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Improvements to Bridging Solids Particle Size Selection Models for Post-Gravel Pack Screens

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Abstract

Controlling fluid losses to the formation, both before and after completions, is critical to optimizing production. Fluid-loss control can be achieved through the use of either mechanical or chemical means. Chemical methods, the discussion of this paper, control losses to the formation by increasing the base fluid viscosity with linear or crosslinked polymers or by forming a low-permeability filter cake on the formation face. Performance limitations however, have prevented the use of such traditional ‘pills' in high-pressure environments compromising operations through having to accept excessive losses or employing less-than-ideal methods. Loss of completion fluids to permeable formations results in increased water saturation, scaling, emulsion generation, or fines migration, all of which can severely impair production. Additionally, excessive losses can compromise well control, complicate fluid management, and increase project costs.

This paper describes the development of a simple and effective Particle-Size Distribution (PSD) model for optimizing the design of solids-laden fluid loss control systems for gravel-pack or frac-pack applications. The model is a combined adaptation of several existing common theories for particle sizing (namely: Abram’s 1/3 rule and Hands’ D_{90}-rule) and Particle-Size Distribution (namely, Ideal Packing Theory; also known as the $D^{½}$ rule). The model was used to define a theoretical optimum Particle-Size Distribution for bridging and sealing against a fixed sized opening equating to gravel-pack screen gauge size (e.g. 6, 8, 10 and 12-gauge screen). Using commercially available sized Calcium Carbonate ($CaCO_3$) products, blends were formulated whose Particle-Size Distribution closely approximated the calculated optimum. The blends were then individually incorporated in to a viscosified Calcium-Bromide ($CaBr_2$) brine and tested for their fluid loss control performance over a 72-hour period using a High-Pressure/High-Temperature (HP/HT) filtration apparatus at 500-psi pressure and 215°F temperature with corresponding 6, 8, 10 and 12-gauge screen. Additional tests at 800-psi pressure and 245°F temperature conditions over a 96-hour period were used to confirm pill performance envelopes.

The laboratory results demonstrate the validity of the new Particle-Size Distribution model and the resulting optimized screen bridging blends. Relatively thin (<2mm), ultra-low permeability filtercakes were formed against the gravel-pack screens; typically spurt loss < 6 mL, average 30-minute filtrate volume < 8 mL, and maximum 72-hour filtrate volume < 26 mL. The resulting filtercakes were also observed to have low lift-off pressures.

Introduction

Workover operations in wells with sand control completions typically require the application of a solids-laden fluid loss control system to temporarily seal against the internal surface of the sand screen and provide a hydraulic barrier for pressure control. TETRA Technologies, Inc.’s Innovation Group identified an opportunity for greater design and operational excellence for its range of thermally stable fluid loss control systems by applying an idealized Particle-Size Distribution model for optimizing blends consistent with screen-gauge size using commercially available grades of Calcium Carbonate. In its formulation, the model is equally applicable for commercial grades of sized-salt and bridging and sealing porous surfaces such as reservoir formation and frac-pack completions.

Abrams (1977) eloquently formulates the problem statement and postulates a methodology for drilling fluid design and specifically the selection and sizing of Calcium Carbonate particles for maximizing sealing capacity against porous formation surfaces and the minimization of fluid invasion (fluid loss). Abrams methodology (Abrams Rule) has been adopted and adapted over the years for designing non-damaging reservoir drill-in fluids and work-over fluids for gravel-pack or a frack-pack completions.

Abrams rule describes particle size to initiate bridging and the formation of an impermeable filter cake to minimize fluid invasion. The rule states that “the mean particle size of the bridging material should be equal to or slightly greater than 1/3 the medium pore size of the formation” (Abrams, 1977). For example, for an average pore size of 20-µm the mean particle size of the bridging blend should be 7-µm (or slightly larger). Abrams also indicated the importance of particle concentration in the rapid formation the filtercake stating that the bridging solids should be at least 5% by volume of the system. Although widely used and adopted as a guideline, Abrams’s rule does not describe the optimal distribution of particles or “address the best packing sequence of a particle size for minimizing fluid invasion and optimizing sealing” (Lai, 2015). To clarify, a wide range of different particle blends can share the same mean particle size (D_{50}) but have very different distributions and uniformity coefficients, and moreover, varying degrees of effectiveness for creating an impermeable filtercake.

The Ideal Packing Theory – as the name implies – describes a theoretical particle size that will result in a close-form packing arrangement sealing all voids including those which form between the particles. The theory, originally presented by Furnas & Fuller-Bollomey for the formulation of paint and replicated by Kaeuffer (1973) describes a semi-logarithmic relationship between particle size and cumulative volume; namely, the cumulative volume is proportional to the square root of the particle size (D); i.e. $D^{\frac{1}{2}}$ (also known as the $D^{\frac{1}{2}}$ rule). The model assumes perfectly spherical particles. The theory reflects observations of particle accumulations in nature that tend to exhibit near semi-logarithmic distributions; for example, Figure 1 compares the ideal particle distribution of the $D^{\frac{1}{2}}$ rule assuming a maximum particle size (D) of 250-μm and a commercial calcium carbonate product.

Figure 1: PSD of a commercial bridging product.

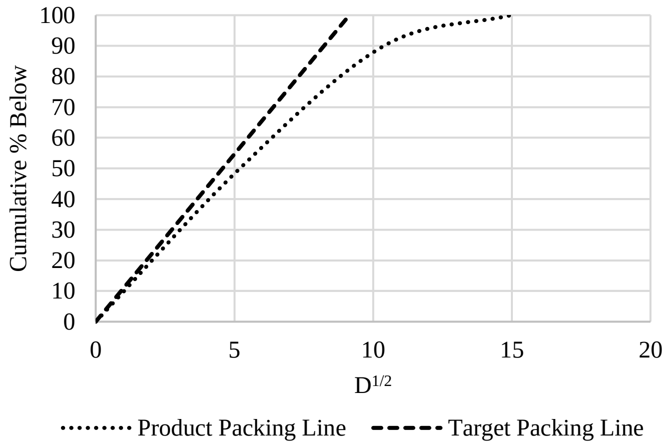

Figure 1: Ideal packing.

The simplicity of the $D^{\frac{1}{2}}$ rule makes it an attractive basis for creating optimum blends of materials (e.g. Calcium Carbonate) that can closely approximate the ideal Particle-Size Distribution. Dick *et al.* (2000) adopted the technique using a graphical approach for formulating optimal blends of bridging materials to plug a defined aperture size. For example, Figure 2 shows multiple particle size distribution curves for different commercially available bridging materials; note their semi-logarithmic characteristics. For our purposes, Figure 3 shows the ideal particle size distributions for sealing against different gauged screens assuming the maximum particle size (D_{100}) is equal to the gauge aperture. Comparing Figure 2 and Figure 3 shows that there is no one commercially available bridging materials with a Particle-Size Distribution corresponding to one of the ideal target distributions; hence the need to formulate blends of materials to begin to approximate the ideal distribution and thus, in theory, form a near perfect filtercake seal against the screen. Note, in their approach Dick *et al* (2000) assumed a target formation pore size to bridge against rather than a screen aperture. They indicate that to seal the targeted formation, the line of the blend’s particle size distribution should be close to and preferably below, or to the right of, the slope of the ideal target distribution.

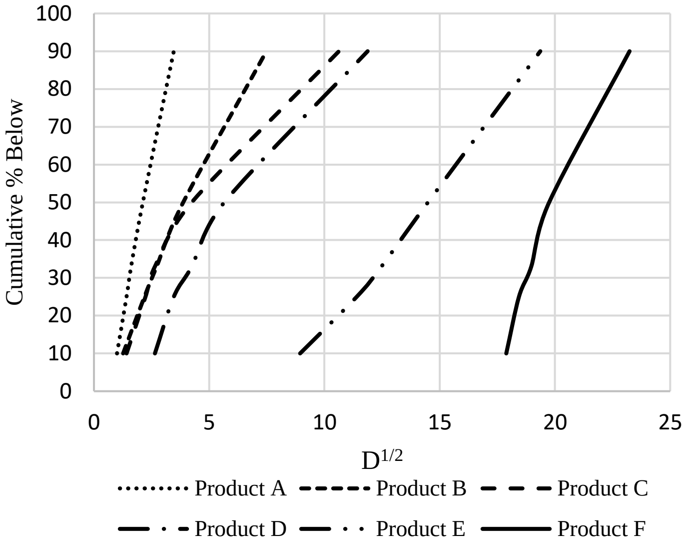

Figure 2: PSD curves of different Calcium Carbonate bridging materials.

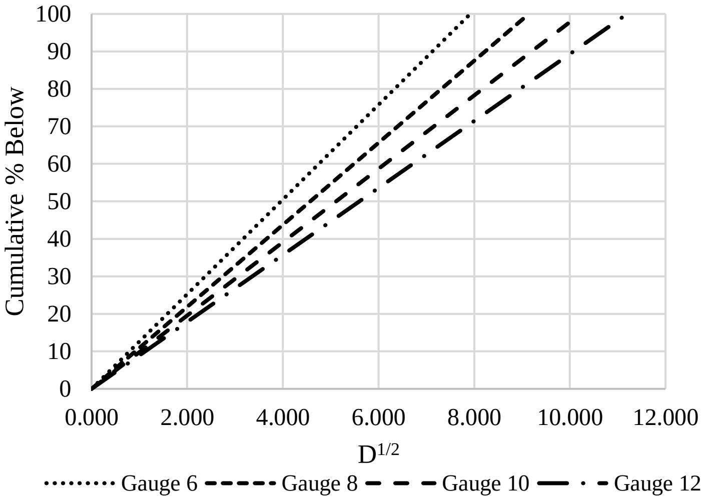

Figure 3: Gauge target lines.

Hands *et al* (1998) and Zhang & Yan (2004) both suggest an additional level of conservatism in designing optimum blends of bridging materials. Rather than formulate a blend based on the largest particle size being equal to the maximum pore size or aperture to be sealed, Hands *et al.* (1998) and later Zhang & Yan (2004) proposed that the D_{90} of the Particle-Size Distribution blend should be equated to the largest pore size of the formation. Further, Zhang & Yan (2004) then extrapolated the particle size distribution from the D_{90} point using the $D^{½}$ rule to determine the optimal Particle-Size Distribution. Using the D_{90} rather than the D_{100} allows for some uncertainty and variation in dominant pore size distribution and shape.

Objective

The objective of this study is to apply a modified Abram's 1/3 rule coupled with the Ideal Packing Theory (also known as the $D^{½}$ rule), to model and design a screen-specific sized Calcium Carbonate (solids-laden) systems for fluid loss control with the following characteristics:

- Capable of forming low-permeability filter cake for minimal invasion;
- Stable under bottomhole conditions (including high-temperature and high-pressure);
- Easily pumpable and removable (lift-off pressure < 5 psi).

Methodology

Fluid Loss System Design

The fluid loss control system was designed with a Calcium-Bromide ($CaBr_2$) brine as the base fluid, xanthan gum for viscosity, a modified starch for fluid loss control, selectively sized Calcium Carbonate with different PSDs were formulated to seal screens of different slot sizes, and other additives to control pH and thermal stability.

Proper Sizing of bridging materials

Different blends of Calcium Carbonate were formulated to optimize a PSD profile capable of forming a seal of an impermeable filter cake on the screen to minimize fluid loss. Ideal sealing of the screens could be achieved when the PSD line of the Calcium Carbonate blend matched that of the screen target line. The theories were adapted to slotted screens as follows:

1. Abram's Theory

- Median particle size (D_{50}) ≥ 1/3 of median pore size of formation;
- The concentration of bridging particles must be at least 5% by volume of solids in the system;
- For laboratory purposes 50 lb/bbl was chosen as the target concentration of Calcium Carbonate
  Assuming SG of $CaCO_3$ = 2.7
  (350.5 mL) × (5%) = (17.53 mL) × (2.7 g/mL) = 47 g or lb/bbl minimum

2. Hands' Theory

D_{90} of the bridging material's PSD = average pore size of the formation pore size or dominant screen slot size.

3. Ideal Packing Theory ($D^{½}$)

Linear plots of cumulative volume % versus $D^{½}$ of each bridging agent (Figure 1 and Figure 2) and formulated blends (Figure 4) were obtained.

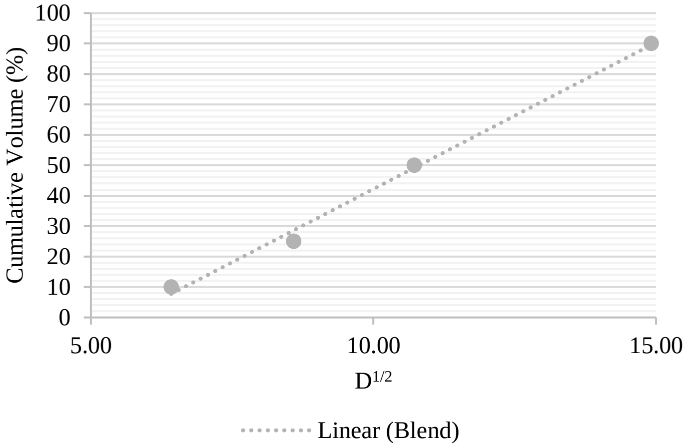

Figure 4: PSD curve example of a formulated blend.

4. Current Laboratory Studies

- Optimal target lines (OTL), where ideal sealing occurs were determined from the largest represented (or dominant) slot opening by setting the D_{90} (rather than D_{50} from Abram's rule) point as ≥ 1/3 of the dominant slot size of the screen and connecting the origin of Cartesian coordinates to the D_{90} point.
- The four slot sizes, or "permeabilities", of screens evaluated in this lab study include gauge 6 (0.006-inch), gauge 8 (0.008-inch), gauge 10 (0.010-inch) and gauge 12 (0.012-inch). Permeability values were estimated from the dimension of the screen slot openings in Table 1.
  1 inch = 25400-µm

Table 1. Target line calculations

Screen Gauge	Dominant screen slot opening (inch)	Equivalent "Permeability" (µm)	D_{90} Point on OTL
6	0.006	152.4	50.8
8	0.008	203.2	67.7
10	0.010	254.0	84.7
12	0.012	304.8	101.6

- The corresponding D_{90} on the OTL was calculated as 1/3 of the "pore size" (Table 2).

Table 2. Particle-Size Distribution of commercially available Calcium Carbonates

Calcium Carbonate	D_{10}	D_{25}	D_{33}	D_{50}	D_{90}
Product A	1.0	2.0	2.6	4.50	12.0
Product B	1.6	4.8	7.4	15.0	56.0
Product C	2.0	5.0	7.0	18.0	113.0
Product D	7.0	12.0	18.4	32.0	141.0

Product E	80.0	130.0	155.6	210.0	375.0
Product F	320.0	340.0	360.0	390.0	540.0

High-Pressure/High-Temperature Fluid Loss Testing

High-Pressure/High-Temperature (HP/HT) Static Filtration Test is similar to a Permeability Plugging Test (PPT), except that the filtration medium is a slotted disc in place of the ceramic disks used in PPT.

The static filtration test evaluated the effectiveness of the sized Calcium Carbonates blends in preventing fluid invasion through the surface of the screen into the formation after gravel-pack or frac-pack operations while maintaining a fluid column to provide sufficient hydrostatic overbalance. A differential pressure of 500-psi and temperature of 215°F was maintained as filtrate was collected at 30 seconds (spurt), 30 minutes, 1 hour, 24 hours, and 3 days. Additional tests at 800-psi pressure and 245°F temperature conditions over a 96-hour period were used to confirm pill performance envelopes. The lift-off pressure was measured by pumping mineral oil at a constant rate (40 ml/min.) for at least 5 minutes through the back side of the screen (production direction), while observing the differential pressure as it gradually increased to a maximum value (lift-off pressure), then dropped and plateaued momentarily.

Results

The optimized formulations are characterized in Table 3, where a differential pressure of 500-psi and temperature of 215°F was maintained.

Table 3. Optimum Blend Characterization Data

	A (gauge 6 & 8)	**B** (gauge 10 & 12)	**C** (gauge 12)
Spurt (mL)	5	5	4
30 minutes/1 hour (mL)	7.5/9.5	7/7.5	8/12
24 hours (mL)	22	22	20
72 hours (mL)	24.5	22	25
Filter cake (mm)	< 2	< 2	< 2
Density (lb/gal)	13	13	14.5
Lift-off Pressure (psi)	< 5	< 5	< 5

Additional optimized field deployed formulations are characterized in Table 4 and Figure 5 where a differential pressure of 800-psi and 245°F was maintained to confirm pill performance envelopes.

Table 4. Additional Optimum Blend Characterization Data

	D (gauge 12)
Spurt (mL)	5
30 minutes/1 hour (mL)	8/9
24 hours (mL)	19
72 hours (mL)	26
96 hours (mL)	26
Filter cake (mm)	< 2
Density (lb/gal)	14.9
Lift-off Pressure (psi)	< 2.5

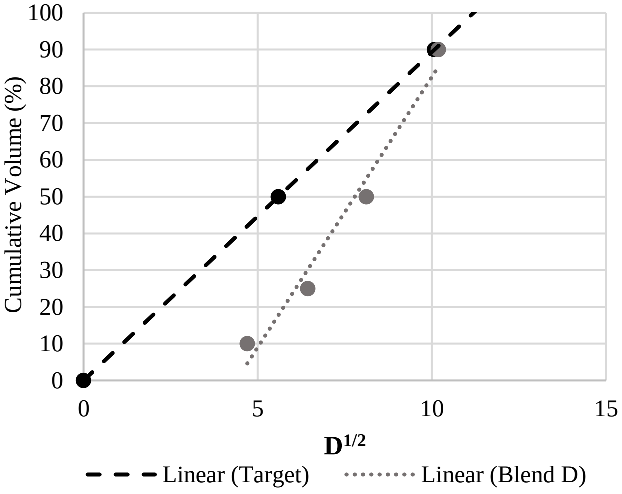

Figure 2: Blend D (Gauge 12) Line.

The spurt loss was less than 6 mL in all the samples while overall fluid loss after 72 hours of testing was less than 26 mL and lift-off pressures were less than 5 psi.

To exemplify how the model predicts the fluid loss control provided by the different blends please refer to Figures 6 and 7.

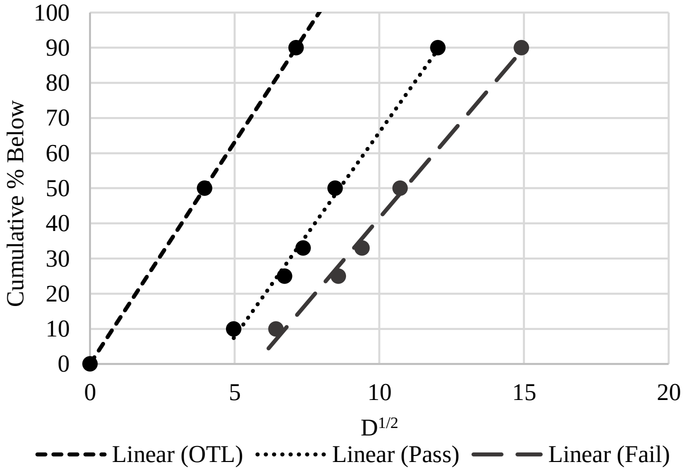

Figure 6: Blend A (Gauge 6) Lines.

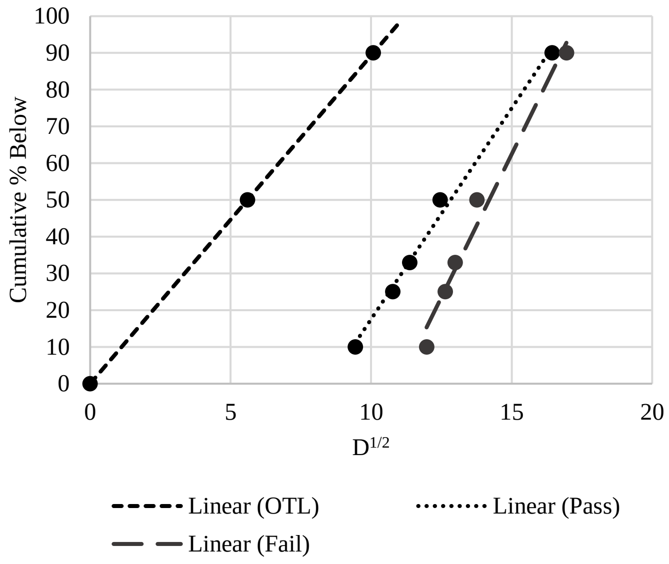

Figure 7: Blend C (Gauge 12) Lines.

The optimized blend line can be seen to approximate the slope of the optimal target line (OTL) while the slope of the failed blend line is not close to the slope of the OTL, even when the two blend lines are slightly below the OTL.

Conclusions

Using modified Particle-Size Distribution models for optimizing blends consistent with screen-gauge size using commercially available grades of Calcium Carbonate (solids-laden fluid loss control systems) and graphical representations to determine their optimal Particle-Size Distribution significantly reduced the time needed to screen and develop an optimal treatment to effectively seal an screen in gravel-pack or frac-pack applications.

Acknowledgments

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Nomenclature

mL = milliliter (milliliter). Unit of Volume. An SI unit of fluid measure equal to 10^{-3} *liters (liters)*
psi = Pound-force per square inch (lbf/in^2*). Unit of pressure.*

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