Application of Thermo-Mechanically Treated Drill Cuttings as an Alternative to Bentonite in Spud Muds

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ABSTRACT

The possibility of applying thermo-mechanically treated drill cuttings as a replacement for bentonite in spud muds was investigated by carrying out an extended laboratory study. A total number of 28 drilling fluid compositions, including two standard reference spud mud fluids, were prepared and tested in accordance with the API 13B-1 practices. As a result, stable drilling fluid compositions with the application of treated drilling cuttings were developed. The designed muds had satisfactory fluid properties comparable to that of drilling fluids conventionally used in the industry.

INTRODUCTION

Drilling fluids play a central role in the drilling of exploration and development wells as the success of the project and its cost depends significantly on the type of fluids selected[1]. Moreover, drilling fluids perform a number of tasks, which actually enable the drilling process. Providing primary pressure control in the well, performing cuttings transport to the surface, cooling and lubricating the bit are just some examples of the drilling fluid functions.

Spud mud is a concept commonly used in the industry to describe a drilling fluid used to drill top sections of the wells. These fluids should possess good rheological properties to compensate for low fluid velocities due to large flow areas. Today spud muds are prepared offshore by mixing pre-hydrated bentonite with seawater. Bentonite (mainly smectite mineral) is often the only additive in these fluids and acts as a viscosifier and filter loss agent. In some cases a native mud can be used instead of a bentonite mud. In these cases, fresh water is used to drill the top sections and the required properties are achieved while drilling. This happens because 75% of the drilled formations are shales[2], which may contain smectite that viscosify the fluid. Therefore, it was of interest to investigate the possibility of preparing native mud at the installation by mixing treated drill cuttings with water[3]. This application would as well turn drill cuttings, what is today considered as waste into a recycled material.

THERMO-MECHANICAL CUTTINGS CLEANING TECHNIQUE

According to the Norwegian Regulations oil contaminated drill cuttings cannot be discharged offshore unless the oil content of the cuttings is less than 10 g of oil per kilogram of dry mass[4]. Due to these regulations drill cuttings can either be treated and deposited onshore in a filling facility, re-injected into wells drilled for this purpose or treated using a thermo-mechanical cuttings cleaner (TCC)[5]. TCC is a technology, which has already been successfully field-tested on the UK

Continental Shelf[6]. The basic principle of this technology is indirect thermal sorption[7]. Here drill cuttings are fed into a series of rotary mills, where significant amounts of heat are released due to the intense friction between the cuttings and the mill. This heat is high enough to evaporate the water and oil phases, which are recovered in a condenser section. Moreover, cleaned cutting material is produced as a result of this process. Material recovered after a treatment in a TCC was used in this work.

EXPERIMENTS

Sample preparation

During the laboratory research 28 different fluid compositions were mixed. The materials used in the experiments include: freshwater, artificial seawater (SW)[3], thermo-mechanically treated drill cuttings, bentonite, polyanionic cellulose (PAC), carboxymethyl cellulose (CMC) both Hi-Vis and Lo-Vis, xanthan gum and barite.

The prepared samples also include two commonly used reference fluids: a bentonite spud mud (B REF) and a bentonite/CMC mud (B CMC REF). These compositions are shown in Table 1.

Table 1. Compositions of the reference fluids used during the experiments.

Component	Sample	
	B REF	B CMC REF
Bentonite, g	25	10.5
CMC Hi-Vis, g	-	0.7
Na_2CO_3, g	-	0.7
Water, ml	350	

The prepared fluid compositions with drill cuttings can be divided into three groups: water-cuttings slurries, water-cuttings slurries and polymers (either CMC or PAC) and water-cuttings slurries and xanthan gum. In the names of the prepared fluids the letters represent a specific component, while the following number reflects the concentration of this component in grams per 350 ml of water. In the following C stands for cuttings, X for xanthan, B for barite and CMC LV for CMC Lo-Vis. CMC and PAC abbreviations were used unchanged.

The simple freshwater-cuttings slurries prepared initially are summarized in Table 2.

Table 2. Compositions of simple water-cutting slurries

Component	Sample			
	C75	C100	C125	C150
Cuttings, g	75	100	125	150
Water, ml	350			

Initially CMC and PAC polymers were tested as stabilizing agents and fluid loss agents. Various amounts of CMC and PAC were added to the C75 slurry (Table 2). The compositions of the resulting fluids are shown in Table 3. As the obtained results using these polymers were unsatisfactory an additional study was carried out where xanthan gum was used instead of the CMC or PAC polymers. The xanthan containing muds are summarized in Table 4. Spud mud compositions presented in Table 4 were prepared both with fresh and SW as base fluids (C75 X1.4 B, C100 X1.4 B and C75 X1.4 CMC were prepared with SW only).

Most of the designed compositions were mixed using a standard Hamilton Mixer. The drill cuttings were slowly added to the water and mixed at a low speed for 12 minutes. Significant foaming of the fluids was observed. Ten drops of antifoam (Delfoam V14) were added and agitated manually with a spoon since mixer agitation resulted in a vortex drawing in more air.

In the cases where polymers were added as well, the drill cuttings were mixed for 10 minutes before adding polymers and mixing for 10 more minutes. Ten drops of antifoam were added after each mixing was commenced. At the later stages of the

Table 3. Compositions of the water-cuttings slurries with either CMC or PAC polymers.

Component	Sample				
	C75 CMC0.7	C75 CMC1.0	C75 CMC1.3	C75 CMC1.6	C75 PAC1.0
Cuttings, g	75	75	75	75	75
CMC Hi-Vis, g	0.7	1.0	1.3	1.6	-
PAC, g	-	-	-	-	1.0
Na_2CO_3, g	0.7	0.7	0.7	0.7	-
Water, ml	350				

Table 4. Compositions of the water-cuttings slurries with xanthan gum polymer.

Component	Sample									
	C75 X1.0	C75 X1.2	C75 X1.4	C75 X1.6	C100 X1.2	C125 X1.2	C150 X1.2	C75 X1.4 B	C100 X1.4 B	C75 X1.4 CMC
Cuttings, g	150	150	150	150	200	250	300	150	200	150
Xanthan, g	2.00	2.40	2.80	3.20	2.40	2.40	2.40	2.80	2.80	2.80
CMC LV, g	-	-	-	-	-	-	-	-	-	2.00
Barite, g	-	-	-	-	-	-	-	178	136	-
Water, ml	700									

experiments larger volumes were required and the fluids were mixed using a Silverson L4RT-A mixer.

Testing procedures

The testing of the prepared fluid compositions was carried out in accordance with the API 13B-1 recommended practices[8]. Rheological measurements were carried out using an automated Fann viscometer.

RESULTS

The original study included full scale testing of the designed fluid compositions, including determination of rheological, physical and chemical properties[3]. In the following rheological results are presented and discussed in details (shear rates are given in RPM and shear stresses in lb/100 ft^2).

Reference fluids

Two reference fluid compositions commonly used in the industry were mixed and tested prior to the start of the main experiments. This was done to achieve an approximate guideline for what range of rheological properties that should be achieved. The obtained results are presented in Table 5.

The Herschel-Bulkley model (H-B) was used for the calculations as this model provided the best data matching for most of the fluids based on the linear correlation coefficient[3]. In the tables τ_0 is a fluid's yield stress, n stands for the power law index and K stands for the consistency index.

Table 5. Reference fluids results.

Fann reading	B REF	B CMC REF
600	35	25
300	27	19
200	24	15
100	21	12
6	14	7
3	13	6
Gel 10s	14	10
H-B		
τ_0, Pa	6.13	2.56
n	0.616	0.514
K, Pa·s^n	0.164	0.290

Water-cuttings slurries

As shown in Table 6 the prepared water-cuttings slurries presented in Table 2 did not demonstrate the required rheological properties. Moreover, the mixtures had low gel strength and low shear rate viscosities regardless cuttings concentration. Even cuttings concentrations six times higher than that of bentonite in B REF did not yield desired results.

Table 6. Water-cuttings slurry results.

Fann Reading	C75	C100	C125	C150
600	5	8	11	14
300	4	5	7	10
200	3	3	5	9
100	2	2	4	7
6	1	2	3	3
3	1	1	2	2
Gel 10s	0	1	2	3
H-B				
τ_0, Pa	0.511	0	0.511	0.511
n	0.415	0.678	0.737	0.530
K, Pa·s^n	0.115	0.0373	0.0310	0.168

These simple fluids were incapable of suspending large solid particles. Quick and severe separation of the solid phase was observed even after few minutes of static fluid condition.

A separate study was performed to evaluate whether the hydration time influenced the cuttings behaviour in water. Identical samples as presented in Table 2 were mixed and aged for 10 days at ambient conditions. Water and solid phases were totally separated and a soft "foam cap" floated on top. The slurries were re-mixed, however, no improvements in rheological properties were observed. The Fann viscometer measurements showed identical results as in Table 6. The material was incapable of hydrating even after a long enough exposure to fresh water.

Water-cuttings slurries and polymers

CMC Hi-Vis and PAC polymers were tested initially as stabilizing agents to obtain better low shear rate viscosity, gel strength and solid suspension. The obtained results are shown in Table 7. Viscosity curves are shown in Fig. 1. (H-B model assumption). However, addition of these polymers to the existing slurries only resulted in a partial improvement. As it can be seen from Table 7, shear stresses at high shear rate values increased significantly with increasing polymer concentration. On the other hand, low shear rate viscosity and gel strength remained unchanged. Moreover, τ_0 calculated using H-B model assumption, was equal to either 0.511 Pa or 0 Pa for the presented fluids, which is unacceptable. The designed fluids were still not capable of suspending heavy particles and large solid particles deposited quickly.

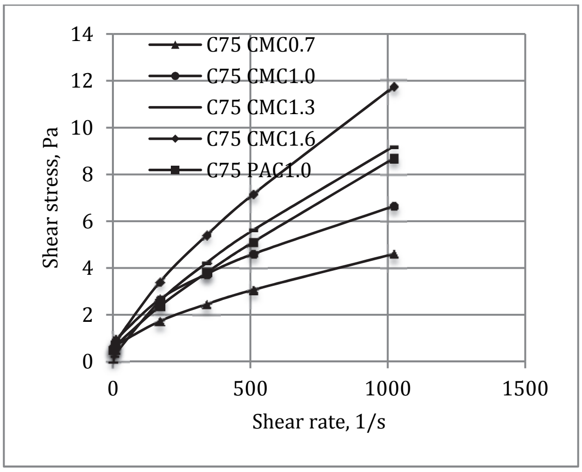

Figure 1. Viscosity curves of fluids presented in Table 7

The power law indexes, n and consistency indexes, K were as well unsatisfactory. High n values indicate poor shear thinning qualities of the fluid, which is as well observable in Fig. 1 as the curves are quite linear. Furthermore, particularly low K values indicate poor low shear rate viscosity and solid suspension ability. Based on the presented results it was concluded that CMC and PAC polymers were not suitable for this

Table 7. Results of the water-cuttings slurries with either CMC or PAC polymers

Fann Reading	C75 CMC0.7	C75 CMC1.0	C75 CMC1.3	C75 CMC1.6	C75 PAC1.0
600	9	13	18	23	17
300	6	9	11	14	10
200	4	6	8	11	8
100	3	3	5	6	4
6	1	1	2	1	1
3	1	1	1	1	1
Gel 10s	1	1	1	1	1
H-B					
τ_0, Pa	0.511	0.511	0	0.511	0.511
n	0.678	0.585	0.710	0.759	0.830
K, Pa·s^n	0.0374	0.107	0.0671	0.0586	0.0260

application.

Water-cuttings slurries and xanthan gum

Xanthan gum was tested as a stabilizing agent for the designed water-cuttings slurries (Table 2). Freshwater based slurries with xanthan polymers demonstrated improved viscous properties and similar compositions were tested using SW as a base fluid (Table 4). Since the obtained results were quite similar regardless of the base fluid type, and SW based fluids are more relevant for an offshore application, only these SW based fluid results are presented in Table 8.

Spud mud compositions with xanthan gum as a stabilizing agent demonstrated satisfactory viscous properties and significant improvements were observed compared to the simple water-cuttings slurries and CMC/PAC based slurries. This can be seen when comparing fluids with equal concentrations of xanthan (C75 X1.0), CMC (C75 CMC1.0) and PAC (C75 PAC 1.0) in Table 7 and Table 8. It is important to emphasize that xanthan based muds were able to suspend large cuttings and heavy barite particles and no segregation was documented. Furthermore, low shear rate viscosity increased significantly by the addition of xanthan. Here the τ_0 value increased by the factor of 5. Increasing xanthan gum concentration resulted in higher gel strengths as well. Even though the fluids developed quite strong gel structures with time, these were easy to break. According to the results presented in Table 8, xanthan based spud muds had significantly better shear thinning properties, as the calculated n values were lower than those in Table 7 when comparing the compositions with equal polymer concentrations. Moreover, K values increased by the factor of several magnitudes, which is in line with the observations made regarding gel strength and low shear rate viscosities.

Another important observation can be made when comparing the results in Table 8 and the reference fluid testing results in Table 5. C75 X1.4 fluid demonstrated quite similar behaviour to the B REF fluid as the main rheological properties were of a comparable range. Moreover, C75 X1.0 spud mud demonstrated approximately the same viscous qualities as B CMC REF in Table 5. So, τ_0 values of both fluids had equal values, while n and K values were approximately the same. These observations indicate, that the xanthan gum polymer is well suited for this application and the properties of the fluid can be adjusted by varying xanthan gum and cuttings' concentration.

Table 8. Results of the spud muds with xanthan gum polymer.

Fann Reading	C75 X1.0	C75 X1.2	C75 X1.4	C75 X1.6	C100 X1.2	C125 X1.2	C150 X1.2	C75 X1.4 B	C100 X1.4 B	C75 X1.4 CMC
600	26	32	36	41	38	42	44	48	49	41
300	20	24	28	31	27	30	32	36	37	31
200	17	20	24	27	23	26	27	31	31	26
100	14	16	19	22	18	20	20	24	24	20
6	7	8	11	13	9	10	10	12	13	10
3	6	7	10	11.5	8	9	9	11	12	9
Gel 10s	7	8	11	12.5	9	10	10	12	12	11
Gel 10m	10	11	14	15	12	14	15	13	14	14
H-B										
τ_0, Pa	2.56	3.066	4.60	5.11	3.58	4.09	4.09	5.11	5.62	4.09
n	0.485	0.530	0.507	0.562	0.632	0.628	0.585	0.547	0.547	0.521
K, Pa·s^n	0.372	0.337	0.412	0.323	0.199	0.225	0.320	0.438	0.438	0.458

An aging test of the C75 X1.2 fluid was conducted as well to test the stability of the designed fluid. The mud was stored at ambient conditions for 10 days, re-mixed and tested by the Fann viscometer. The obtained results were exactly the same as the initial measurements meaning (Table 8) that the designed fluid was stable as well.

DISCUSSION

Performance of drill cuttings in water

As the results in Table 6 demonstrate simple replacement of bentonite with treated drill cuttings did not provide the desired results. Viscous properties were unsatisfactory with 10s gel strength values as low as 0. High chloride and Ca^{2+} content in the resulting mixtures and low amount of active clay minerals are considered the main reasons for this behaviour. Both chloride and Ca^{2+} are present in the cuttings material as it is recovered after drilling with oil-based mud, which contains these compounds. Standard chloride tests were carried out and the amount varied from 2400 mg/l to 4400 mg/l depending on the cuttings concentration[3]. Chloride content has important influence on the swelling of clay minerals and high chloride amounts hinder osmotic swelling of Na$^+$ montmorillonite, which accounts for 90% of total swelling. Skjeggestad[9] mentions that bentonite should be pre-hydrated in water with chloride content less than 5000 mg/l. Although this value is higher than those measured in the experiments, keeping in mind that drill cuttings are not pure bentonite material, the existing chloride content could be sufficient to hinder the hydration. Furthermore, Skjeggestad emphasized that Ca^{2+} concentrations of the water used for pre-hydration should not exceed 200 mg/l since divalent ions can bind two clay crystals together and hinder hydration. Calcium tests were as well carried out on the designed fluids and Ca^{2+} content varied from 600 mg/l to 1360 mg/l depending on the cuttings concentrations[3]. Even at the lowest cuttings concentration the resulting value was 3 times higher than that stated by Skjeggestad. Yet another reason for poor hydration performance was the low amount of active clay minerals. Standard methylene blue tests[8] were carried out to identify the active clay content. Approximately 10% of the total cuttings mass was comprised by active clay minerals based on these test results[3] meaning that 10 times higher concentration of cuttings would be required to achieve similar fluid parameters to the B REF fluid. However, higher cuttings concentrations would result in undesired high fluid density and even higher chloride and calcium content leading to a closed loop situation.

Gel strength and yield stress of the fluid depend on the electrical interactions between particles[9]. This requires the presence of charged particles. Zeta potential measurements were carried out on cuttings particles using an AcoustoSizer II and the result was equal to -7.6 mV while that of bentonite particles was equal to -35 mV. High absolute zeta potential values result in stable suspensions, when at low values van der Waals forces start to dominate yielding particle deposition[10]. Thus, the relative neutrality of the cuttings particles can describe the quick solid settling observed in the experiments.

Effect of xanthan gum concentration

Xanthan gum was the only polymer among the selected types, which provided the required rheological properties. As it is seen from Table 8, τ_0 and gel strength values increased with increasing xanthan concentration for each spud mud composition. The comparison of viscosity curves is shown in Fig. 2.

As it can be seen from Fig. 2 increased polymer concentrations resulted in a shift in the viscosity curves towards higher shear stress values, meaning that gel strength and yield stress depend mainly on the xanthan concentration.

The B REF and the C75 X1.4 fluids have quite similar viscosity curves (Fig. 2) meaning that addition of xanthan gum can provide required properties to the water-cuttings slurries.

Effect of cuttings concentration

Effect of cuttings concentration on the rheological properties of stable fluids can be studied by comparing respective parameters of the fluids in Table 8.

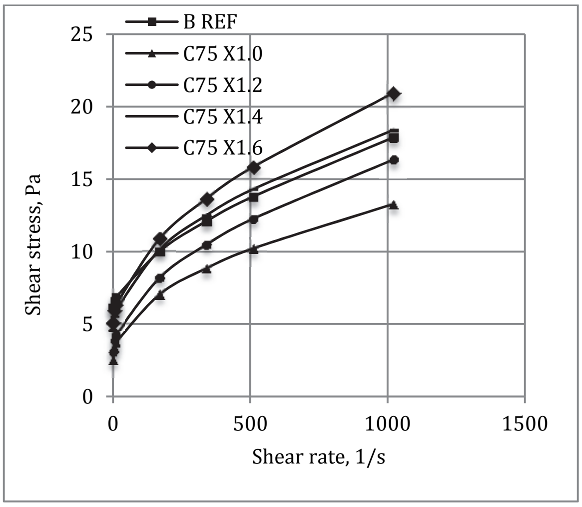

Figure 2. Effect of xanthan gum concentration.

At low shear rate values, where electrical interaction between the particles dominates, very minor increase in shear stresses was observed. Thus, the τ_0 value and gel strengths were affected to a minor degree with increasing cuttings concentration. On the other hand, more severe increase in high shear rate viscosity was observed. Increased concentration of electrically neutral drill cuttings particles contributed to higher friction between the fluid components (solid particles and water molecules), hence leading to increased shear stress values. This observation was in line with expectations, as drill cuttings were not capable of altering low shear rate viscosity of the fluids when simply added to water. However, a slight increase in τ_0 values was registered due to the mass effect. Increased cuttings concentration resulted in more dense fluids, where particles interact closer with each other, thus causing higher τ_0. This is in line with the description given by Skjeggestad[9], where he mentions that τ_0 may slightly increase with increase solid content of the fluid.

Increased drill cuttings concentration had as well an undesired effect on n and K values. This can be seen when comparing respective values of C75 X1.2 fluids with C100/125/150 X1.2 fluids. This resulted in increased n values, meaning that fluids became less shear thinning. Moreover, K values slightly reduced with increased cuttings concentration, yielding reduced low shear rate viscosity.

CONCLUSION

The possibility of using treated drill cuttings as a replacement of bentonite in top hole drilling mud was investigated by an extensive laboratory testing. The results of the experiments revealed that simple replacement of bentonite by cuttings did not yield desired rheological properties. High chloride and calcium ion content of the mixtures and low active clay content of the material were considered as the main reasons. Moreover, the material was as well incapable of hydrating even after long enough exposure to fresh water.

Stable drilling fluid compositions were, however, developed as the result of this experimental work. Xanthan gum polymers qualified as a stabilizing agent suitable for this application and modified water-cuttings slurries with xanthan gum had similar to the standard spud muds rheological properties. CMC and PAC polymers were, on the other hand, not suitable for this application.

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