicating filter cake development.**

The filter cake, as shown in **Fig. 9,** was an optimal thickness of just under 1/16". The spurt loss is defined as the amount of filtrate before the filter cake is built. All of the spurt loss for this drilling fluid was less than 10 seconds, indicating that the filter cake was built very fast.

**Fig. 9 - Ceramic disc after optimal bridging test.**

### 3.2 Fluid Additive Analysis

The next phase of the experimental work was to analyze the effects of each fluid additive to the total filtrate loss in a fresh ceramic disc. As **Table 2** shows, the experiments started using water and additives were included with each progressive test. The results of the filtrate losses versus time for each of these tests are shown in **Fig. 10**.

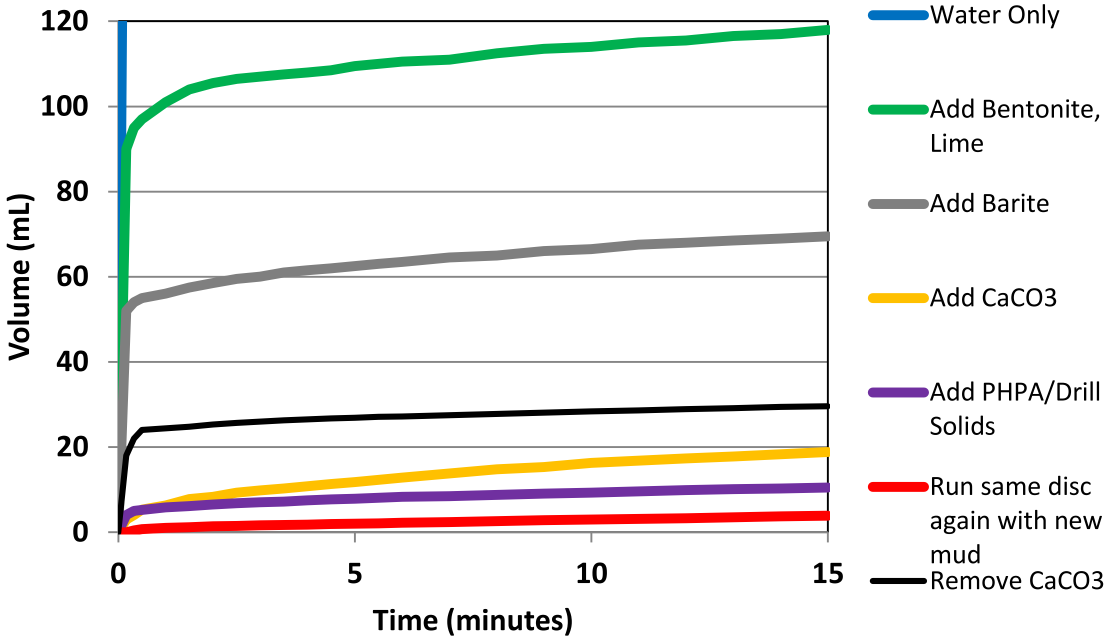


**Fig. 10 – Reduced total filtrate loss occurs with each successive additive. Removing the CaCO$_3$ from the drill fluid does have a negative impact on filtrate loss.**

**Fig. 10** shows the effects that each additive have to improving the overall spurt and filtrate loss. Test 1 contained water only. All 250 mL of the water was expelled through the ceramic disc in about 6 seconds. An interesting observation was made in test 5 with the addition of the PHPA and drill solids. When adding drill solids to the total drill fluid mix, the total filtrate loss improved from 18.8 mL in test 4 to 10.5 mL in Test 5. This is likely due to the PHPA which is a 1 micron polymer chain that viscosifies the fluid phase and acts similarly to a bridging particle. Test 6 is the only test which the same ceramic disc was used in a successive API FL run. The results show the effect of the filtrate losses as if the cake is already established and what the effects of adding additional bridging materials would do. The filtrate loss was reduced dramatically, from 10.5 mL in Test 5 to 3.9 mL in Test 6. Additionally, the spurt loss was reduced from 5.2 mL in Test 5 to 0.7 mL in Test 6, an 87% reduction. The last test in this series, Test 7 contains no calcium carbonates and shows the effects of a drill fluid containing lime, bentonite, barite, PHPA, and drill solids. This test proves the effect of adding bridging materials to a mud formulation that is very typical of those used in the industry today. When comparted to Test 5, where the only difference in fluid formulation is that Test 5 has bridging materials and Test 7 does not, the results differ greatly. The spurt loss goes from 5.2 mL in Test 5 to 24 mL in Test 7, a 360% increase. Total filtrate loss in Test 5 is 10.5 mL, compared to Test 7, which has a total filtrate loss of 29.6 mL, which is a 182% increase.

This series of tests are conclusive that fluid additives are crucial in obtaining an effective filter cake. Bridging material is shown to dramatically reduce overall filtrate losses and when paired with the other additives, a drill fluid that is effective in many regards can be formed. The effectiveness of a filter cake can be translated to wellbore enlargement and stability in a sense. As the filter cake is improved and becomes less permeable, it will act as a surface that higher mud weight drill fluid can be added to, increasing hydrostatic pressure, pushing against the wellbore. This effect results in an overall reduction in hoop stress and a more stable wellbore is achieved.

### 3.3 Stabilizer Effect – Base Case

The effects of stabilizer conditioning on filter cakes were studied next. The fluid components and properties were identical for each test and are shown in **Table 3** and **Table 4**, respectively. The results for this part of the experiment are shown in **Fig. 11**.

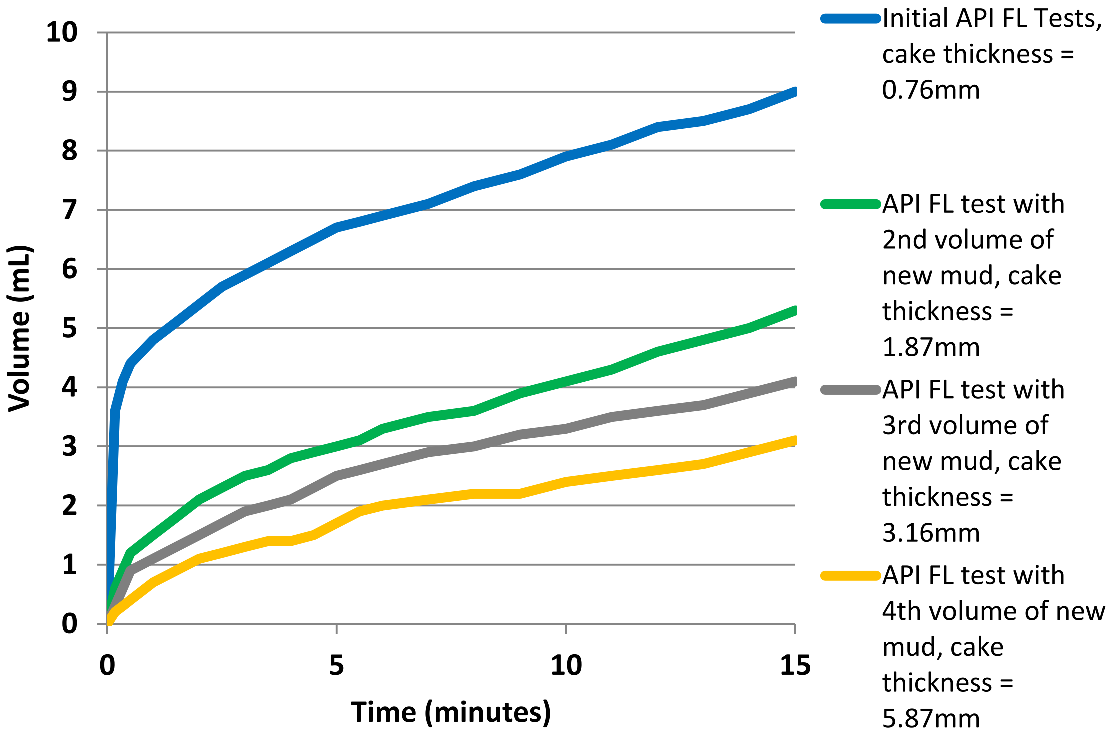


**Fig. 11 - Filtrate loss decreases over circulating time (replicated by changing test mud volume repeatedly) but with no stabilizers, the filter cake thickness increases dramatically.**

**Fig. 11** shows the effects of each successive test while conducting the base case. Both spurt losses and total filtrate losses are reduced with each progressive test. However, the cake thicknesses increase substantially, growing up to 5.87 mm, or almost a quarter of an inch, by the end of the final test. This is about four times the thickness that is considered as ideal by the industry. **Fig. 12** shows what the disc looks like out of the filter cell after the final API FL test.

**Fig. 12 - Base case after test 4, cake thickness 5.87mm.**

### 3.4 Stabilizer Effect – Scraping

The next series of tests illustrate how stabilizers can condition the filter cake. This can reduce the filtrate loss, improving the effectiveness of the filter cake which leads to better stability and a more gauge wellbore. The drill fluid formulation and properties are the same as the base case and are shown in **Table 3** and **Table 4**, respectively. The cake thickness was measured before and after scraping. A picture of this process is shown in **Fig. 14**. The cake thicknesses can be seen in **Table 5**. The filtrate losses were plotted against time and are shown in **Fig. 13**. **Fig. 15** shows a picture of the disc after the final scrape in Test 4.

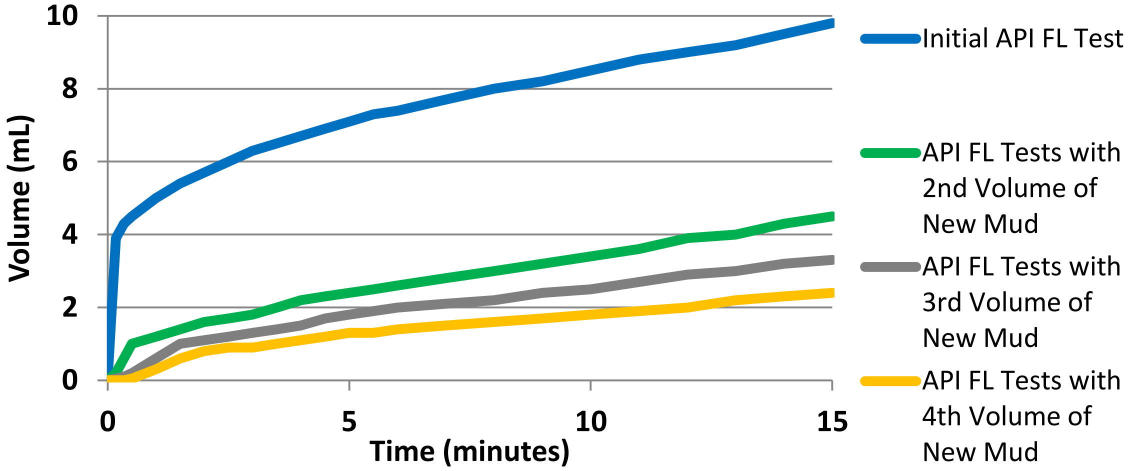


**Fig. 13 - Filtrate loss decreases over circulating time (replicated by changing test mud volume repeatedly) but by including stabilizers, the filter cake thickness remains relatively thin dramatically.**

The spurt loss and total filtrate losses were both reduced with each consecutive scrape process. A notable difference in the scrape test versus the base case is the thickness of the filter cake. After the fourth test in the base case, the filter cake was 5.87 mm. In the scraping experiments, the final cake thickness after the fourth test was 1.04mm, which is less than 1/16th of an inch.

| | **TEST 1** | **TEST 2** | **TEST 3** | **TEST 4** |
|---|---|---|---|---|
| **Initial Cake Thickness (mm)** | 0.7 | 2.16 | 0.98 | 1.04 |
| **Cake Thickness Post-Scrape (mm)** | 0.4 | 0.59 | 0.61 | - |

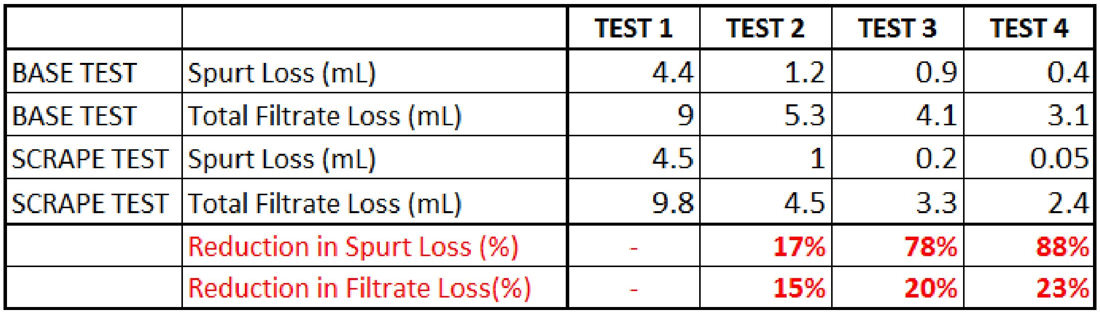
**Table 5 - Cake thickness for scrape tests and thickness scraped**

Fig. 14 - Ceramic disc during scrape process.

Fig. 15 - Disc after test 4 scrape.

### 3.5 Comparison of Base and Scrape Tests

A comparison of the scraping and base tests is shown in **Table 6**. While the overall reductions in total filtrate losses were modest (around 20%), the reduction in spurt loss was much higher and seemed to grow with each successive test. The spurt loss for the fourth scrape test was 88% less than that of the base case. When comparing the cake thicknesses, an 83% reduction in the amount of filter cake removed by scraping was observed when comparing the first and fourth tests.



| | | TEST 1 | TEST 2 | TEST 3 | TEST 4 |
|---|---|---|---|---|---|
| BASE TEST | Spurt Loss (mL) | 4.4 | 1.2 | 0.9 | 0.4 |
| BASE TEST | Total Filtrate Loss (mL) | 9 | 5.3 | 4.1 | 3.1 |
| SCRAPE TEST | Spurt Loss (mL) | 4.5 | 1 | 0.2 | 0.05 |
| SCRAPE TEST | Total Filtrate Loss (mL) | 9.8 | 4.5 | 3.3 | 2.4 |
| | Reduction in Spurt Loss (%) | - | **17%** | **78%** | **88%** |
| | Reduction in Filtrate Loss(%) | - | **15%** | **20%** | **23%** |

**Table 6 - Comparison of cake thicknesses in base and scrape tests.**

**Fig. 16** shows the final filter cakes from the test series which replicated stabilizers and the filter cake from the test series which utilized no scraping. Contrary to what some might think, the disc on the left, which replicates a well drilled with stabilizers is better conditioned and serves as a more effective filter cake than the disc in which no scraping occurred. It will have less spurt loss and total filtrate loss while being much thinner. These characteristics will benefit hydraulic properties and will reduce issues relating to torque and drag.

**Fig. 16 - Comparison of scrape (left) and base (right) tests shows the scraping, which replicates stabilizers, yields a superior filter cake. This results in a better API FL and thus a reduction in wellbore enlargement.**

### 3.6 Long Term Fluid Loss Test

Upon completion of the previous experiments, another point to investigate was introduced. The fluid loss versus time seemed to be linear or nearly linear after the spurt loss occurs. A hypothesis that came up was that after time, the filter cake should become increasingly effective and thus the curve should approach an asymptote. The API FL test was run for 3 hours, rather than the normal 15 minutes we have used for all previous experiments. **Fig. 17** shows the results from this test. It was found that over a time period of over 3 hours, the slope of the fluid loss versus time does not change significantly. This result is important first because it proves that the API specifications for conducting a fluid-loss test for 15 minutes is sufficient.

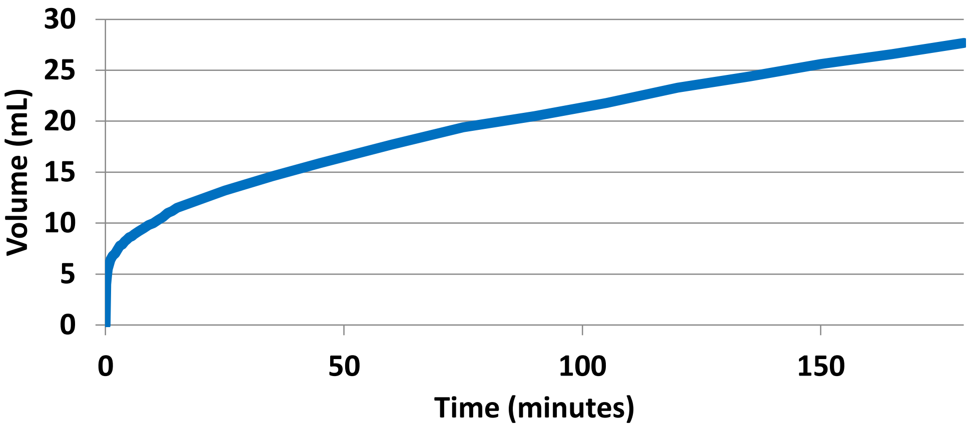


**Fig. 17 – Extended API test shows fluid loss versus a 3 hour time period.**

### 3.7 Micro CT Scans

Micro CT scans, which produce images in terms of cross-sectional "slices", were utilized to identify the makeup of the filter cake and also to determine if any internal filter cakes were built. Micro CT scans output images of a sample and the grayscale is dependent on density. The brighter or whiter a segment is, the more dense it is. The darker or blacker in color a segment is, the less dense it is. Four main components make up the filter cakes that were designed in these experiments: sand, calcium carbonates, bentonite, and barite. Sand and calcium carbonates are very similar in density at around 2.68 grams/cm$^3$. Bentonite is the lightest at around 0.8 grams/cm$^3$ and barite is heaviest in density at 4.5 grams/cm$^3$.

**Fig. 18** displays a side view of the filter cake on top of the disc from the optimal bridging selection test referred to in **Fig. 6**. Labels in **Fig. 18** show best estimates for the particles of barite, bentonite, sand, and the calcium carbonates. Micro CT scans will not produce any scale to tell what the density of each shade is and is just a relative shading system. With the densities of the components of the filter cake known, the shades of the filter cake can then be identified as the individual parts of the filter cake. The images show that the disc and filter cake have very little interaction internally as seen by the very distinct border shown between the disc and the filter cake. The scans showed a slight amount heterogeneity deeper into the discs in the terms of specks or light inclusions. However, given the size of the inclusions relative to the pore size of the disc, it was determined they were inherent to the disc and existed prior to testing.

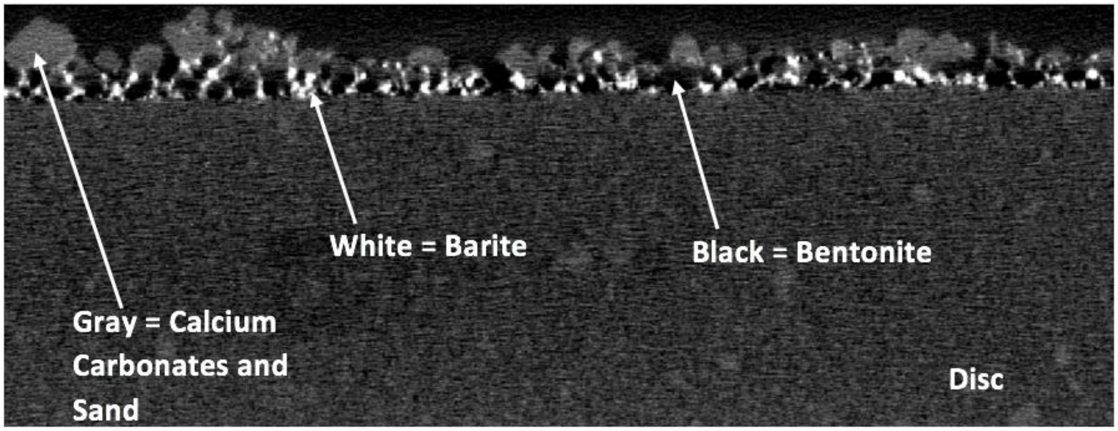


**Fig. 18 - 2D expanded side view shows barite, bentonite, calcium carbonate, and sand particles.**

### 3.8 Workflow to Reduce Wellbore Enlargement

The workflow can be used in the field fairly easily. First, some of the formation properties must be known. Pore throat size is best, though Pittman's correlation can be used with permeability and porosity to obtain an estimated pore throat size (Pittman, 1992). These values can be used to find a ceramic disc that contains similar properties. The permeability will be used with the Ideal Packing Theory to create the target line as shown in **Fig. 3**. Second, particle size distributions will need to be obtained from the calcium carbonate supplier. It is helpful to have more than one type of calcium carbonate so that they can be combined to create a more optimal mix. Enter the particle size distribution info for each calcium carbonate formulation into an excel sheet and then set it up as a formula that will allow one to combine formulations and output an average particle size distribution plot. Third, graph this with the target line and adjust formula amounts in order to make the actual mix distribution line up closely to the target line. Finally, API FL tests can be used with a modified filter cell and ceramic disc to double check the formulation.

# 4. CONCLUSIONS

The objective of this project was to identify for the operator the effects of bridging materials and stabilizers on the quality and effectiveness of filter cakes in order to reduce wellbore enlargement. Several points were made. Wellbore enlargement in unconsolidated sandstones is due to hoop stress, not axial hydraulic forces. Benefits of reducing enlargement include gains in rates of penetration, reduction in cement volumes, elimination of bridges, reduced cuttings disposal costs and reduction in circulating and tripping times. Higher quality cement jobs can be completed allowing for a higher certainty of reliability and safety. Fluid additives play a crucial role in crafting a high quality filter cake. Calcium carbonates are an effective bridging material and can be optimized if their grain size distribution and basic formation properties are known. As simple excel sheet was created to optimize mixing more than one type of calcium carbonates. Ideal Packing Theory is a simple, yet effective method for sizing calcium carbonates given basic formation properties. API FL testing procedures are inappropriate for testing the effectiveness of a fluid in high permeability formations. Ceramic discs along with modified filter cells play a critical role in obtaining accurate drill fluids. Ceramic discs come in a variety of permeability to allow one to closely match downhole conditions. Micro CT scans show that the filter cakes were built entirely on the surface and no internal cakes were formed. Stabilizers play a huge advantage in conditioning and optimizing the effectiveness of the filter cake. Experiments compared a base case in which no scraping was simulated and a case in which stabilizer scraping was simulated. The filter cakes that were scraped possessed lower fluid losses and permeability, and were also significantly thinner.

As reiterated in **Fig. 19**, the process for reducing or eliminating wellbore enlargement can be accomplished.

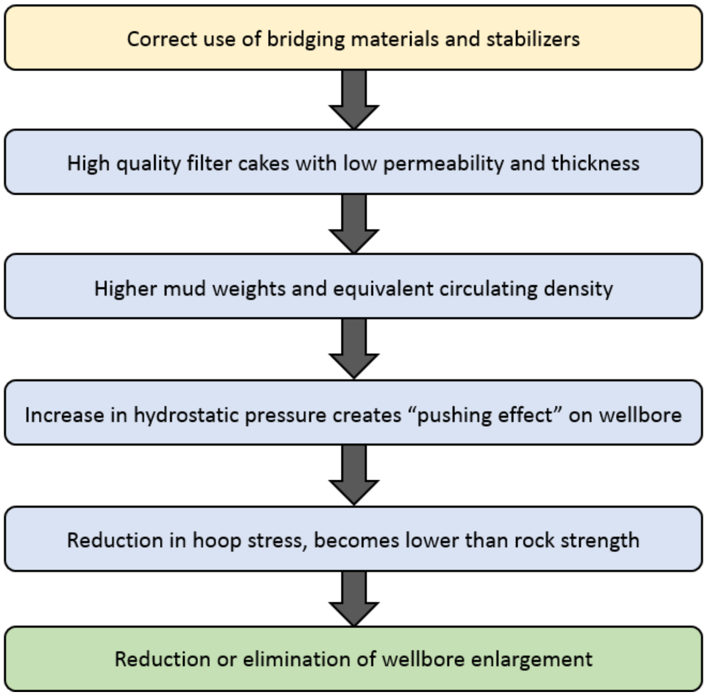


**Fig. 19 - Workflow to eliminate wellbore enlargement using bridging solids.**

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