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What Happens to Invert Mud Left Behind the Casing?

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Abstract

With increasing focus on well design to improve well integrity for offshore operations, one frequently asked question is about the density variation of the fluid left behind casing over a long period of time. The main concern is that the fluid may segregate over time resulting in drastic density changes between the top and bottom of the fluid column that can lead to casing failures.

In order to better understand the behavior of drilling fluid left behind casing over time, long-term static aging tests of up to one year were set up for different temperatures and hole angles. Treatment with various products to improve long-term fluid stability was also included in the test matrix to suggest possible solutions. After aging, the test samples were measured for syneresis, static shear strength and density stratification.

Normal drilling fluids showed reasonable stability over a short period of time, but syneresis and density stratification were observed over longer periods, and the severity of the syneresis and mud-weight stratification worsened as aging time increased. Treatment with certain products to change the rheology profile showed that the long-term stability of invert fluids could be improved appreciably. This paper describes the test methods and designs used and discusses test results generated under various conditions.

Introduction

Invert drilling fluids have long been used in drilling operations and often are intentionally or unintentionally left behind casings between intervals and during completion operations. Some of the fluids could be left behind for many years before they need to be circulated out for workover operations. A typical example is the use of oil-based packer fluids to provide long-term pressure isolation between the sealing equipment and the formation pressure. The fluid is designed to be non-corrosive and thermally stable to resist viscosity changes over long periods of time. However, sometimes invert drilling fluids without packer-fluid-like properties are used for temporary well abandonment that is intended to last a shorter period of time.

With recent offshore concerns, the long-term stability of invert drilling fluids under such applications has become a subject of various discussions. The main concern is the long-term suspension of weighting material under static conditions and particularly at different well angles. This concern partially arises from the barite sag tendency of invert drilling fluids when hole angles reaches a certain point and the fluid is circulated at reduced flow rates or the fluid cannot develop gel structure due to operational interferences.[1,2] In these cases, the barite tends to settle to the low side of the hole forming a barite layer or bed and may eventually change the distribution of hydrostatic pressures along the borehole. In contrast, under a completely static condition, the fluid can develop a good gel structure for suspension of weighting material.

However, under long-term conditions, the emulsion along with weighting material can start aggregating and slowly move towards the bottom of the fluid column. This slow movement may break the established gel structure and promote further barite sag. The consequence of the settling of weighting materials in a fluid left behind the casing may have a profound impact on well integrity.

The objective of this paper is to share some test results of long-term static aging of invert drilling fluids under different conditions. These results, however, by no means provide a complete picture of the complex issue nor a definitive answer to the title question of this article. Presentation of the data hopefully will improve understanding of the fluid-related issues and help promote finding effective solutions.

Method of Study

Several test methods have been used to evaluate the fluid stability in attempts to find out what could happen if the invert fluid is left behind casing for long periods of time. The methods and procedures used for generating data for this paper are described below.

I. Static Aging Method

The static aging test was used to evaluate the barite settling tendency with the fluid sample in vertical position, although a stand with adjustable angles can be used to set up the test at any desired angle. This test can be run at various temperatures from 40 to 300°F. To ensure fluid consistency, a large batch of stock fluid sufficient for testing, usually one to two gallons, was made and immediately split into desired aliquots for future use. This avoided impact of the long pre-testing storage time and un-representative sampling of stock fluid in the testing.

The test fluid samples were sheared on a high speed mixer and subsequently heat aged at 150-200°F to stabilize the test fluid before static aging test. Initial rheological property and electrical stability measurements were carried out to generate baselines for future comparisons. Enough of the fluid samples were prepared so they could be taken out after different time intervals at different temperatures. A set of control samples was always run with each set of test samples for comparison. The static aged samples were then cooled down to room temperature before testing for different properties, including static shear strength, syneresis and mud-weight stratification measurements. The term syneresis is referred to the base fluid breakout observed after the aging. The procedures used to obtain these measurements are described in the following steps:

a. A shearometer tube is placed on the mud sample in a vertical position. A gradual increase in load is placed on the tube until 95% of the length of the tube is driven into the mud column. The shear strength is then determined from a nomograph that came with the shearometer.
b. The shearometer tube is removed from the mud column and the next step can be conducted. However, before any fluid is removed, the mud column is arbitrarily divided into five layers from top to bottom for sampling. If the starting volume is 350 mL and stays the same after aging, then approximately 70 mL will be taken out from each layer.
c. A syringe is first used to draw out the base fluid from the top of the column, if there is any. The volume of base fluid in mL is recorded and used as an indicator to estimate the extent of syneresis. The free base fluid is set aside to be combined with the mud in the next step.
d. If the free base fluid content is less than 70 mL, then enough mud is either siphoned out or scooped out from the top and added to the free base fluid to make a total volume of 70 mL as close as possible.
e. The mixture of base fluid and mud is thoroughly blended on a mixer to homogenize the mixture. A pyconometer then is used to determine the average density of the first layer of the test fluid.
f. This procedure is continued for the subsequent layers until the average density of each of the five layers is thus measured.
g. If the free base fluid content is more than 70 mL, then 70 mL of free base fluid is set aside as the first layer and the average density is measured accordingly. The remaining fluid is counted as part of the second layer and will be mixed with mud from the second layer.
h. The distribution of mud weight in five layers should depict the syneresis and barite settling trend from top to bottom of the mud column. This variation of mud weight is referred to as the mud-weight stratification.

After these measurements, the five subsamples were combined and homogenized for electrical stability and rheology measurements.

II. Static Aging at Room Temperature and Angles

Boycott settling[1] at different angles was measured using a specially developed slant-tube apparatus shown in Figure 1. The set up consisted of 0.682-in**.** I.D. glass tubes positioned at 0, 15, 30, 45, 60, 75 and 90° from vertical. Three tubes were positioned at each of the seven angles. A linear measuring scale was placed along each tube. Each tube had two sampling taps mounted at the bottom diametrically opposed at the high and low sides. The density gradient of each tube was measured by vacuuming out layers of fluid using separate cannulae of defined lengths.

Figure 1. Slant-tube ambient static aging apparatus showing three tubes at each angle, linear scales along each tube and bottom sampling taps.

Measurements from the device include the syneresis volume, density gradient and sample port plugging potential. The experimental procedure consisted of the following steps:

a. Obtain consistent mud sample of sufficient volume to fill all tubes
b. Fill tubes using a cannula which reaches to tube bottom. Ensure no air is trapped along the tube. Cap tube to reduce evaporative effects.
c. Periodically (daily at first) record observations consisting of length of clarified zone and any other phenomenon of note.
d. Measure the density gradient of one tube at each angle for three time periods.

III. Centrifuge Method

This method was evaluated as a possible method to expedite the process of syneresis and mud-weight stratification using a high-speed centrifuge. For each test sample, about 50 mL of fluid was used to fill the centrifuge tube. Test fluids were centrifuged at room temperature and at 150°F for 15 and 60 minutes at 625 and 2,500 rpm. After centrifuging, the volume and weight of supernatant were determined. This information was then used to calculate the mud weight of the supernatant (top layer) and the remaining fluid (bottom layer).

Results and Discussion

I. Static Aging Method

Figure 2a shows a plot of the volume % of syneresis from a 16-lb/gal synthetic-based mud (SBM) after being statically aged at 220°F for up to 4 months at a vertical angle. The % of syneresis is defined as the 100 x Free Base Fluid Volume / Mud Sample Volume. The SBM showed rapid syneresis in the first 30 days and started to level off afterwards. The syneresis is a result of settling of emulsion droplets along with weighting material, and this process seems to have stabilized after 30 days.

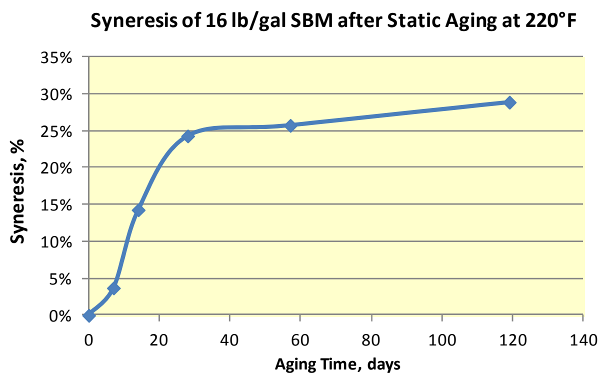

Figure 2a – Syneresis of a 16-lb/gal SBM after static aging at 220°F for 120 days in vertical position. The free base fluid breakout leveled off after 30 days suggesting the process had stabilized.

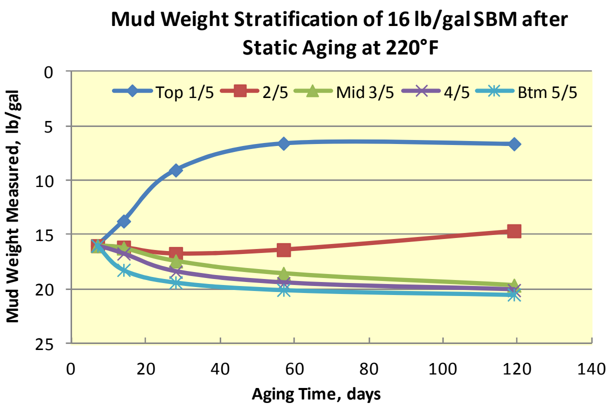

Figure 2b – Mud-weight stratification of a 16-lb/gal SBM after static aging at 220°F for up to 120 days at vertical position. The mud weights from top to bottom leveled off after 30 days.

As expected from syneresis data, the mud-weight stratification measurements showed a rapid mud weight increase as static aging time increased (Figure 2b). The lowest and highest mud weights observed leveled off at about 6.7 and 20.5 lb/gal, respectively, after 30-60 days. No major changes in mud weight were observed afterwards. This suggests that equilibrium could have been reached, and a further change in density was unlikely to occur.

By knowing the amount of free base fluid generated, a simple back calculation indicated that the remaining fluid had an average density of 20 lb/gal with a synthetic/water ratio (SWR) of 62/38. This was a significant change from the original 16-lb/gal mud with 80/20 SWR. This suggests that the final 62/28 SWR could be the critical SWR required to keep the 20-lb/gal mud stable at 220°F.

However, this might not be true in the field where conditions are different, including well angle, mud weight temperature, downhole pressure, and fluid properties. It is possible that the emulsion stability and suspension quality play significant roles in determining the minimum and maximum mud weights observed. With poor emulsion stability and suspension quality, the maximum mud weight observed could be higher as the packing of barite would be tighter and the stratification would be more pronounced.

In a slightly different test, a 13.5-lb/gal SBM was treated with a gelling agent then statically aged for 330 days at 140°F in a vertical position. A control without the treatment was aged for 30 days for comparison. Figure 3a shows the untreated SBM had 20% syneresis after 30 days, while the treated fluid had less than 5% syneresis after 330 days.

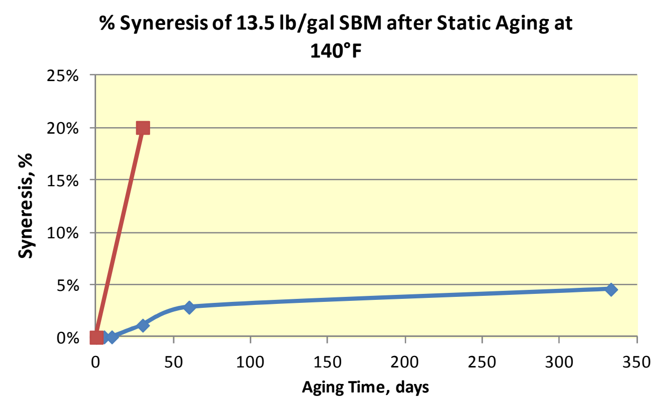

Figure 3a – Syneresis of a 13.5-lb/gal SBM after static aging at 140°F for 330 days. The syneresis of untreated SBM (red line) reached 20% by volume after 30 days, while the gelling-agent treated SBM (blue line) was less than 5% at the completion of the test.

Mud-weight stratification of the treated SBM after 330 days indicated some settling of emulsion droplets and barite still occurred, but at a much lower rate than the untreated SBM (Figure 3b). This suggests the development of a strong gel structure was critical for long-term suspension of weighting agent, and additives that help to develop gel structure can be used to minimize syneresis and mud-weight stratification.

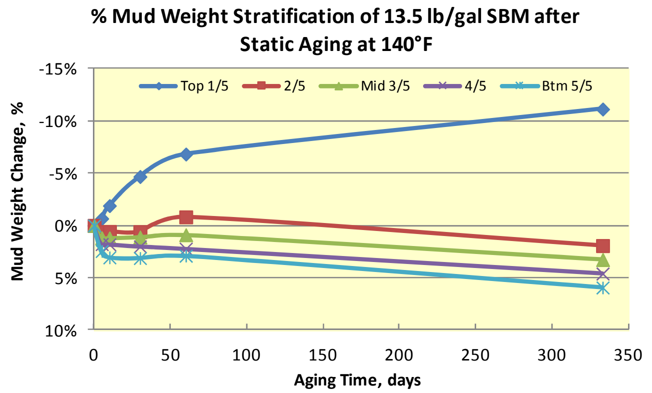

Figure 3b – Mud-weight stratification of a 13.5-lb/gal SBM after static aging for 330 days at 140°F in the presence of a gelling agent, which reduced settling rate of barite and emulsion.

To determine the effect of temperature, another SBM was treated with the gelling agent and statically aged at temperatures varying from 40 to 150°F in a vertical position. Figure 4 shows syneresis of a gelling-agent-treated SBM at 40, 75, 120 and 150°F. The settling rate of emulsion and barite appeared to decrease proportionally to decreasing temperature after 60 days. This was likely related to the viscosity increase of SBM with decreasing temperature. At 150°F, however, the rate was significantly reduced due to activation of the gelling agent at this temperature.

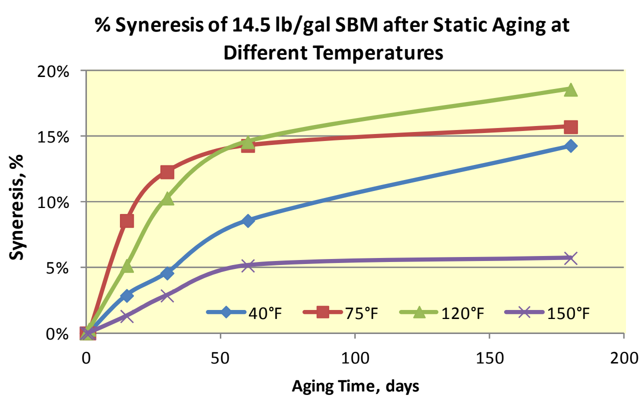

Figure 4 – Syneresis of a 14.5-lb/gal SBM after static aging at different temperatures with a gelling agent. The syneresis varied from 6 to 18% and appeared to be temperature dependent in the temperature range from 40 to 120°F.

The effect of temperature on mud-weight stratification is illustrated in Figures 5a-5c, which shows the percentage mud weight changes in three different layers as a function of temperature. The mud weight measurements of the top layer showed that at temperatures below 120°F, settling in the top layer was still significant even with the gelling agent.

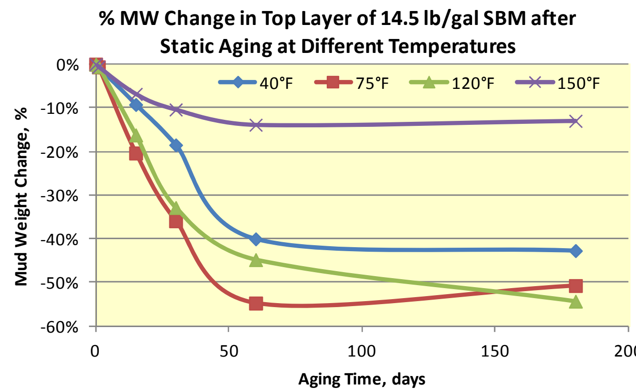

Figure 5a – At temperatures below 120°F, mud weight drops in the top layer were still significant even with gelling agent due to non-activation of the gelling agent.

The mud weight changes in the middle and bottom layers of the fluid column showed a slow down after 60 days at 120 and 150°F, but the trend was still going up at lower temperatures. This is again probably related to the non-activation of the gelling agent at the lower temperatures.

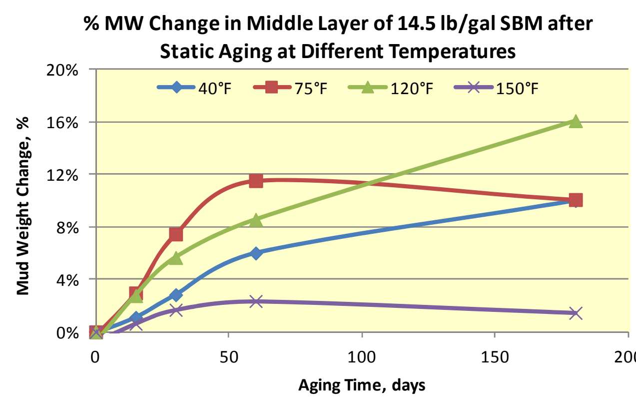

Figure 5b – At temperatures above 120°F, mud weight increases in the middle layer leveled off as a result of gelling agent activation, but below 120°F the mud weight increases were still going on.

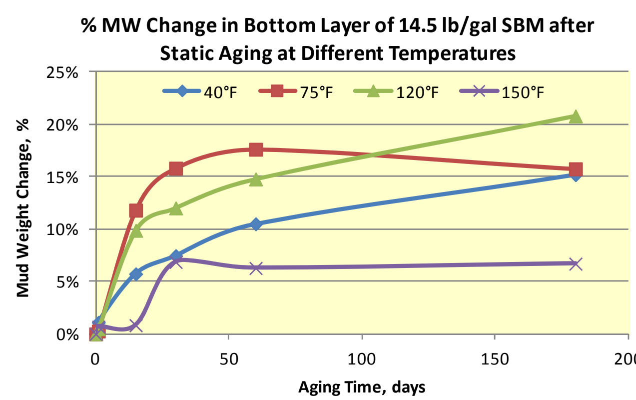

Figure 5c – At temperatures above 120°F, mud weight increases in the middle layer leveled off as a result of gelling agent activation, but below 120°F the mud weight increases were still going on.

II. Static Aging at Room Temperature and Angles

Figure 6 shows a plot of the percent volume syneresis generated from a 13.0-lb/gal lab-prepared SBM as a function of time and angle.

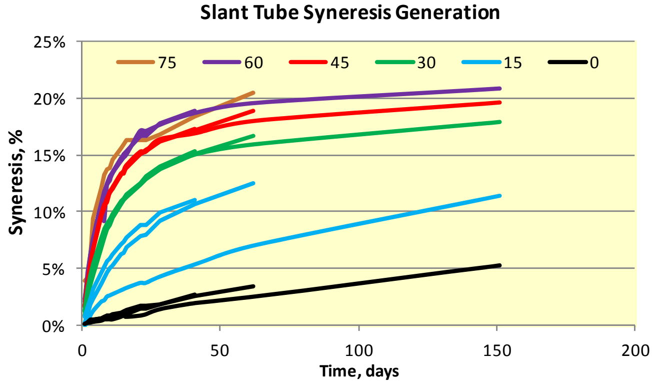

Figure 6 – . Syneresis % volume generated is a function of time and angle. Three curves at each angle represent each of the individual tubes.

As in the previous static aging experiment, syneresis generation was rapid at start, tapered off after 30 to 40 days, and then appeared to be asymptotic. It is interesting to note the differences in the syneresis generation among tubes at the same angle. Some differences could be related to parallax, such as those seen at 0, 30, 45, and 60°; however, the 15° tube set showed a clear syneresis volume generation difference. The inconsistency was verified in Fig. 1 by the right-side 15° tube showing less syneresis than the two 15° tubes to the left.

Observations from the 75° tube (Figure 7) indicated settling was hindered by high angle. Syneresis was generated along the entire tube length and idealized as migrating upward as shown by middle tube in Figure 7. The upper and lower tube shows the base fluid collecting in several localized zones, some which show totally separation of whole mud from the base fluid. The data indicated localized heavy and light zones could occur at high angles.

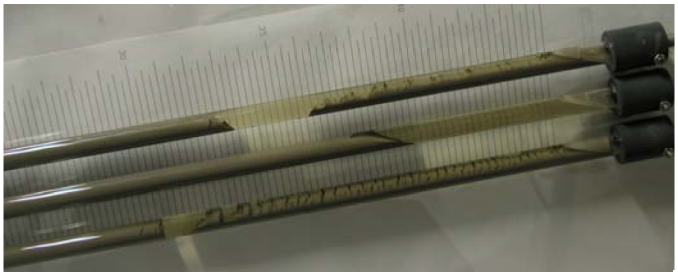

Figure 7 – Slant-tube ambient static aging. Day 18, the high 75° angle impeded movement of settled solids in the tubes. Behavior clearly was not consistent among the tubes.

Measured density gradient as shown in Figure 8 followed the percentage volume generation as function of distance from the bottom. High-quality density data were difficult to obtain as the cannulae disturbed the fluid and could not pick up the bed of settled barite.

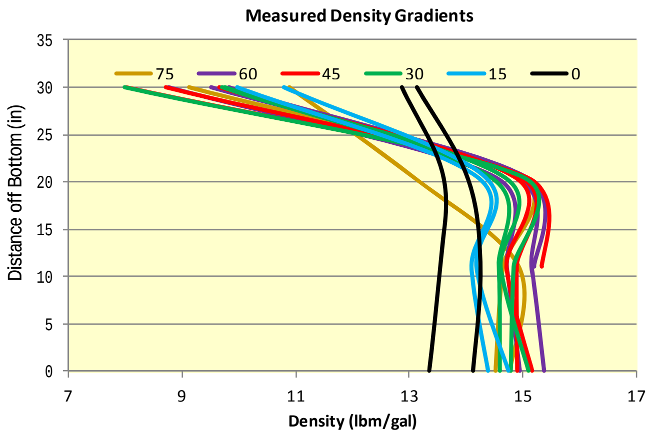

Figure 8 – Density gradient of all tubes at completion of test. Original mud density was 13.0-lb/gal.

III. Centrifugal Method

Density stratification measurements using a centrifuge showed that the minimum and maximum mud weights obtained were not significantly affected by the centrifuge speed and time (Figure 9). Although the measured mud weight values were slightly higher than those measured by the static aging method, both test methods seem to generate similar results for the 16-lb/gal SBM. A comparison showed centrifuging 15 minutes at 2,500 rpm was approximately equivalent to 60 days under static conditions for the top layer fluid, but closer to 120 days for the bottom layer. This suggests that the centrifuge method may be useful to expedite long-term simulation; however, more data will be needed to correlate and validate the effect of speed and test time. Temperature did not significantly affect the results.

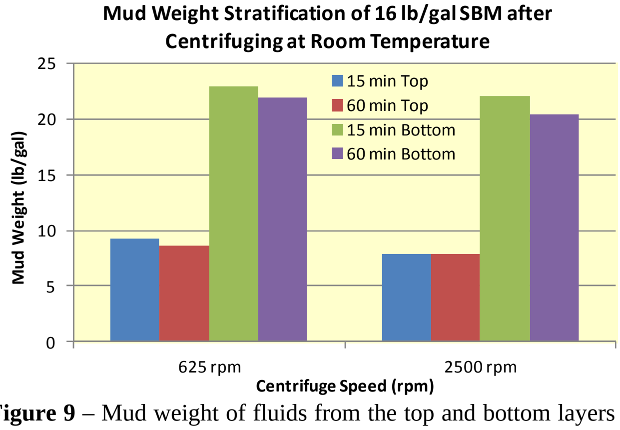

Figure 9 – Mud weight of fluids from the top and bottom layers of a 16-lb/gal SBM after centrifuging.

Conclusions

1. Long-term static aging at temperature in the laboratory can be used to evaluate syneresis and mud-weight stratification of invert drilling fluids intended to be left behind casing.
2. Syneresis and mud-weight stratification are affected by temperature and gel structure development. Tests

showed that without gelling agent treatment, fluids reached equilibrium after 30-60 days of aging. The top layer would reach a minimal density similar to the base fluid density, while the bottom layer would reach a maximum density determined in part by the degree of syneresis.
3. Fluid viscosity and development of strong gel structures also can impact the rate of syneresis and mud-weight stratification. Gelling agent treatment can delay and stabilize the process, thereby avoiding the extra pressure or stress on the casing that may arise from syneresis and mud-weight stratification.
4. The centrifuge method has potential as a means to simulate long-term testing as results were similar to those observed with static aging. Further study is needed to validate this connection.

Acknowledgments

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Nomenclature

SBM = *Synthetic-Based Mud*
SWR = *Synthetic/Water Ratio*

References

1. Zamora, Mario. “Mechanisms, Measurement and Mitigation of Barite Sag.” Offshore Mediterranean Conference and Exhibition, Ravenna, Italy, March 25-27, 2009.
2. Schlemmer, R.P., Lee, J.L., Friedheim, J.E. and Growcock, F.B. “A Comparison of Sag Measurement Methods and Implications for Additive Performance and Selection.” AADE03-NTCE-57, 2003.