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Drilling Fluid Maintenance during Continuous Wellbore Strengthening Treatment

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Abstract

Wellbore strengthening (WS) can be accomplished with treatment of the whole drilling fluid with particulates that are designed to plug and seal incipient fractures in the wellbore. Typically these particulates are much larger than the bridging particles normally used in reservoir drilling fluids for controlling seepage losses. Solids-control equipment is usually configured to remove all particulates in the drilling fluid, including these large particulates. Because the WS technique requires maintenance of particle size and concentration at a constant level, it is difficult to maintain the required concentrations of these large particulates. Furthermore, the particulates degrade as they make their way through the circulating system, leading to a build-up of fine low-gravity solids (LGS) that creates difficulties with maintenance of drilling fluid properties. Thus, drilling fluid maintenance during a whole-mud WS treatment is both complex and critical.

Maintenance of the particulate treatment in the drilling fluid during continuous WS treatment is often carried out either through bypassing the solids-control equipment – if the WS treatment is applied to a very short section – or using the primary shakers to remove the drilled cuttings. In either case, the concentration of fine LGS can build up rapidly. Using drilling fluids that are very tolerant to LGS can help to make these methods successful. Employing highly concentrated slurries of wellbore strengthening materials (WSM) to prepare fresh whole mud at the rig can also be very helpful. An alternative strategy employs several devices to remove both the drilled cuttings and the fines while returning the WSM to the active mud system. Recently a device was introduced to consolidate the functions of these many devices into a single unit. The results from three field trials suggest that this triple-deck shaker has promise as a WSM recovery device.

Introduction

Wellbores can be strengthened or stabilized through the use of particulate wellbore strengthening materials (WSM) that can invade and seal incipient fractures, thereby preserving the increased circumferential (hoop) stress that was required to open the fractures and/or isolating the fracture tips from the fluid and pressure in the wellbore. This technique generally is most successful when the whole drilling fluid is treated with the correct type, concentration and size distribution of WSM, so that the incipient fractures are able to admit the particles to plug and seal the fractures before they propagate very far. However, whole mud treatment, especially with WSM that may approach the size of cuttings, is considered risky to downhole tools. Furthermore, the quantities of WSM that are required are on the same order or even larger than those typically used as bridging materials in reservoir drilling fluids. Exacerbating this is comminution, which occurs at the bit and at impact points along the drilling column, grinding of the particulates results in loss of larger particulates and simultaneous creation of fine LGS in the mud, which creates difficulties for the control of drilling fluid properties and requires additional treatment with WSM.

Maintenance of the fluid during continuous WS treatment is generally carried out through a combination of dilution and removal of drilled solids, just as in normal drilling operations. However, maintenance of the concentration and size distribution of WSM is much more difficult and can become quite expensive unless certain measures are taken. These include using drilling fluids that are very tolerant to LGS,[1] using a highly concentrated slurry of WSM for the treatment itself, and/or using WSM recovery techniques to remove fine LGS.

In the past, when it was necessary to maintain high concentrations of fibrous and/or mixed lost circulation materials (LCM) in the whole mud, dedicated shakers were used to recover some of the LCM, which were then diverted back into the active mud system.[2] With the advent of whole mud wellbore strengthening treatments, a similar need has arisen. The WSM that are typically used in these applications are large granular LCM, and the requirements for recovery efficiency are greater. Nevertheless, it has been possible to recover the WSM and clean the drilling fluid of fines economically by configuring available solids control devices in an appropriate manner.[3,4] An even more promising technique is the use of a single shaker designed and configured not only to recover WSM efficiently but also remove drilled cuttings and fines. This paper discusses the results of three field trials that were carried out to investigate the performance of such a shaker.

The Triple-Deck Shaker

The Triple-Deck Shaker (TDS) is designed to recover WSM while removing drilled cuttings and fines so as to maintain desired mud properties. This type of shaker is engineered to provide efficient solids separation using a top scalping deck and two primary lower decks (middle and bottom) to be used in series or in parallel configuration. The series configuration allows solids to be progressively and preferentially screened, thereby simultaneously recovering WSM and cleaning the drilling fluid of undesirable solids as shown in **Fig. 1**. A photograph of the unit is shown in **Fig. 2**. The drilling fluid returned from a well is processed through a top scalping deck to remove the cuttings, a middle deck to recover WSM that is returned back to the active fluid system, and a bottom deck to discard the LGS and degraded WSM, which are detrimental to mud performance This preferential separation results in less overall product consumption, less waste and reduced cost.

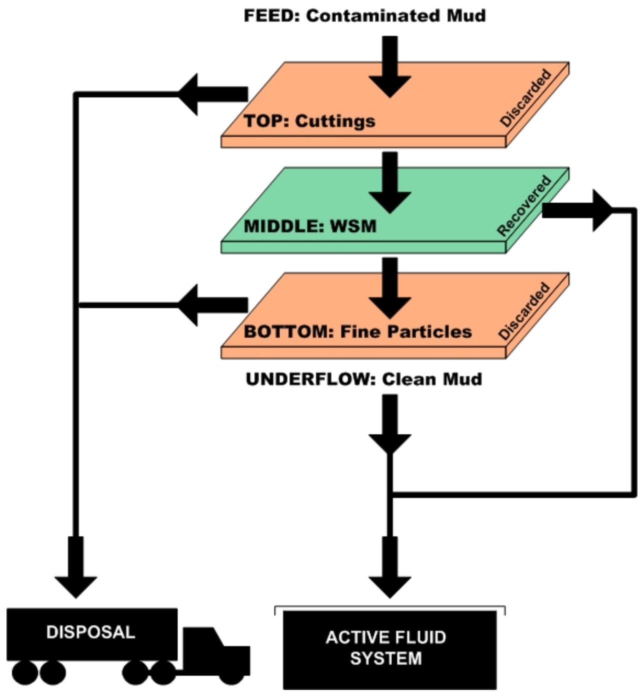

Fig. 1: Fluid process distribution from Triple-Deck Shaker.

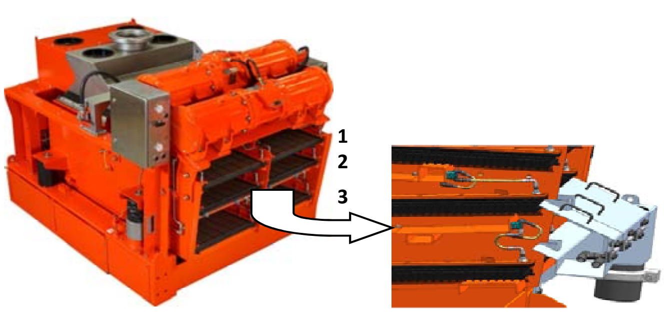

Fig. 2: Triple-Deck Shaker with stationary trough for return of WSM from Deck 2 to active system.

Field Trial 1

In Field Trial 1, the 7.2-in. interval was drilled with a 1.74-SG (14.5-lb/gal) diesel oil invert emulsion mud from 6315 to 6720-m (20,200 to 21,500-ft) TVD. The ECD was expected to be 1.75 SG (14.6 lb/gal) throughout the interval. The sand/sandstone formations had a fracture gradient that was expected to fall below this wellbore pressure to different extents along the 1,300-ft interval; consequently, the wellbore strengthening program was implemented as five consecutive but separate applications. Maximum fracture width in the five sections was calculated to vary from 370 to 810 µm. The WSM blend used to treat the full mud system varied in total concentration from 57 to 100 kg/m^3 (20 to 35 lb/bbl), but in all cases was composed of $CaCO_3$ (D_{50} ranging from 250 to 700 µm) and a carbon-based material (CBM). As a result, the entire interval was drilled with essentially no downhole losses.

Performance of the Triple-Deck Shaker

The TDS trial was conducted using a +1 degree shaker angle and five different screen configurations (at various times), as shown in **Table 1**.

Table 1: Screen Configurations Tested in Field Trial #1

#	Top Deck	Middle Deck		Bottom Deck	
1	10x20	165HC	API 100	200XR	API 120
2	10x20	165HC	API 100	230XR	API 140
3	10x20	165HC	API 100	270XR	API 170
4	10x20	200XR	API 120	270XR	API 170
5	10x20	200XR	API 120	230XR	API 140

Configurations #1 and #2 appeared to give the best combination of WSM recovery and fluid cleanliness. Testing of the TDS took place at a TVD of about 6,560 m (21,540 ft), using a flow rate of 62 m^3/hr (275 gal/min) and an average rate of penetration of 0.6 m/hr (2 ft/hr). After TDS treatment, density decreased from 1.77 to 1.71 SG (14.74 to 14.26 lb/gal), as did total solids content, from 35.36 to 31.74 vol%.

On average, it was determined that 57% of the total mass treated was recovered by the middle deck, 36% was returned to the underflow, and 7% of the total treated mass was discarded by the top and bottom screen decks.

WSM concentration and size distribution were measured using a stacked wet sieve analysis technique fitted with sieves having openings ranging between 75 and 710 µm. These results showed that particles less than 75 µm were reduced from 220 kg/m^3 (77 lb/bbl) in the feed stream of the TDS to 40 kg/m^3 (14 lb/bbl) in the underflow, which was returned to the active system.

Although both the middle and bottom decks contained a mixture of solids, it was determined through X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF) that most of the material recovered in the middle deck was WSM in a desirable size range, as shown in Table 2. The material discarded in the bottom deck was mainly degraded WSM, large barite particles, and LGS. Other materials encountered were dolomite, hematite, and pyrite.

Table 2: Composition of Material Recovered from the Middle and Bottom Decks of the TDS

Material	Middle Deck (lb/min)	Bottom Deck (lb/min)
WSM	38.1	3.0
Quartz	2.9	0.4
Barite	14.9	2.8
Others	3.8	0.3

Comparing the ratio of the WSM recovered from the middle deck and the WSM discarded from the bottom deck leads to an estimate of 93% for the volume of WSM recovered and returned back to the mud system.

Previously, the concentration of LGS in the mud typically reached 285 kg/m^3 (100 lb/bbl), because the only solids control used was the top deck of a traditional shaker. This only removed essentially intact cuttings, so the fluid system eventually had to be heavily diluted or discarded due to excessive rheology and reductions in drilling efficiency. After installing the TDS, the LGS concentration dropped to about 110 kg/m^3 (40 lb/bbl), and the fluid could continue to be used.

Field Trial 2

Wellbore strengthening was carried out from 19,000 to 19,700-ft TVD in the 8½-in. interval of this well. The drilling fluid again was a diesel invert emulsion mud. A variety of sands/sandstones were at risk of lost circulation. The mud weight throughout the interval was maintained at 1.82 SG (15.2 lb/gal), and the drilling ECD was expected to rise to 1.87 SG (15.6 lb/gal). Because of the wildly varying fracture gradient, the maximum induced fracture width generated while drilling was expected to range from 150 to 775 µm. Consequently, the required WSM blend also varied considerably. In all cases, only CBM and $CaCO_3$ were used, but blends of the latter included material with D_{50} as low as 40 µm and as high as 700 µm. The total WSM concentration varied up to 100 kg/m^3 (35 lb/bbl). No downhole losses were observed while drilling the interval.

Performance of the Triple-Deck Shaker

The TDS was tested during the drilling of a 1532-ft section of the 8½-in. interval, which generated 17 m^3 (107 bbl) of cuttings. Before adding WSM, the drilling fluid tested at 10-11 vol% LGS. During the TDS test, an average of 105-kg/m^3 (37-lb/bbl) WSM was added, which increased the LGS concentration to 14.5 vol%. Return flow was divided between a primary shaker (10-mesh scalping screen) and the TDS, which was dressed with 10/165/200-mesh screens on the top/middle/bottom decks, respectively.

From the Flask method for density of cuttings and stacked wet sieve analysis, it was estimated that the scalping shaker and the top deck of the TDS removed 5.6 m^3 (35 bbl) of cuttings, while 15 m^3 (93 bbl) of dried solids were captured and discarded from the bottom deck of the TDS. XRD analysis indicated that 5 m^3 (31 bbl) of this was drilled cuttings fines and the balance was fine $CaCO_3$, evidently formed by degradation of the WSM at the bit and various impact points in the annulus. The vast majority of the remaining $CaCO_3$ and CBM was captured by the middle deck, which was then returned to the active mud system.

During the sixteen-day trial of the TDS, an economic analysis was performed calculating the deployment expense comprised by installation, shaker rental and screens and comparing it to the delivered benefit of recovered WSM and avoiding standard dilution due to drilled cuttings fines and comminuted WSM particles. The volume of dilution that was avoided was estimated to be 80 to 100 m^3 (500 to 600 bbl) for each of those types of solids.

Using field measurements and analytical chemistry methods, it was possible to quantify the amount of solids processed, and qualify their size and type. For this particular exercise the main focus was to determine the contribution of the shaker by eliminating undesired solids detrimental to mud properties and thus the net benefit for the operator.

For this field trial, the deployment cost (installation, rental, and screens) was approximately 47% of the delivered benefit, meaning that the TDS expenditure was less than half of the benefit of having it installed.

Field Trial 3

The 5⅞-in. interval of this well was drilled with a water-based mud. During earlier operations in this region, severe and sometimes total losses were experienced while drilling this depleted, permeable formation. Based on these experiences, it was decided to treat the drilling fluid with large particulates to strengthen the formation and minimize losses.

The previous interval had been drilled with a mud weight of 1.90 SG (15.85 lb/gal), and casing was set at 4688-m (15000-ft) TVD. The subsequent 365-m (1170-ft) 5⅞-in. interval needed to be drilled with a minimum mud weight of 1.44 SG (12.01 lb/gal) to minimize the risk of wellbore collapse. These formations had an initial average pore pressure of 654 bar (9614 psi).

When entering the target formation, the anticipated fracture gradient was 600 bar (8820 psi), which is equivalent to a mud weight of 1.40 SG (11.68 lb/gal). The pore pressure in this formation varied between 250 and 370 bar (3675-5439 psi). As the mud weight exceeded the fracture gradient at this depth, fractures were expected to appear even under static conditions. During drilling, the ECD was in the range 1.50-1.55 SG (12.51-12.93 lb/gal).

A line-crack elastic model was used to calculate how large the fracture openings in the formation might become. This model incorporates rock properties, including Young's Modulus and Poisson's Ratio; rock stress parameters, including stress anisotropy and the minimum and maximum horizontal stresses; and geometric properties, including azimuth, hole size and deviation. These input parameters yielded calculated maximum fracture widths ranging from 900 to 1700 µm. Based on experimental data from extensive fracture sealing tests, the program also generated the particles sizes and the concentrations of WSM needed to plug and seal those fractures before they propagated uncontrollably and led to lost circulation.

Ten meters above the target formation, 215 kg/m³ (75 lb/bbl) of the designed WSM blend was introduced into the whole drilling fluid. This WSM contained 52-kg/m³ (18-lb/bbl) CBM and 163-kg/m³ (57-lb/bbl) $CaCO_3$, whose nominal particle size distributions (PSD) are shown in **Table 3**.

Table 3: Nominal PSD of WSM			
Product	**D_{10} (µm)**	**D_{50} (µm)**	**D_{90} (µm)**
CBM	35	150	880
$CaCO_3$	680	1060	1610

Drilling continued with a rate of penetration (ROP) of 0.5-1.0 m/hr (1.6 to 3.2 ft/hr). No losses were observed when entering the target formation. Over a 40-hr period of drilling, only 6.5 m³ (40 bbl) of downhole losses were observed, which were attributed to seepage (matrix permeability) losses.

When entering the formation below the target formation, the WSM was screened out of the rig shakers, using 50-mesh screens (D_{100} = 320 µm). All the $CaCO_3$ was screened out and a theoretical concentration of 7.5-kg/m³ (2.6-lb/bbl) CBM remained in the drilling fluid system. The lower part of the interval was successfully drilled to TD without further additions of WSM or further losses.

To test the capability and efficiency of the TDS to recover WSM, between 20-50% of the return flow was routed over the TDS. The remaining flow bypassed the solids-control equipment.

The return fluid was monitored for plugging ability using a Production Screen Tester (PST) with a slot width of 1500 µm, close to the upper end of the expected maximum fracture width. While drilling the target interval, total fluid loss through the PST varied between 10 and 300 mL (**Fig. 3**), averaging 92 mL. Anything less than 100 mL was considered to be a tight, stable bridge. A photograph of the PST slot after a satisfactory test is shown in **Fig. 4**.

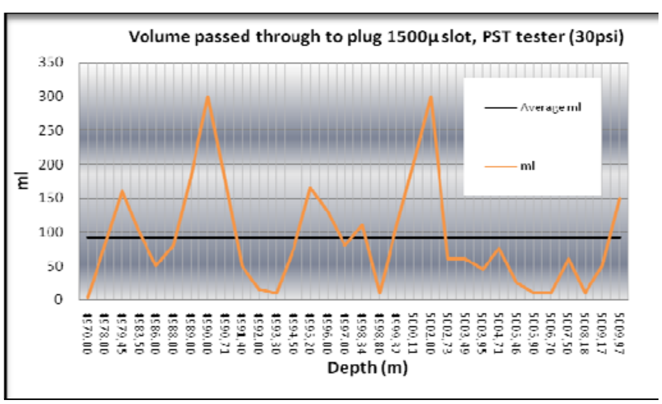

Fig. 3: Slot test results vs depth (1500-µm slot).

Fig. 4: Photograph of sealed 1500-µm slot.

During drilling, the WSM degraded and the entire particle-size distribution gradually shifted to smaller sized particles. To maintain good plugging capability and replace degraded WSM, continuous addition of $CaCO_3$ was necessary, which averaged 250 kg (550 lb) per circulation. Furthermore, whenever an increase in fluid loss was observed in the PST, additional coarse particles were added to the system; re-testing of the additionally treated fluid after it had returned to the surface 4 hr later demonstrated its improved plugging capability on the PST.

Performance of the Triple-Deck Shaker

The initial screen set-up was with 10-mesh screens on top deck (cuttings discharge), 165-mesh on middle deck (WSM recovery deck) and 200-mesh on the lower deck (fines discharge). **Table 4** shows the cut points of these screens.

Table 4: Shaker Screen Cut Points		
Mesh Designation	**Mesh** *API RP 13 C*	**Max Opening (µm)** *API RP 13C*
XS 10	API 10	2030
WMD3XL165C	API 140	116
WMD3XL200C	API 140	100

Theoretical concentrations of the WSM passing through this screen configuration are shown in **Table 5**.

Table 5: Theoretical WSM Concentration in System				
Product	**Retained (%)**	**Retained (kg/m³)**	**Removed (%)**	**Removed (kg/m³)**
CBM	55	29	45	23
$CaCO_3$	95	155	5	8

The contribution of drilled cuttings to the total solid content and "wear and tear" of the screens could be disregarded, as the 40 m (128 ft) of formation drilled in the

5⅞-in. interval was only 0.7 m³ (4.3 bbl), in a total system volume of 250 m^3 (1540 bbl), i.e., 0.3 vol% LGS. Based on the above calculations, the maximum theoretical concentration of WSM was 184 kg/m³ (65 lb/bbl), as shown in **Table 5**.

Particle-size distributions were measured for the feed (the fluid returned from the well), the material recovered on each screen, and the fluid returned from the third deck. A Beckmann Coulter LS (laser scattering) 13320, which can measure particle sizes up to about 2000 µm, was used for these measurements.

Typical results (**Fig. 5)** show the WSM recovered from Deck 2 (and shunted through a trough back into the active system), the fine LGS recovered from Deck 3 (discarded), and the underflow from Deck 3 (returned to the active system). The separation among the three cuts is quite good.

The acceptable separation efficiency and large amount of WSM returned to the active drilling fluid system demonstrated the utility of the TDS for continuous wellbore strengthening treatments.

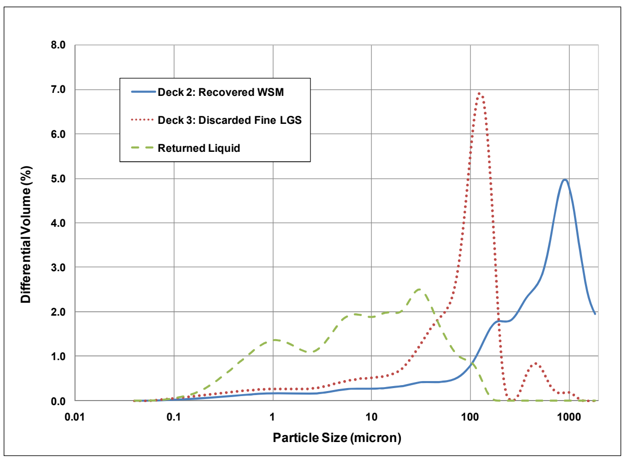

Fig. 5: Typical PSD of recovered WSM (Deck 2), discarded fine LGS (Deck 3) and returned fluid from TDS.

Conclusions

Three field trials of the Triple-Deck Shaker demonstrated the technical and economic benefits of this device for recovery of wellbore strengthening material (WSM).

- A significant fraction of un-degraded WSM was recovered and recycled to the active system. The screens used on the middle and bottom decks were primarily 165 and 200 mesh, respectively.
- The drilling fluid returned to the active system – the underflow from the TDS – was as clean as expected from using 200-mesh screens on primary shakers.
- Significantly less dilution of the mud with fresh drilling fluid was required.

Acknowledgments

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