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Improved Wellsite Test for Monitoring Barite Sag

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Abstract

The Viscometer Sag Test (VST) is one of very few wellsite tests available to directly measure barite sag tendency of drilling fluids. Despite its practical and technical benefits, industry acceptance of this test has been limited by inconsistency of results and lack of convincing correlation to flow-loop or field results. A new, low-cost improvement involves insertion of a thermoplastic "shoe" in the bottom of the thermocup before running an otherwise standard VST procedure. The primary focus of this paper is to show how this modification can improve the utility of the standard VST.

The upper surface of a VST shoe is characterized by two sloped, hemispherical sections. The complex surface facilitates settling and helps concentrate the weight material into a single collection well at the bottom of the thermocup. This design also adds two important, new dimensions to the VST procedure. Firstly, it permits measurement of the relative capability of the test mud to pick up a sag bed formed in the thermocup. Secondly, data can be taken at periodic intervals to allow trends to be compared to dynamic sag flow-loop tests.

Data are presented from field and lab-prepared drilling fluids using several test methods. Also included are preliminary results from a computational fluids dynamics study designed to evaluate fluid behavior under test conditions in the original and improved VSTs.

Introduction

Barite sag is a persistent and potentially serious problem that can occur in directional wells drilled with weighted muds. The complex phenomenon involves dynamic and static settling of weight material, followed by downward slumping of the fluidized beds that form on the low side of the wellbore. The formation of these high-density beds and their subsequent recirculation can lead to severe operational problems, including well-control issues, lost circulation, borehole instability, and stuck pipe.

Several qualitative and quantitative field indicators can precede these common drilling problems. The most definitive of these is the significant variation in flowline mud weight, lighter and heavier than nominal, when circulating bottoms up after the mud has been static for a period of time.

Despite considerable efforts on many fronts, the drilling industry continues to struggle with managing sag.[1] One of the key reasons is lack of suitable, industry-accepted test methods for quantifying sag. Testing is necessary for planning and development of mud systems, and maintenance of mud properties and problem diagnosis at the wellsite.

Static cells often are used to test sag in the laboratory, but sag severity most commonly is inferred from low-shear-rate rheological properties measured with standard-issue oilfield viscometers. Advanced viscometers also are used as sag indicators[2] and to evaluate the role of rheology on sag.[3] However, direct tests which measure mud-weight change over a period of time arguably are preferable. Few direct sag tests are applicable in the wellsite environment and most increase time demands on field personnel.

The Viscometer Sag Test (VST),[4] introduced in 1991 as a practical wellsite test, has seen some success in the field and in the laboratory as a direct indicator of sag tendencies. Simplicity, low-cost, and equipment availability notwithstanding, the VST has not received sufficient industry support to become a *de facto* or API standard. Other field tests[5] have been proposed; however, most have been variations on the VST procedure and have not achieved the same level of use as the VST.

The subject of this paper is yet another improvement to the original VST field test called the VST Sag "Shoe".[6] This low-cost modification was developed to improve the consistency, sensitivity, and accuracy of the standard VST. The improved design also can characterize the sag bed to help determine the best course of action to correct a sag problem in the field. Like the original VST, the new version can also be used in the laboratory for evaluating the sag-tolerance of mud systems and products.

Supporting data presented in this paper were measured on several field and lab-prepared drilling fluids using the VST, VST Shoe, and a sag flow loop. Also included are preliminary results from a computational fluids dynamics (CFD) study designed to investigate sag behavior of Herschel-Bulkley drilling fluids in the original and improved VSTs.

Viscometer Sag Test

The original VST measures the density increase at the bottom of an API mud thermocup after mixing the mud sample at 100 rpm with a standard field viscometer for 30 min. It was developed at a time when the industry was beginning to fully recognize the negative effect of sag in directional wells. An important intent of the VST was to reinforce the concept that barite sag is primarily caused by dynamic settling, since sag generally was treated as a static settling problem prior to that time. Circulating sag flow loops[7] had just been introduced, but the need for a simple wellsite test was already evident.

For practical reasons, the required equipment was purposely limited, as much as possible, to that typically available and used by rigsite mud engineers. The VST was designed around the 6-speed rotational viscometer and thermocup used routinely to measure mud rheological properties. The viscometer provides the consistent (though somewhat complex) shear to simulate dynamic conditions; the thermocup serves as the mud container and heats the mud to 180°F maximum (although the test normally is run at 120 or 150°F).

A syringe with a blunt cannula is used to extract samples from the bottom of the thermocup. The sag-bed sample volume (10 or 20 mL) depends on the method used to determine the sample density. A retort cup, pycnometer, or the syringe itself can be used to provide an accurate volume; a digital balance or triple-beam balance can be used to measure sample weight. The initial procedure included an alternative method using a small-volume, “pocket” mud balance to measure density up to 17 lb/gal, but these balances have not been available for some time.

Geometry of the VST is illustrated in **Fig. 1**. The mud level matches the scribed line on the viscometer rotor sleeve as it should for conventional rheological measurements. However, this does not ensure a consistent distance from the bottom of the sleeve to the bottom of the thermocup. Any inconsistency from test to test can affect the ultimate barite concentration and sag-bed distribution at the bottom of the thermocup.

Improved Viscometer Sag Test

The improved VST (**Fig. 2**) involves the insertion of a thermoplastic “shoe” in the bottom of the thermocup before running an otherwise standard VST procedure. The sloping surface on the Shoe helps to accelerate settling and to concentrate the weight material into a single collection well at the bottom of the thermocup. Consistency is helped by maintaining a constant 7-mm distance between the bottom of the viscometer sleeve and where the sleeve would touch the uppermost surface of the Shoe.

The collection well plays a key role in this design, since it can easily be detected by the tip of the cannula to ensure that bed samples are extracted and replaced in the same location. This means that data can be taken at multiple time intervals to allow trend comparisons to other tests, such as circulating sag flow loops. Also, it permits measurement of the relative capability of the test mud to pick up a sag bed formed in the thermocup. Characterization of the sag bed can suggest how easily it can be removed from a well prior to tripping out of the hole.

The Shoe can be made from most materials that can handle test temperatures up to 180°F and are resistant to water, oil and synthetic-based drilling muds. Thermoplastics are ideal choices since they are inexpensive and easily machined or cast. Many of the prototypes were “printed” on a 3-D printer using ABS plastic stock. While the surfaces were not as smooth as those made on a milling machine, printed Shoes have worked well in the laboratory and field tests.

The Shoe design was constrained by the geometry of the viscometer and thermocup used in the test, shown together in the photo in **Fig. 3a**. A review of **Fig. 2** illustrates a key issue created by the limited space. With the Shoe in place and the sleeve positioned correctly above the Shoe surface, the scribed line on the viscometer sleeve is very close to the top of the thermocup. For some muds, the mud level may have to be slightly below the scribed line in order to minimize spillage when rotating at high speed without suitable protection. A steeper slope that would increase bed slumping was clearly not possible.

The insert is enlarged in **Fig. 3b** to show more detail. The 2.35-in. diameter at the base is the maximum size permitting easy insertion and removal in an API thermocup. The upper surface consists of two sloping, hemispherical sections that end at the “collection well” on the lowest edge. Surface “B” is slightly lower and steeper than the curved Surface “A”. The “lip” caused by the misalignment discourages settled barite from being recirculated during the sag-deposition testing phase. However, the lip is not too high to prevent bed pickup at the high viscometer speed applied during the bed pick-up phase.

Test equipment and an abbreviated procedure for the VST Shoe test are provided in the **Appendix** of this paper. The VST Shoe procedure is similar to the VST version, except that it includes steps to measure sag pick up. At the conclusion of the normal 30-min sag test, the bed sample can be replaced in the Shoe collection well using the syringe. The viscometer speed is then increased to 600 rpm for 20 min, after which another sample is extracted and weighed. This gives an indication on how easily the bed can be picked up by increased shear. The bed pick up (VST BPU) is reported as the percentage of the mud-weight increase that can be “recovered” in the 20-min period. The VST Sag is reported as the mud weight increase (VST Sag) at the bottom of the thermocup after mixing at 100 rpm for 30 min.

CFD Analyses

A special study using computational fluid dynamics (Fluent 6.1.22) was initiated to mathematically model sag behavior in the original and improved VSTs. The study is in its early stages, but preliminary results are presented here to demonstrate the intent and value of this concept.

CFD, especially powerful as a visualization tool, is able to model complex physical fluid phenomena that cannot be simulated analytically or measured with physical experiments. Technically speaking, it is a numerical method that solves fluid-mechanic equations using finite-volume discretization on a computational mesh. In this sag study, CFD is being used to predict velocity profiles and barite concentrations for different weight materials, rheological models (including Herschel-Bulkley), and fluid properties. (It should be pointed out that these simulations require considerable computer resources to achieve convergence, despite the relative simplicity of the geometry. In most cases, a full day is required to generate the first few seconds of simulation. Fortunately, the time step can be systematically increased over the course of the job.)

Fig. 4a shows the computational mesh for a standard VST, while **Fig. 4b** shows results of the 3-D, transient simulation for barite concentration after 30 min for a typical, deepwater SBM. Tests are run in the vertical position, but both figures have been rotated for better illustration. **Fig. 4c** shows the cross-sectional views of this same test after 30 and 60 min. The blue colors represent lower barite concentrations and the red colors represent higher concentrations. Interestingly for this example, the barite bed concentrated directly below the sleeve (modeled as a solid, rotating cylinder). This could make the bed inconvenient to reach using a syringe when conducting a standard VST. Rheological properties for the 12.7 lb/gal SBM were PV = 30 cP, YP = 17 lb/100 ft^2, and τ_y = 8.9 lb/100 ft^2. While the software can handle a particle-size distribution, this example assumed a single barite particle size of 19.7 μm. It is expected that different rheological properties or particle sizes would be alter the barite particle distribution at the bottom.

The computational mesh for the VST Shoe shown in **Fig. 5a** is considerably more complex and computer resource requirements are much higher. **Fig. 5b** is the 3-D model of the barite concentration of a relatively sag-resistant SBM after 20 min. As before, **Figs. 5a** and **5b** have been rotated so that the 3-D model can be viewed more easily. The highest barite concentration is immediately below the lower right edge of the sleeve, as seen in the cross-sectional views after 66 sec and 20 min (**Fig. 5c**). Note the progression of higher barite concentrations towards the collection well.

The rheological properties of the mud from **Figs. 5a-5c** were lowered in the next series of simulations in order to induce sag. **Figs. 6a-6b** show the rotated 3-D models of the VST Shoe mesh and barite distribution after 20 min. In this case, the highest barite concentration was at the bottom of the collection well. **Fig. 6c** shows cross-sectional views after 20.76 sec and 20 min. As in the previous case, barite settling started near the edge of the rotor sleeve closest to the Shoe surface. Because of the lower rheology, there was more shear near the bottom of the cell and barite particles were able to slide down and into the collection well.

A continuation of this study is planned, with Shoe-design optimization high on the priority list. Long-term goals include means to discriminate among various rheological and weight-material characteristics that affect sag. One of the more interesting opportunities is use of this technique to investigate effects of specific and less-conventional rheological properties. Eventually, this CFD study will include sag modeling in directional wells.

Sag-Shoe Test Data

Data presented in this paper were generated during the normal work stream of four laboratories. As such, they were limited to synthetic- and mineral-oil-based muds, and did not include a parametric study of the VST Shoe procedure. Nevertheless, it is useful to compare results from the Shoe, the standard VST and a sag flow loop, and to demonstrate use of the Shoe to screen products and mud formulations.

The first data set (**Table 1**), from a North Sea study, compares the effects of weight-material particle size and specific gravity on barite sag. Low-toxicity, mineral-oil-based fluids formulated with API barite, fine-grind barite, hematite, and Micromax were tested using the VST and VST shoe. Design properties for the fluids were 12 lb/gal, 25% w/w $CaCl_2$, 80/20 OWR, and 1-mL HTHP fluid loss at 200°F and 500 psi. The rheology of each mud was adjusted for a 6-rpm dial reading of 6-7 at 120°F (translating to LSYP values of 4-5 lb/100 ft^2).

As expected, the API-barite base mud exhibited significant sag (1.5 lb/gal) because of the low 6-rpm rheology. VST Shoe results on this base fluid at 70/30 and 75/25 OWRs were 1.18 and 1.26 lb/gal, respectively. Sag was considerably less for the fine-barite and Micromax fluids (0.53 and 0.21 lb/gal, respectively), but the 1.8-mL HTHP fluid loss was higher than desired when Micromax was used as the weighting agent. Sag from the hematite fluid was worse than that from the base mud, without the benefit of reduced PV. An oil-based fluid weighted with coated, micronized barite was also tested in this series for comparison. This fluid was virtually sag free, with VST Shoe results of 0.007 and 0.018 lb/gal at 120 and 180°F, respectively.

The next data set (**Table 2**) is for eight field SBMs from five deepwater wells in the Gulf of Mexico where sag was a potential concern. Mud weights ranged from 12.7 to 14.8 lb/gal. Mud D was run at 150 and 120°F and exhibited sag values of 1.3 and 1.0 lb/gal. Muds B2 and B3 (0.8 and 0.3-lb/gal sag) were treated versions of Mud B which had a 1.1-lb/gal sag. Mud E arguably was the worst performer of these fluids – the 1.2-lb/gal sag was among the highest and the 42% pick up was the lowest.

The SBMs were tested at multiple intervals during the bed-deposition and pick-up phases. **Fig. 7** summarizes the VST Shoe data for fluids A-D; beds were deposited at 100 rpm and picked up at 600 rpm. The trends are notably similar, probably because the muds were comparable in formulation.

Additional field SBMs from different wells were tested using three sag techniques and listed in **Table 3**. Three different mud types are represented in this table. The first five were conventional SBMs for the Gulf of Mexico, the next three were formulated with a different emulsifier package, and the last mud in the table was weighted with fine-grind hematite. Mud rheologies were measured at 150°F, but the VST and VST Shoe were run at 120°F. Furthermore, mud temperatures during the sag flow-loop tests were considerably cooler in the 100-110°F range.

Table 4 summarizes results from a pilot study designed to look at the effects of different products and rheological properties on sag of a 13.5-lb/gal field SBM. All of the data were measured at 120°F. **Fig. 8** is a graph of VST Shoe sag versus YP and LSYP for these muds. Both correlations are reasonable, but the LSYP correlation appears to be stronger. The reasonable correlation also holds for VST Shoe versus LSYP data plotted for all the fluids in **Fig. 9**.

Sag-Test Comparisons

The bar chart in **Fig. 10** plots the difference between Shoe and standard VST measurements for most of the fluids included in this paper. On average, the Shoe results were 0.2 lb/gal higher, but the VST values were slightly higher in about half of the cases. Also, duplicate Shoe tests were run on several of the field muds to evaluate repeatability. In **Fig. 11**, mud-weight variance between first and second runs for each mud are plotted against the time that both measurements were taken. .Values plotted at 30 min or less were taken at 100 rpm (while depositing a sag bed); those plotted after 30 min were measured at 600 rpm (while picking up a sag bed). The results are encouraging, although the scatter was more than expected.

Muds A-D listed in **Table 2** were also run on the sag flow loop for comparison to the VST tests. **Fig. 12** is a sample run from this flow loop which uses a mass flow meter to measure the density of the circulating fluid. Because of geometric dissimilarities, the VST Shoe and flow loop results were compared using a modified "sag register"[8]:

$$S_R = \exp\left(-k\frac{\Delta MW}{MW}\right)$$

The negative sign in the equation forces $0 < S_R \leq 1$; a value of 1.0 means no sag and lower S_R values indicate poorer sag tolerance. Based on empirical data, the correlation constant *k* is around 10 for the VST and 50 for the sag flow loop.

The sag register comparisons versus time for SBMs A-D are shown in **Fig. 13**. A single value of *k* was selected for the VST Shoe data for the four muds. Muds C and D were excellent matches, much better than the other two muds. The sag-register approach also was used to test the correlation among 13 of the test muds that were also run on the sag flow loop (**Fig. 14**). The *k* values used were 10.9 for the Shoe data and 50 for the flow-loop data.

VST Shoe Observations and Comments

Each of the laboratories using the VST Shoe for routine testing provided constructive comments and observations on the improved test. Overall, it was viewed as a logical refinement of the VST. Improved reproducibility was noted, especially for new and occasional users. Other comments are summarized below.

Temperature. A standard test temperature of 120°F was considered to be the most "technician friendly". Expansion of the thermoplastic apparently made it more difficult to remove the Shoe after running the test at higher temperatures. Also, significant settling occurred while stirring the sample at only 300 rpm (to minimize spillage), waiting for the mud to reach 180°F (600 rpm is recommended, if possible). Settling during mixing is an issue that would have to be considered before extending the Shoe concept to an HTHP test environment.

Sample Extraction. Some operators found it easier to locate the collection well by first stopping the viscometer and lowering the thermocup rather than trying to maneuver in the sleeve/cup gap, especially if the sleeve was still rotating. It is difficult to tell if this would appreciably disturb the test fluid.

Sample Volume. Although sample volumes of 10 and 20 mL are both used when running the standard VST, the smaller volume seemed more appropriate when using the Shoe. The Shoe reduces overall mud volume by 42.6 cm^3, and the 20-mL sample volume was considered excessive considering the smaller test volume. (The 10-mL sample represents roughly half of the Shoe height at the thermocup bottom.) On the other hand, the larger sample volume reduced the experimental error when weighing the sample. Further testing will be required to determine optimum sample volume.

Timing. The 30-min time for bed deposition and 20-min time for the pick up seem reasonable for these tests.

Weight Container. Choice for the container used to weigh the bed sample depends on how the test is run. A pycnometer is the best choice if only the sag-deposition test will be run. However, it is more practical to weigh the sample in the syringe used for extraction if multiple measurements will be taken during the 30-min test and/or if the pick-up test will be included. An accurate volume can be achieved in the syringe, if care is taken to consider cannula volume.

Pick-up Test. While this seems to be a useful new feature, there were insufficient data available to determine the utility of this information for field use.

Conclusions

1. A simple, low-cost modification to the Viscometer Sag Test has been developed to improve the consistency, sensitivity, and accuracy of measuring barite-sag tendencies at the wellsite.
2. A thermoplastic "shoe" insert in the thermocup can facilitate settling and help concentrate weight material in a collection well at the bottom of the thermocup.
3. The collection well ensures that bed samples are extracted from and replaced in the same location, thereby allowing multiple sampling and measurement of the relative ability of the test mud to pick up the sag bed.
4. Preliminary results show opportunities to apply computational fluid dynamics to model barite sag in laboratory tests and later in directional wells.
5. Comments from different laboratories using this modification in their routine work schedule were positive, encouraging, and useful for refining the new method.

Nomenclature

ΔMW	=	*Change in Mud Weight*
τ_y	=	*Yield Stress*
CFD	=	*Computational Fluid Dynamics*
k	=	*Sag-Register Correlation Constant*
LSYP	=	*Low-Shear Yield Point*
MW	=	*Mud Weight*
OWR	=	*Oil/Water Ratio*
PV	=	*Plastic Viscosity*
SBM	=	*Synthetic-Based Mud*
Sr	=	*Sag Register*
VST	=	*Viscometer Sag Test*
YP	=	*Yield Point*

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Appendix A – VST Shoe Test Equipment

The equipment list assumes the density of a 10-mL sample will be determined by weighing the sample in the syringe. Alternatives include extracting a 20-mL sample and using a pycnometer to determine density

1. 6-speed oilfield viscometer
2. API thermocup
3. Thermometer (32 – 212°F, ±1°F)
4. VST Sag Shoe
5. 10-mL luer syringe (2-piece, solvent-resistant "Norm-Ject" from HSW GMBH) and cannula – 6-inch, 14-g tube with luer connector
6. Digital balance with 0.01-g resolution, or triple-beam balance if rig vibration is excessive
7. Small, 6-inch spatula
8. Timer, ± 1 sec
9. Ruler or caliper, ± 0.5 mm

Appendix B – VST Shoe Test Procedure

This abbreviated procedure provides a consistent measurement of barite sag and bed pickup using the improved Viscometer Sag Test (VST Shoe).

1. Calibrate syringe with cannula attached using distilled water and balance.
2. Stage Setup
   a. Insert Sag Shoe in the thermocup and position collection well at 7:00 to 9:00 o'clock.
   b. Place thermocup on the viscometer stage, raise the stage until the bottom of the viscometer sleeve touches the top of the Shoe, then lower precisely 7 mm. Lock stage at this level.
3. Sag Measurement (**VST Sag**)
   a. Preheat thermocup to 120°F or other selected temperature (180°F maximum).
   b. Pour 140 mL of mud into the thermocup. Mix at 600 rpm for 15 min and until mud temperature has stabilized at the set point for at least 5 min.
   c. Using 10-mL syringe with 6-inch cannula (cleared of air), draw slightly more than 10 mL of mud from the collection well. The well can be found using the tip on the cannula. Carefully clear syringe and cannula of residual air and push plunger to the established true 10-mL calibration mark.
   d. Wipe cannula and syringe surfaces clean and to dryness. Weigh and record as VST_1.
   e. Gently expel the previously sampled 10 mL of mud into the collection well of the Shoe.
   f. Shift viscometer to 100 rpm, and run for 30 min.
   g. Repeat steps 3c – 3e, except record the syringe + cannula weight as VST_2.
   h. Convert VST_1 and VST_2 to lb/gal, subtract VST_1 from VST_2, and report as **VST Sag** in lb/gal.
   i. For a detailed analysis (e.g. to compare to sag flow loop results), also take and measure a sample after 5, 10, 15 and 20 min. Remember to carefully return the sample to the collection well after each test.
4. Bed Pickup Measurement (**VST BPU)**
   a. Gently return the last bed sample to the Shoe collection well.
   b. Run viscometer at 600 rpm for 20 min.
   c. Repeat 3c – 3e, except record the syringe + cannula weight as VST_3.
   d. Convert VST_3 to lb/gal, subtract VST_3 from VST_2, and calculate the percentage change compared to **VST Sag**. Report as **VST BPU** in %.
   e. For a detailed analysis, also take and measure bed samples after 2, 5 and 10 min. Carefully return the test sample to the collection well after each test.

Table 1 – VST and VST Shoe results for 12-lb/gal, low-toxicity oil-based fluids formulated with four different weight materials

Fluid		API Barite	Fine Barite	Hematite	Micromax
Mud Weight	lb/gal	12.0	12.0	12.0	12.0
Temperature	°F	120	120	120	120
PV	cP	22	23	24	22
YP	lb/100 ft^2	10	13	11	12
LSYP	lb/100 ft^2	4	5	4	4
HTHP @200ºF	mL/30 min	1.0	0.8	1.0	1.8
VST	lb/gal	**1.32**	**0.69**	**1.42**	**0.27**
VST Shoe	lb/gal	**1.50**	**0.53**	**1.66**	**0.21**

Table 2 – VST Shoe sag and pick-up data for several field SBMs

Field Mud		A	B	C	D	D	E	B2	B3
Mud Weight	lb/gal	14.8	12.7	13.4	14.8	14.8	12.7	13.7	13.9
Temperature	°F	120	120	120	150	120	120	120	120
PV	cP	52	40	24	41	50	29	50	54
YP	lb/100 ft^2	22	20	28	20	23	19	28	32
LSYP	lb/100 ft^2	13	11	16	10	10	13	12	14
VST Shoe Sag	lb/gal	**1.0**	**1.1**	**1.1**	**1.3**	**1.0**	**1.2**	**0.8**	**0.3**
VST Shoe BPU	%	**92**	**92**	**83**	**83**	**61**	**42**	**61**	**50**

Table 3 – Comparison of sag tendencies for several field SBMs tested using three different test methods

Mud Weight	lb/gal	14.0	13.9	12.7	15.0	14.7	12.9	13.0	12.9	13.5
Temperature	°F	150	150	150	150	150	150	150	150	150
PV	cP	37	42	31	38	36	25	21	26	22
YP	lb/100 ft^2	21	24	16	22	19	22	17	22	29
LSYP	lb/100 ft^2	10	10	8	11	11	11	8	14	17
Gel 10s	lb/100 ft^2	14	15	11	19	23	19	17	29	20
Gel 10m	lb/100 ft^2	19	21	17	26	30	30	28	39	23
VST	lb/gal	**0.79**	**0.52**	**0.94**	**1.22**	**1.28**	**1.58**	**1.56**	**1.17**	**0.71**
VST Shoe Sag	lb/gal	**0.78**	**0.31**	**1.10**	**0.94**	**1.02**	**1.16**	**2.54**	**0.73**	**0.59**
Sag Flow Loop	lb/gal	**0.14**	**0.11**	**0.17**	**0.24**	**0.27**	**0.30**	**0.66**	**0.12**	**0.20**

Table 4 – VST and VST Shoe results from a pilot study to evaluate the effects of different products and rheology on sag

Mud Weight	lb/gal	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5	13.5
Temperature	°F	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
PV	cP	35	55	59	39	44	36	50	41	38	47	41	40	46	54	41
YP	lb/100 ft^2	12	32	24	13	32	9	21	10	9	15	13	16	16	33	13
LSYP	lb/100 ft^2	6	19	12	5	13	5	10	6	5	9	7	8	7	12	7
Gel 10s	lb/100 ft^2	16	46	28	18	21	10	21	11	13	21	16	21	15	30	17
Gel 10m	lb/100 ft^2	30	64	56	30	45	31	38	30	30	38	32	35	31	45	30
VST	lb/gal	**1.31**	**0.54**	**1.04**	**1.13**	**1.37**	**2.29**	**1.58**	**1.54**	**2.02**	**1.31**	**0.80**	**1.03**	**1.24**	**0.42**	**1.14**
VST Shoe Sag	lb/gal	**2.11**	**0.27**	**0.72**	**1.62**	**0.64**	**2.56**	**0.77**	**1.92**	**2.38**	**1.26**	**2.33**	**2.62**	**1.60**	**0.37**	**2.47**

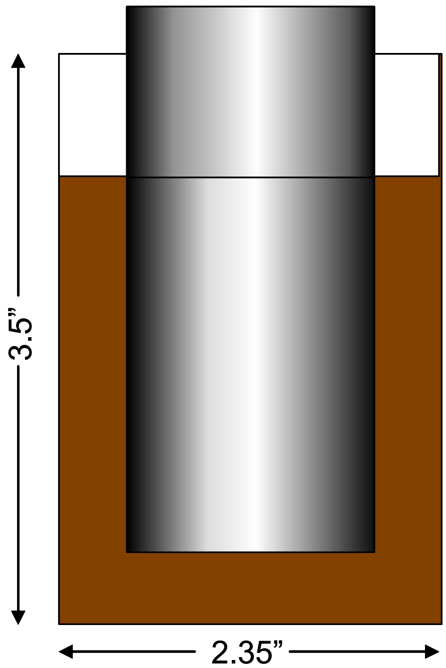

Fig. 1 – Schematic showing the geometry of the VST method.

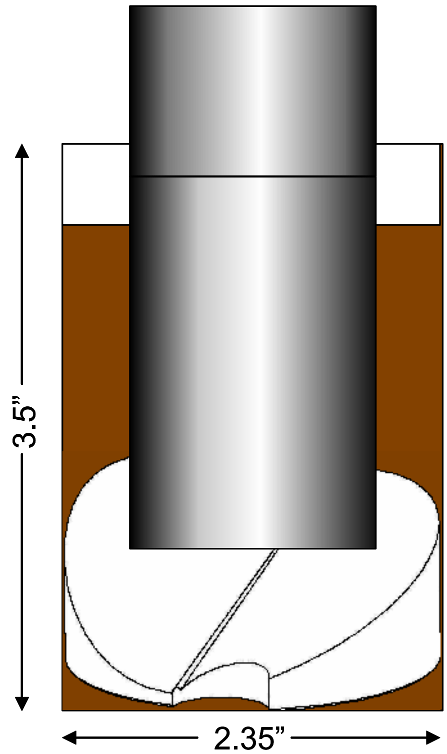

Fig. 2 - Schematic showing the geometry of the VST Shoe method.

Fig. 3a – Viscometer, thermocup, and thermoplastic insert required for the VST Shoe method.

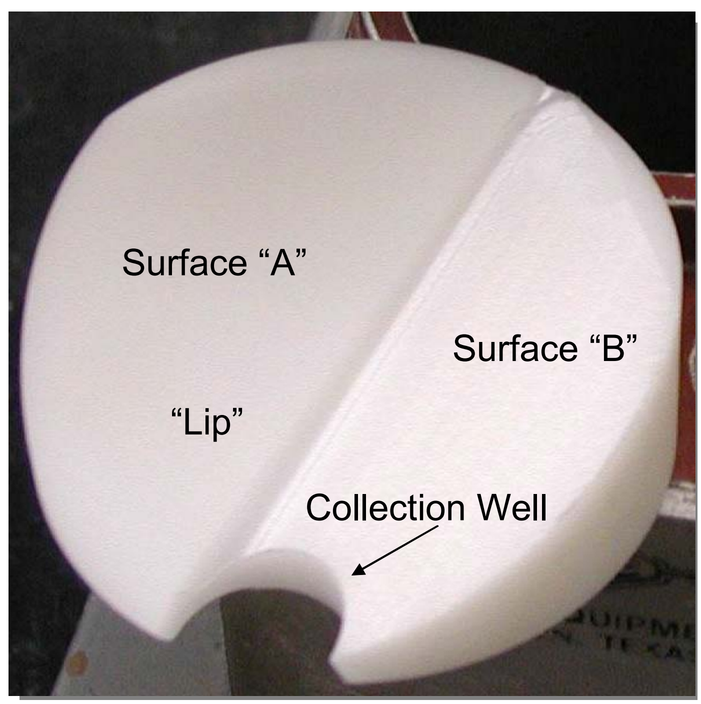

Fig. 3b – Enlarged view of the VST Shoe showing the upper surfaces, lip, and collection well.

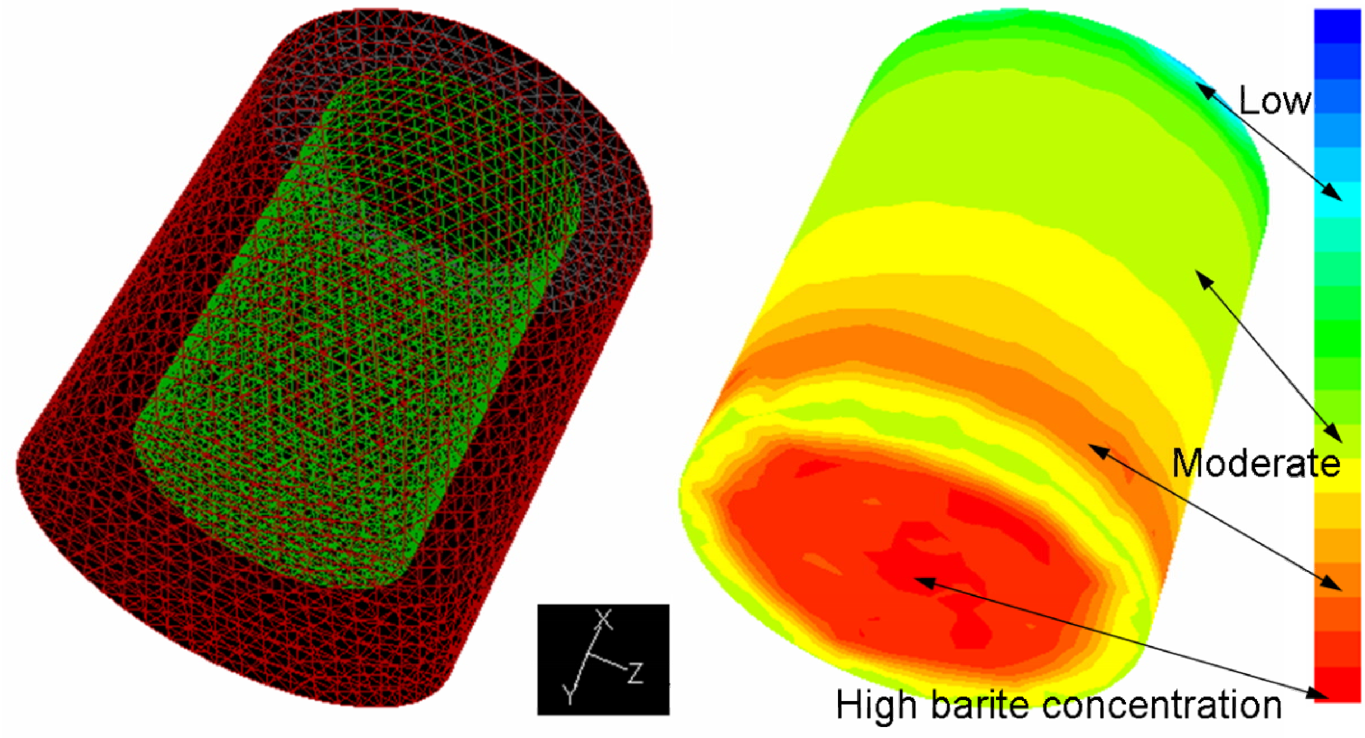

Fig. 4a (left) – CFD mesh for the VST method. **Fig. 4b (right)** – 3-D view of the CFD barite concentration for a typical 12.7-lb/gal SBM after completing a 30-min VST.

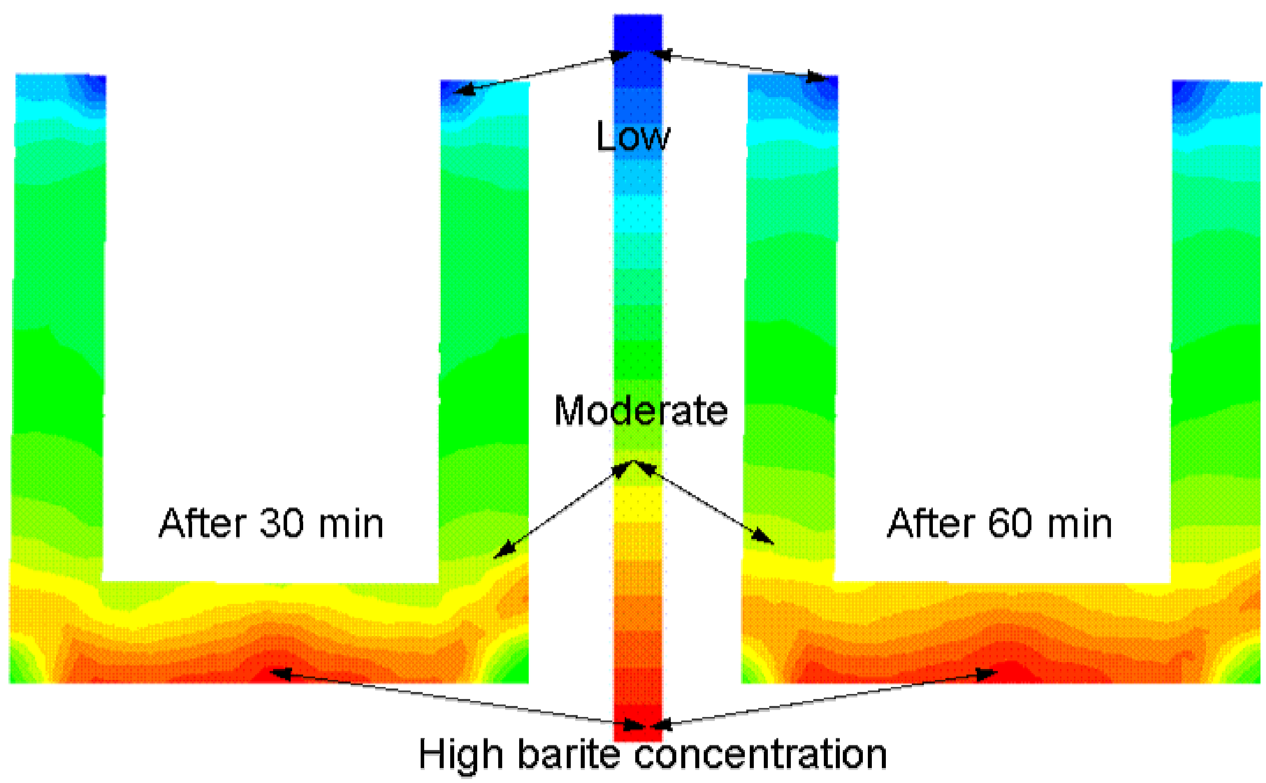

Fig. 4c – CFD cross-sectional views of barite concentration after running the standard VST for 30 and 60 min. . The model on the left matches the 3-D model in Fig. 4b.

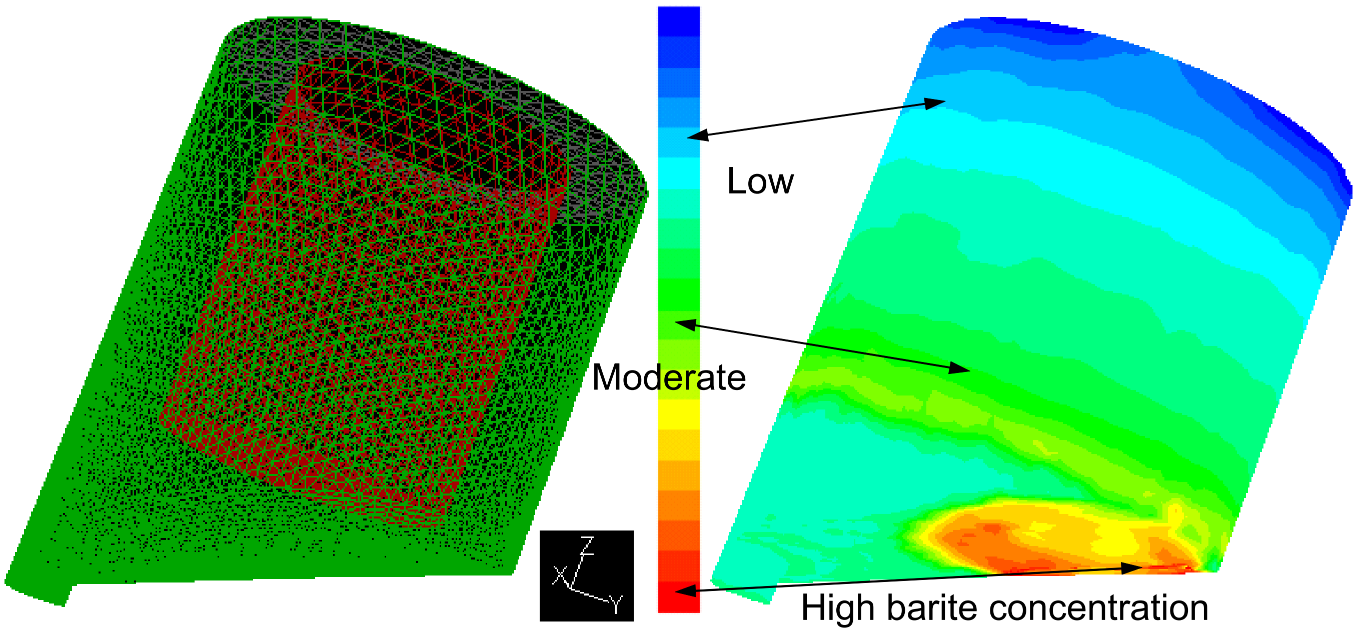

Fig. 5a (left) - CFD mesh for the VST Shoe method. **Fig. 5b (right)** – CFD 3-D view of the VST Shoe barite concentration for a well-treated SBM after 20 min.

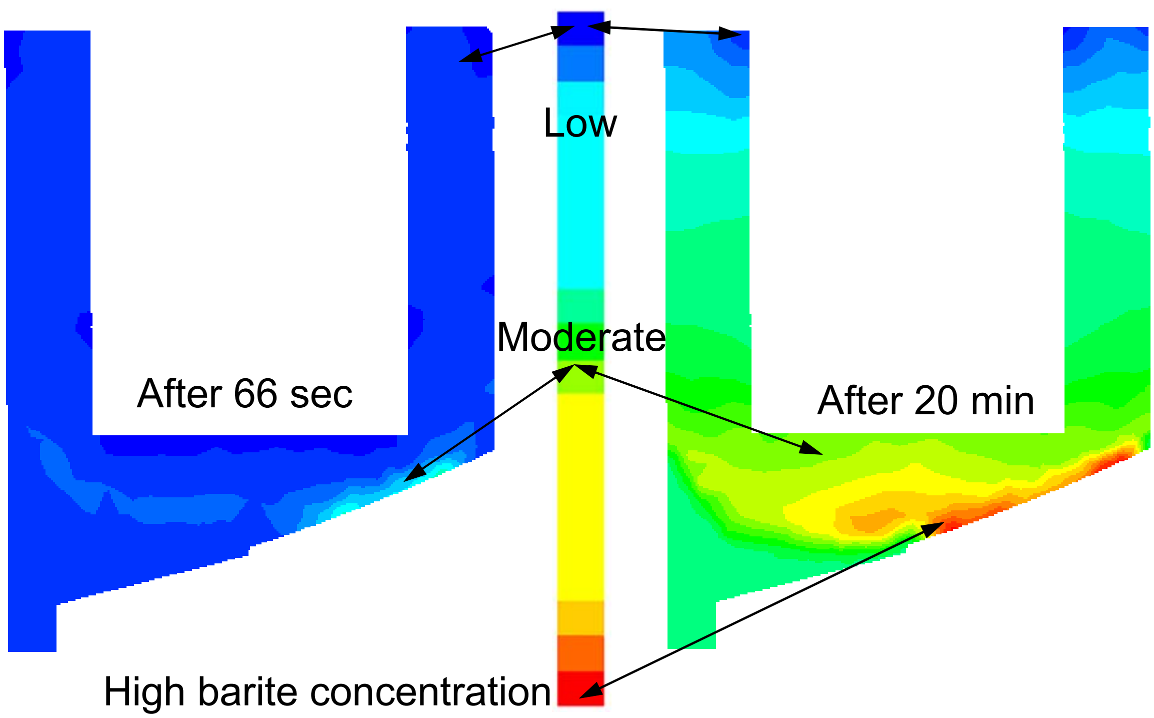

Fig. 5c - CFD cross-sectional views of the VST Shoe barite concentration after 66 sec and 20 min. The model on the right matches the 3-D model in Fig. 5b.

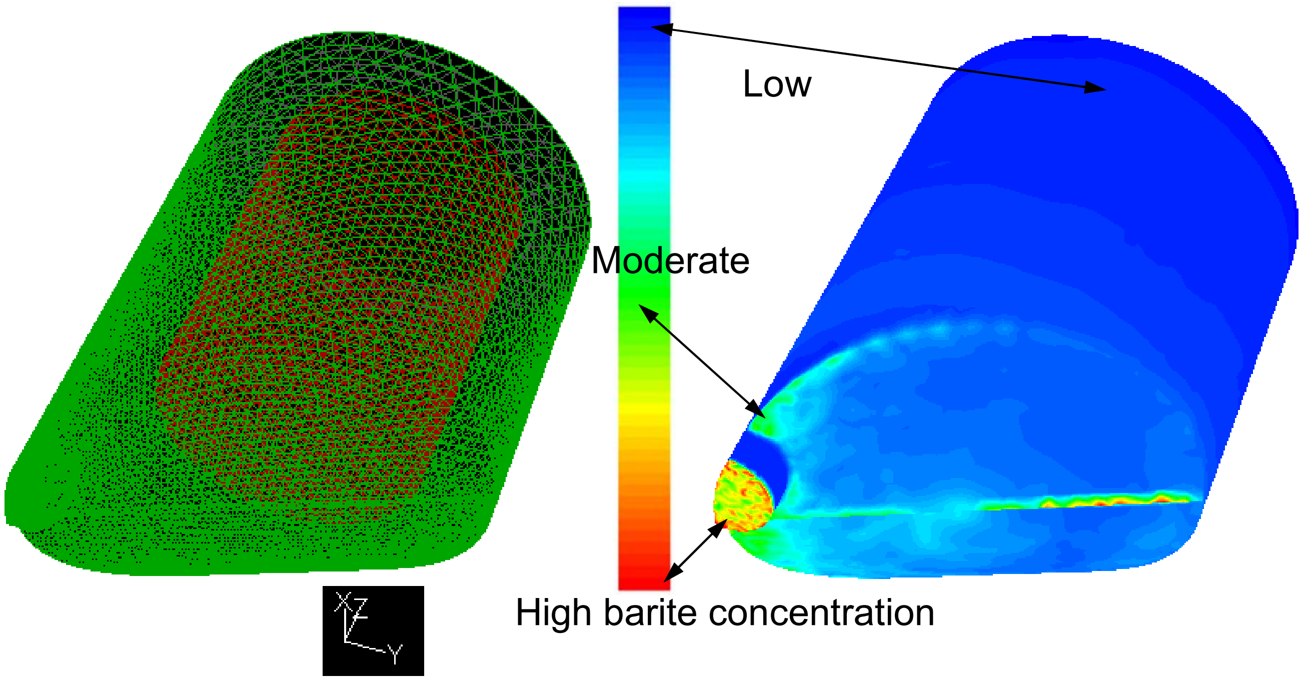

Fig. 6a (left) - CFD mesh for the VST Shoe method. **Fig. 6b (right)** – CFD 3-D view of the VST Shoe barite concentration for a typical SBM after 30 min.

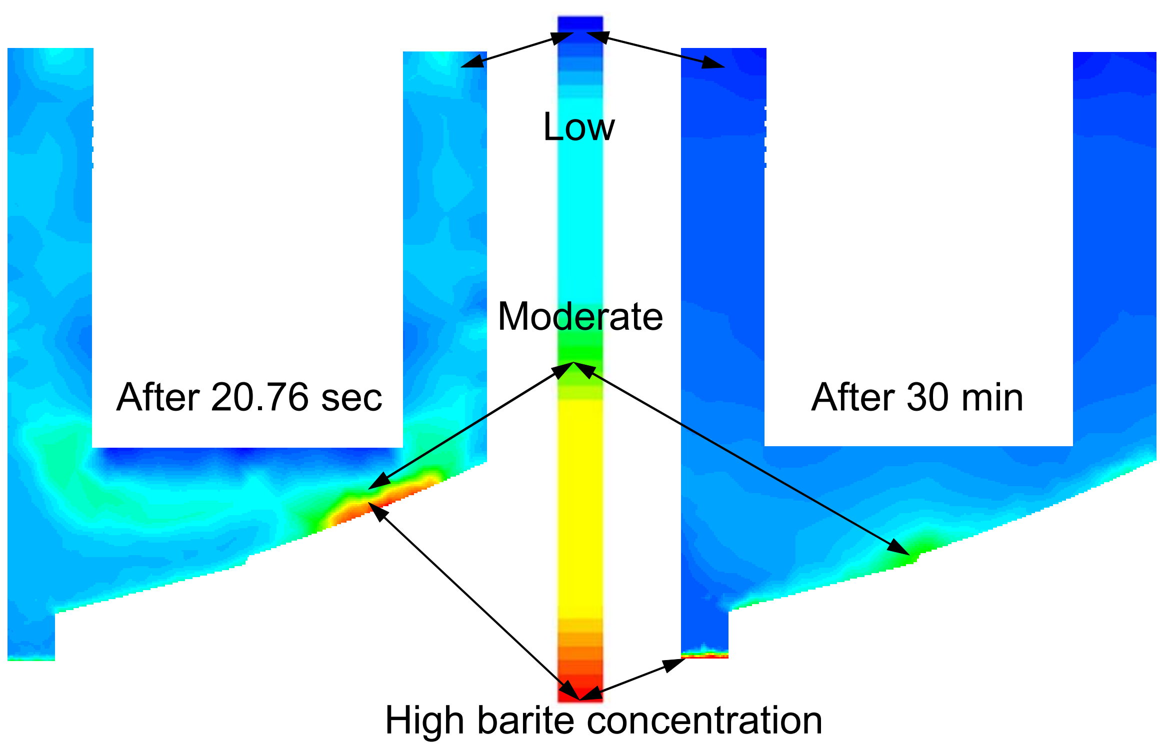

Fig. 5c - CFD cross-sectional views of the VST Shoe barite concentration after 20.76 sec and 30 min.

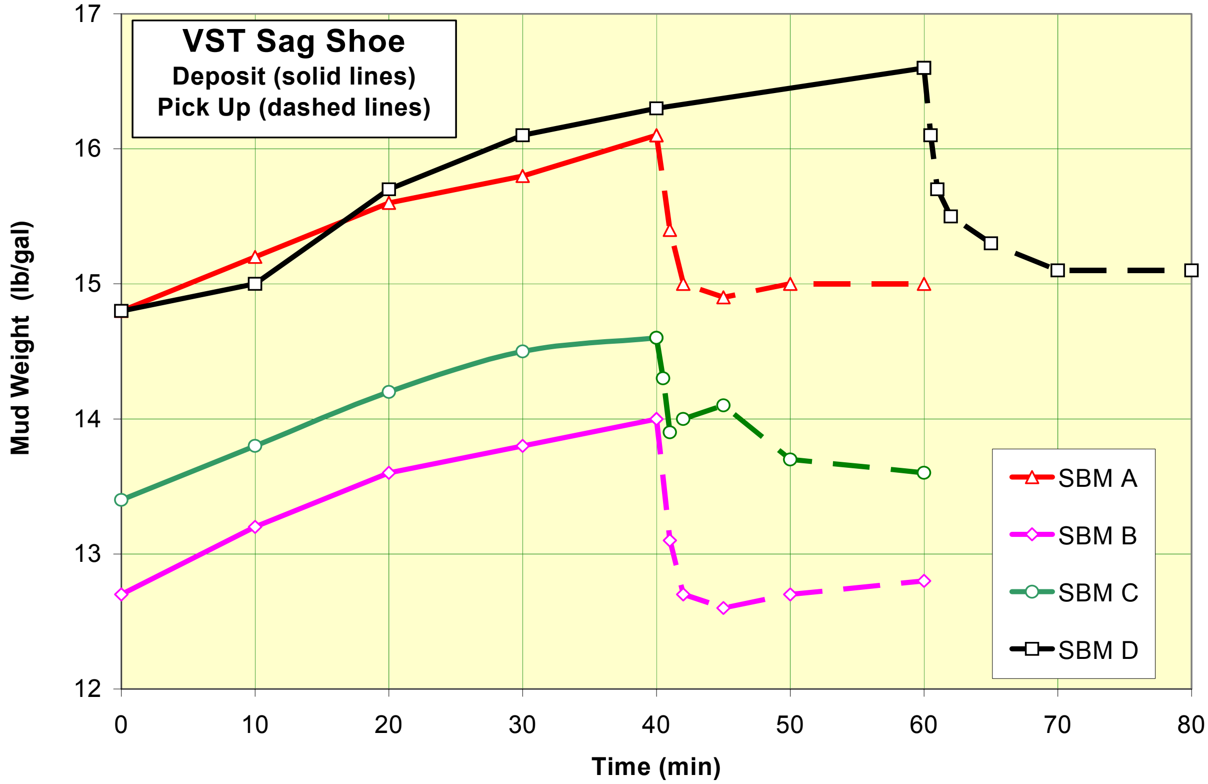

Fig. 7 – Sag and bed pick-up results for four field SBMs listed in Table 2.

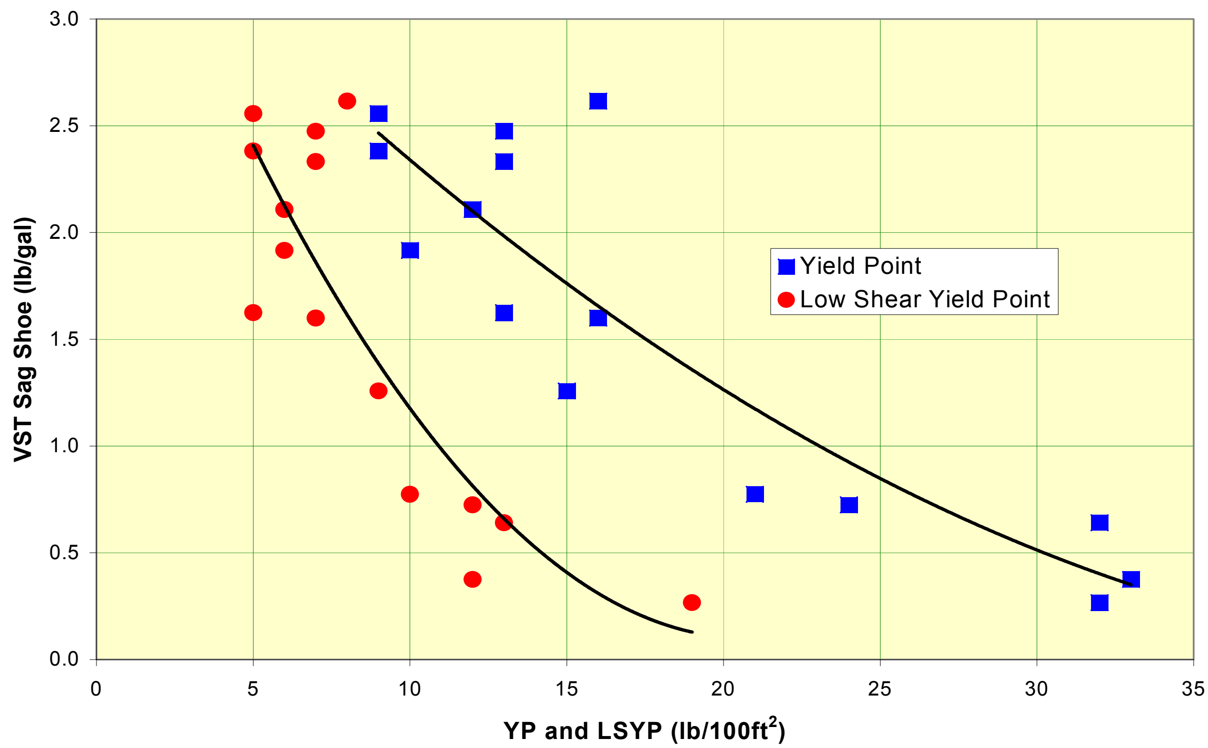

Fig. 8 – Comparison of YP and LSYP values versus VST Shoe results for the pilot-study muds listed in Table 4.

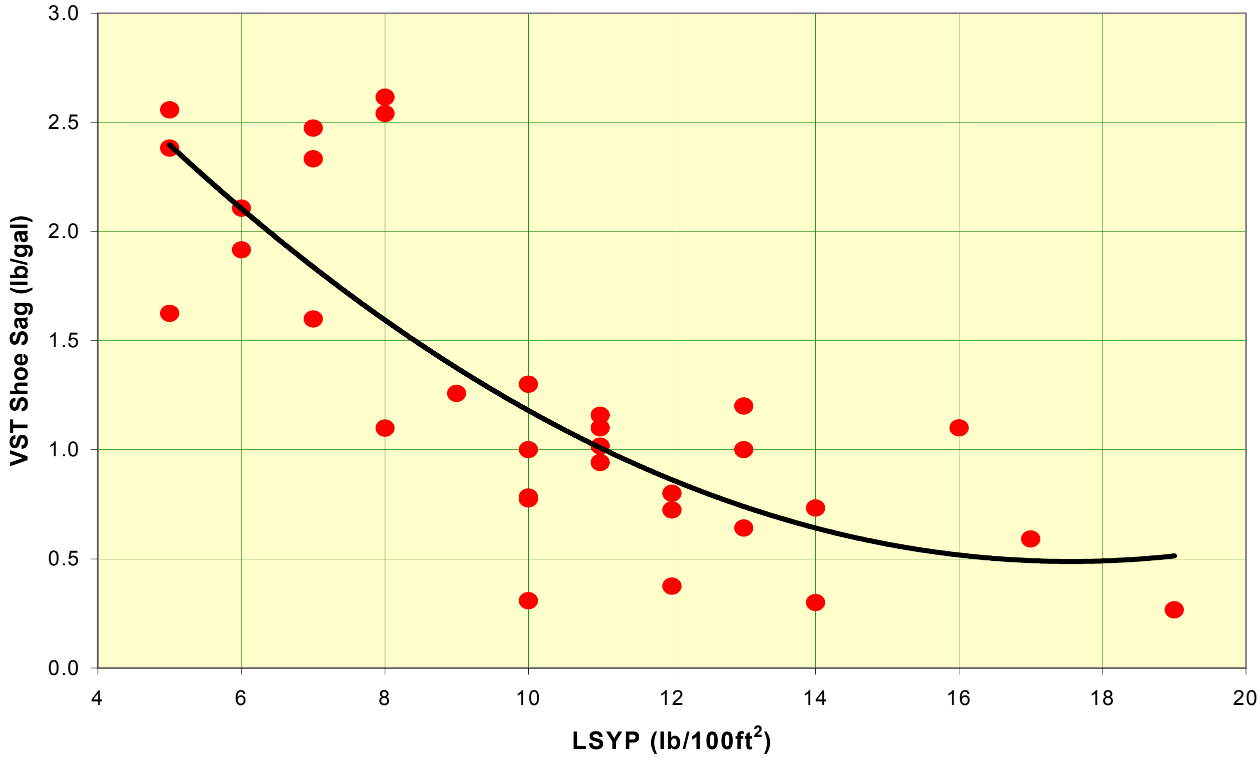

Fig. 9 - Comparison of LSYP values versus VST Shoe results for all muds studied in this paper.

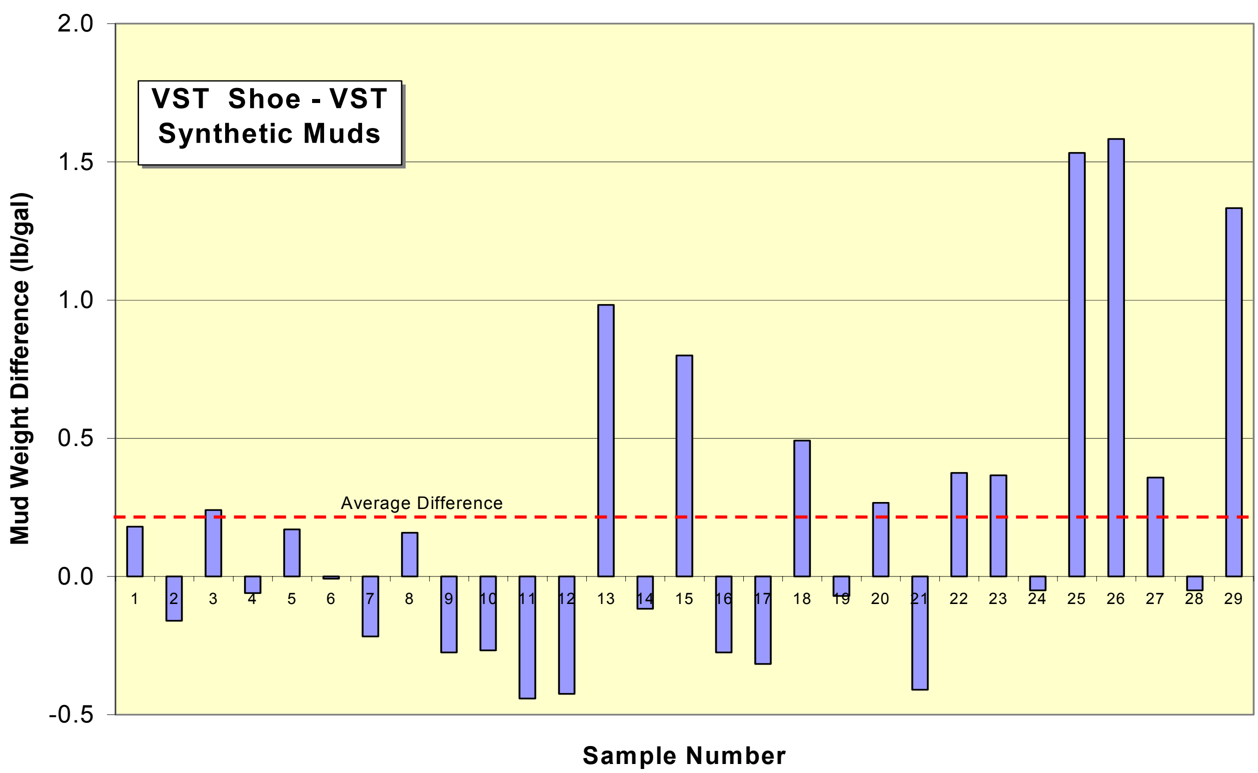

Fig. 10 – Differences among VST Shoe and VST results for different muds. The average difference was 0.2 lb/gal.

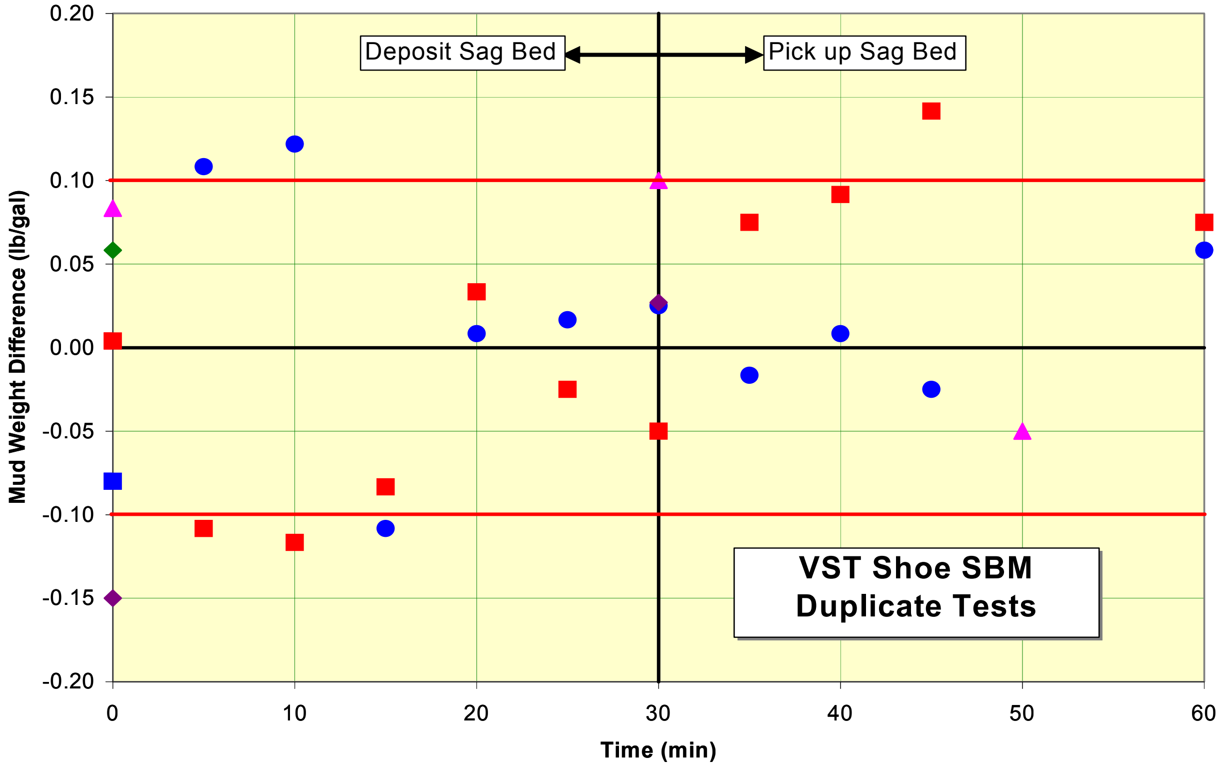

Fig. 11 – Summary of duplicate VST Shoe results, including bed deposition and pick up.

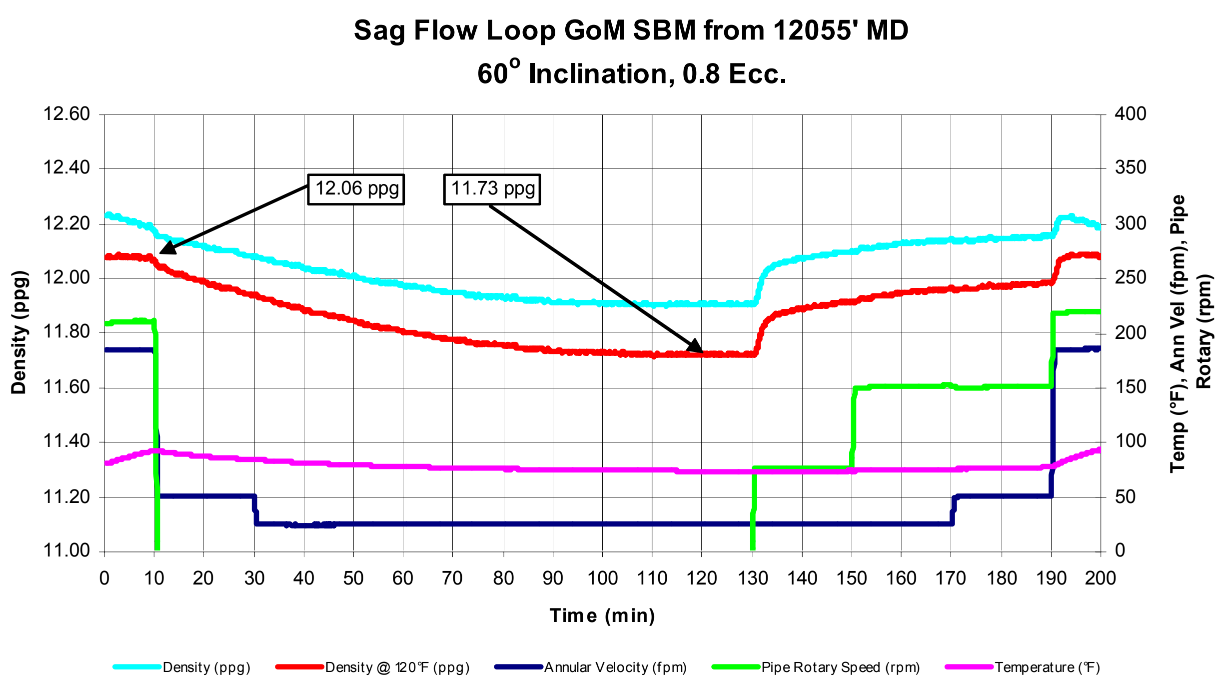

Fig. 12 – Sample results from the sag flow loop.

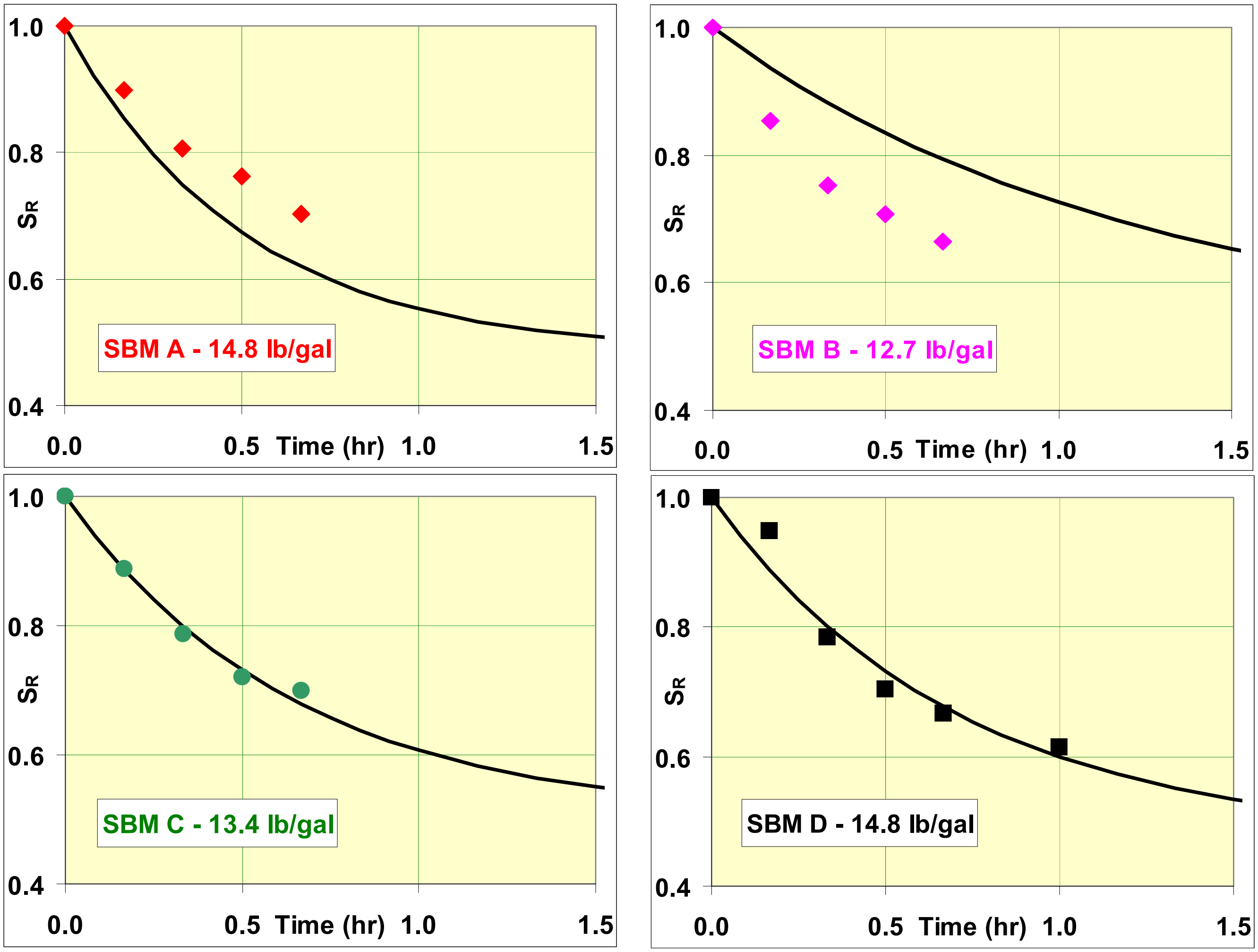

Fig. 12 – Comparison of VST Shoe and sag flow loop results using the modified sag register concept for four of the SBMs listed in Table 2.

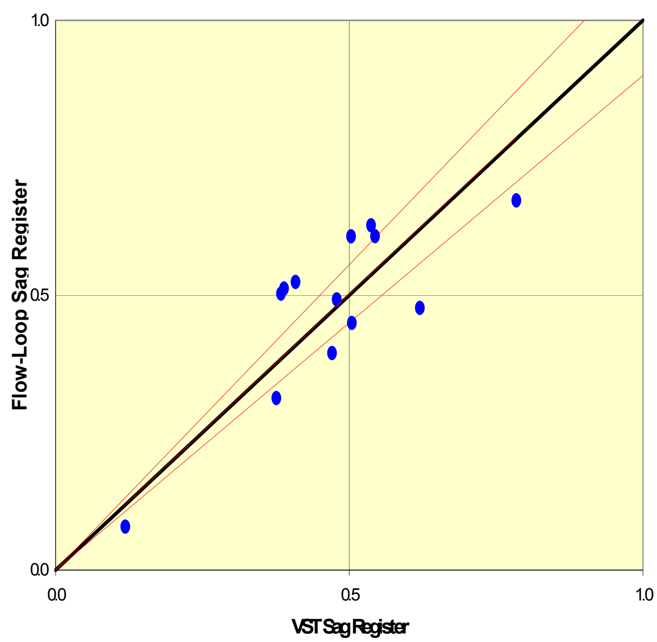

Fig. 13 – Correlation chart of VST Shoe and sag flow loop using the modified sag register concept.