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The Effect of Lost Circulation Material on Herschel-Bulkley Parameters

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ABSTRACT

To hinder loss of drilling fluids into downhole formations while drilling geothermal, CO_2 injection or petroleum wells, Lost Circulation Material (LCM) is added to the drilling fluids. These materials consist of many granular, fibrous, and flaky materials. The current article contains an assessment of the addition of fresh and worn granular and cellulose fibre based LCM on the viscous properties of drilling fluids. The viscosity is described as Herschel-Bulkley fluids using dimensionless shear rates. The viscosity data is combined with data on the LCM's ability to alter filtration loss.

FUNCTIONS OF DRILLING FLUIDS AND THEIR PERFORMANCE UNDER ACTUAL WELL CONDITIONS

Drilling fluid is one of the main components when drilling wells, and it has several important functions. One of the primary roles of drilling fluid is to control pore pressure and prevent leakage while also preventing the influx of formation water and gases into the wellbore. During drilling, the tools are subjected to high temperatures and pressures, and the drilling fluid helps to cool the tools and provide necessary lubrication to prevent overheating. As the drilling fluid flows through the drill bit nozzles, it is subjected to mechanical stress, high pressure, and high velocity, resulting in aeration, which occurs when the drilling fluid mixes with air or gas. The temperature in the well can also impact the drilling fluid through thermal degradation. Increased temperature in the formation can alter the chemical and physical composition of the drilling fluid, causing it to expand, increase pressure, reduce viscosity, or form foam, resulting in increased wear and tear on the drill bit and nozzles. To determine the behaviour of drilling fluid under actual well conditions, it is essential to test it at high temperatures and during circulation through nozzles, simulating the relevant well conditions. Hot-rolling is one method used to simulate thermal wear and tear. However, hot-rolling alone cannot provide information on wear and tear associated with circulation in the borehole. To address this limitation, Klungtvedt and Saasen[1] describes a method that involves hot-rolling with a threaded steel rod placed in the cells while rolling at 90 degrees for 16 hours. This new approach enables more comprehensive assessment of a drilling fluid's performance in borehole conditions. The results showed that mechanical degradation had a significant impact on the sealing ability of the drilling fluid.

To hinder loss of drilling fluid to a porous or a fractured formation, Lost Circulation Material (LCM) can be added to the drilling fluid. Calcium carbonate is one of the most commonly used additives as LCM and is easily available and cost-effective as it can be obtained both naturally and synthetically. This mineral is alkaline and increases the pH value when dissolved in water, which helps prevent corrosion of drilling tools and reduces the risk of formation damage. Calcium carbonate contributes to increasing the effective density of the drilling fluid, which helps maintain pressure in the formation and may increase oil and gas recovery. Another advantage of using calcium carbonate is improved formation water control. N-Dril-HT is a highly crosslinked starch and Dextrid-E is another modified starch commonly used in drilling fluids to control fluid loss. N-Dril-HT is a high-temperature resistant starch. Auracoat UF is a mixture of cellulose fibres used to hinder fluid loss and formation damage.

The addition of fibres to drilling fluids increases the viscosity of these fluids. Increased viscosity normally helps reduce fluid loss from the wellbore. Calcium carbonate is ideal for use as a LCM in low-permeability formations, as it can bridge off openings and effectively seal leaks. It is most effective in water-based circulating fluids but can also be used in low-pressure formations. Incorporating fibres into drilling fluids is beneficial in wells where the fluid properties need improvement, such as high-temperature or formation damage-prone wells, or where increased viscosity is needed to enhance carrying capacity.

MATERIALS AND EXPERIMENTAL PROCEDURES

In this article multiple tests were performed on a water-based drilling fluid with different LCM added. The recipes can be found in the Appendix. Following the recipes, all components were weighed on a Mettler Toledo scale. Once all components were added, the mixer speed is set to high speed and the fluid is mixed for 10 minutes. The mixture was then transferred into cells for hot-rolling. The cells are hot-rolled for 16 hours at 90 degrees Celsius. Subsequently, they are then cooled down to room temperature before being mixed again for 10 minutes at high speed. Finally, viscosity tests are conducted using an Ofite 800 viscometer.

Viscosity tests were performed in a viscometer with cup and bob geometry in accordance with oilfield standards[2,3]. To perform the test, the viscometer cup was filled with drilling fluid. This container was rotated at speeds of 600, 300, 200, 100, 60, 30, 6, and 3 rpm, corresponding to shear rates of 1022, 511, 340.7, 170.3, 102.2, 51.1, 10.2 and 5.11 1/s. All measurements were recorded after the values had stabilised. All tests were conducted in descending order of speed. After completing the viscosity tests, the gel strength of the fluid was measured by first setting the speed to 600 rpm and allowing it to stand for 15 seconds. The speed was then reduced to zero and the fluid was left to stand still for 10 seconds before the speed was set to 3 rpm and the highest reading was recorded. This process was repeated with a waiting time of 10 minutes before the viscometer was set to 3 rpm and the following peak measurement was recorded.

The experimental procedure involved placing the cell in a filter press under ambient conditions of temperature and pressure, with measurements recorded at 5-minute intervals over a 30-minute duration as per oilfield standards[2,3]. To accurately quantify fluid loss, a filter paper with a pore size of 2.2 μm was employed to conduct a fluid loss test on drilling fluids containing fibres of varying sizes. This particular pore size was deemed optimal efficient capture of drilling fluid particles and fibres, while allowing for unimpeded fluid flow to ensure precision in measurement. Utilisation of a filter paper with a thicker pore size could result in blockages and hence, inaccurate measurements of fluid loss.

THE HERSCHEL-BULKLEY MODEL

The Herschel-Bulkley model is the most widely used viscosity model for drilling fluids due to its ability to provide reasonably accurate predictions over a broad range of shear rates. This model incorporates both Power-law behaviour and yield stress as shown in Eq. 1.

$$\tau = \tau_0 + k(\gamma)^n \tag{1}$$

In Equation 1, the Herschel-Bulkley model is defined with three parameters: k, n, and τ_y, representing the consistency index, flow behaviour index and yield stress, respectively. However, using these parameters in comparing fluids can be challenging because the consistency index, k, is not directly related to viscosity but is dependent on the flow behaviour index, n, i.e., $k=k(n)$. To address this issue, Saasen and Ytrehus[4] developed a modified model based on a model by Nelson and Ewoldt[5]. This modified model, presented in Eq. 2, uses dimensionless shear rates to provide independent parameters.

$$\tau = \tau_y + \tau_s \left(\frac{\dot{\gamma}}{\dot{\gamma}_s}\right)^n \qquad (2)$$

In the following, τ_y is determined using a linear regression of the 5.11 and 10.22 1/s readings as suggested by Power and Zamora[6], τ_s is determined at 102.2 1/s and n is determined at 1022 1/s.

RESULTS AND DISCUSSIONS

Fig. 1 shows the plot of the viscosity measurement data for samples 1, 2, and 3. With the exception of carbonate content, these fluids were constructed equally. Fluids 1, 2 and 3 had 20, 40 and 60 g calcium carbonate per 350 mL respectively. The yield stress, surplus stress, and n-value were calculated using Eq. 2. From the data shown in **Fig. 1**, it seems that addition of the two larger concentration of calcium carbonate only added to the viscosity of the fluid at higher shear rates. In Table 1 it is tabulated the Herschel-Bulkley parameters for dimensionless shear rates for these fluids. It is seen that the shear thinning index, n, became a bit larger for Fluids 2 and 3. This is expected as the content of solid particles became higher for these fluids giving a higher high shear rate viscosity.

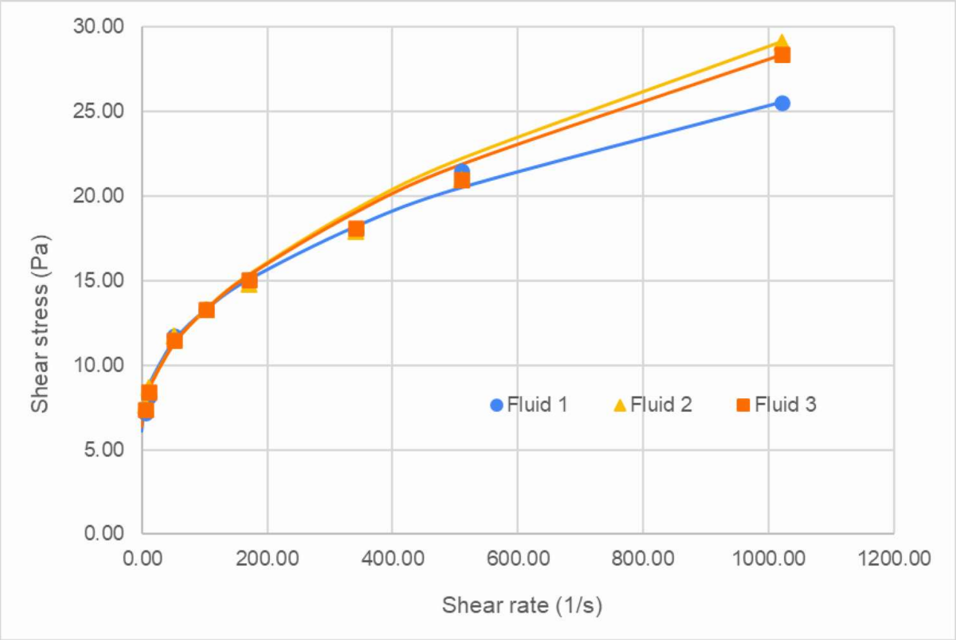

FIGURE 1: Flow curve of Fluids 1, 2 and 3 with three different concentrations of $CaCO_3$. Solid line is their Herschel-Bulkley parameters.

The measurements shown in **Fig. 1** provide insights into the behaviour of drilling fluids if no fibres are added to the fluids. The results from the experiments demonstrate that Fluid 2, containing both the smaller and larger size particles of calcium carbonate, exhibits the highest viscosity readings on the viscometer. This can be attributed to the fact that the two different particle sizes can fill the voids between each other, resulting in a denser and more stable structure. The increase in amount calcium carbonate from 10 grams to 20 grams will also have an impact on the viscosity of the drilling fluid.

TABLE 1: Dimensionless shear rate based Herschel-Bulkley parameters of Fluids 1, 2 and 3.

	Yield Stress	Surplus Stress	*n*
Fluid 1:	6.132	7.154	0.43
Fluid 2:	6.643	6.643	0.53
Fluid 3:	6.388	6.899	0.50

TABLE 2: Dimensionless shear rate based Herschel-Bulkley parameters of Fluids 4, 5, 6 and 7.

	Yield Stress	Surplus Stress	n
Fluid 4:	7.154	7.410	0.477
Fluid 5:	4.088	7.665	0.556
Fluid 6:	5.621	9.965	0.542
Fluid 7:	9.709	11.753	0.499

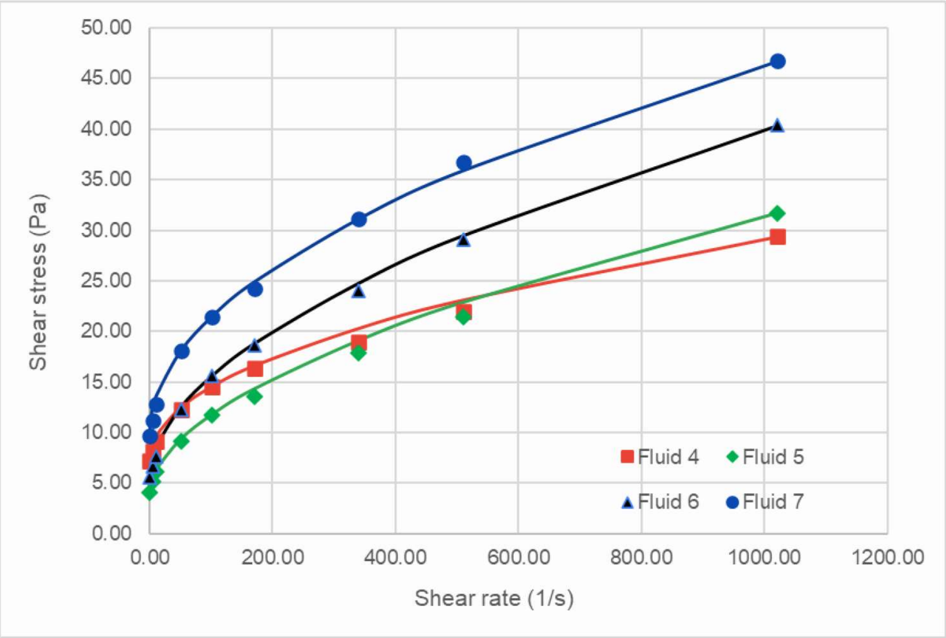

FIGURE 2: Flow curves of the fluids with added starch.

The flow curves of a series of drilling fluids with addition of starch is shown in **Fig. 2**. Their Herschel-Bulkley parameters are shown in Table 2. The total concentration of addition of starch and fibres increased with the fluid number in this series. Fluid 4 had the lowest concentration of starch, in this case N-Dril-HT. Exchanging 2g N-Dril-HT with 5g Dextrid-E resulted in a reduction in low shear viscosity and an increase in high-shear viscosity. Further addition of starch and fibres resulted in an overall increase in viscosity.

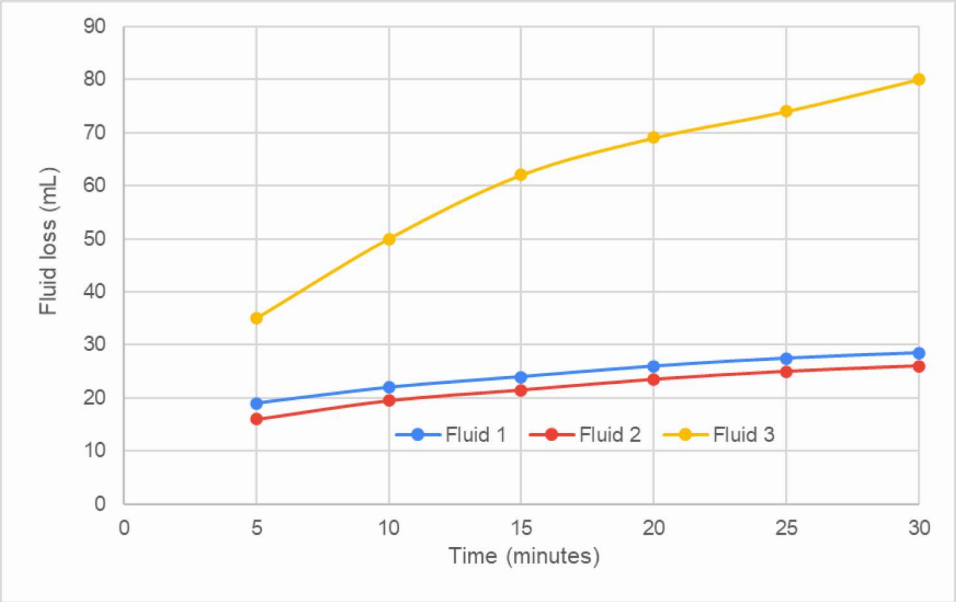

FIGURE 3: Fluid Loss test for base fluid with three different sizes of $CaCO_3$.

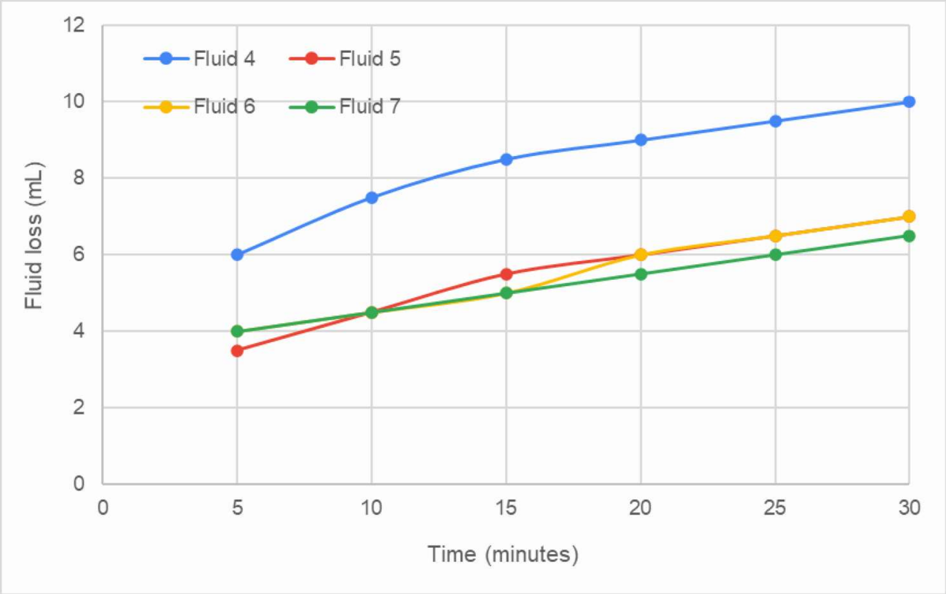

FIGURE 4: Fluid Loss test for base fluid with added starch

The results shown in **Fig. 3** shows the effect of calcium carbonate on fluid loss. The fluid loss increases when the CaCO3 particles are too large, as the filter cake is not packed tightly enough. Additionally, the fluid loss is higher when the drilling fluid is only supplemented with calcium carbonate, as opposed to when starch is added as shown in **Fig. 4** Furthermore, when starch and Aurocoat are added, the fluid loss decreases even further. The inclusion of cellulose fibres in drilling fluids enhances the binding of polymers to the filter cake, leading to reduced release of polymers into the formation. This could be attributed to the polar properties of both cellulose particles and polymers, which potentially lead to increased inter-particle adhesive and frictional forces. While the fluid loss tests in this study were conducted at 100 psi, Klungtvedt and Saasen[7] discovered that the most significant variations in Fluid Loss, attributed to the use of N-Dril HT cross linked starch and Dextrid-E modified starch in conjunction with Auracoat UF, which is a cellulosic fibre mixture, were observed at pressure ranges of 500-1000 psi.

CONCLUSIONS

A series of experiments shows that some starch polymers provide better fluid loss control than calcium carbonate, at least as long as the test pressure is as described in oilfield standards. The viscosity of the fluids was not very sensitive to the calcium carbonate content, but as expected increased with increasing particle content. The variation in viscosity was significant when the drilling fluid polymer content was varied.

ACKNOWLEDGEMENT

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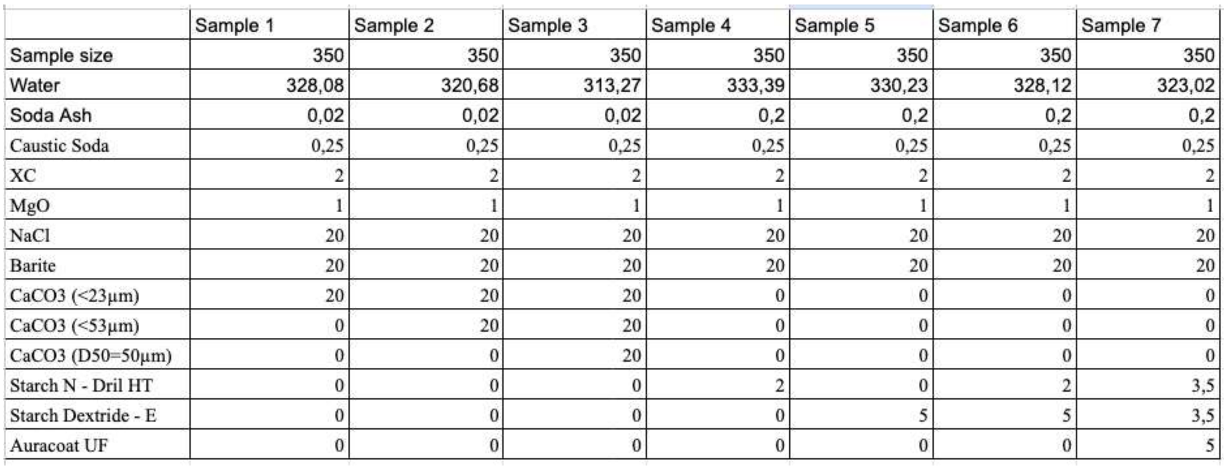
APPENDIX

Recipe for the fluids. All values in gram. Fluid # is made from Sample #.



	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Sample size	350	350	350	350	350	350	350
Water	328,08	320,68	313,27	333,39	330,23	328,12	323,02
Soda Ash	0,02	0,02	0,02	0,2	0,2	0,2	0,2
Caustic Soda	0,25	0,25	0,25	0,25	0,25	0,25	0,25
XC	2	2	2	2	2	2	2
MgO	1	1	1	1	1	1	1
NaCl	20	20	20	20	20	20	20
Barite	20	20	20	20	20	20	20
CaCO3 (<23µm)	20	20	20	0	0	0	0
CaCO3 (<53µm)	0	20	20	0	0	0	0
CaCO3 (D50=50µm)	0	0	20	0	0	0	0
Starch N - Dril HT	0	0	0	2	0	2	3,5
Starch Dextride - E	0	0	0	0	5	5	3,5
Auracoat UF	0	0	0	0	0	0	5