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Mud systems applied to problematic formations in core drilling rigs

Bülent TOKA[a*]

[a]*General Directorate of Mineral Research and Exploration, Department of Drilling, Ankara, Türkiye*

Research Article

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ABSTRACT

The two most important features of drilling rigs based on the core drilling principles are the drill set rotating at high speeds and the very precise spacing between the pipe and the well wall. Formation pieces that swell, flow into the well, spill or collapse during the drilling of problematic formations mix into the mud or narrow the annulus and cause well problems by restraining the rotation of the drill string and circulation. The spilled formation pieces cause an excessive solid material increase in the mud structure and due to the effect of centrifugal force, the solids adhere to the inner wall of the pipes near the surface and form a cake. Excessive cake thickness in the pipes obstruct the descent of the core barrel inner tube catcher into the well. During the removal of the inner tube, a vacuum occurs in the well due to the mud discharged from the rod and the problematic formations are poured into the annulus and block the core between the core barrel and the well wall. In this study, the performance of mud systems determined by trial and error method against the problems encountered in unconsolidated claystone, mudstone (shale), siltstone and sand - pebble stones in core coal exploration drillings in Çorum - Amasya region were evaluated. Monitoring and regular improvement of the rheological values of the mud compositions, changing the mud composition according to the well conditions, keeping the gel strength high and increasing its density with salt was found to play an important role in keeping the unconsolidated formations physically balanced. Salt mud also minimized the formation of cake in the pipe.

1. Introduction

Diamond (core) drilling is based on the principle of taking a cylindrical original sample (core) that demonstrates the ground structure along the progression using a diamond drill bit (cutting tip). This method, which works with a rotary drilling system, is generally referred to as diamond drilling as diamond drill bits are used as the cutting tips.

The difference of diamond drilling rigs from the drilling rigs based on the principle of cuttings drilling are the drill string rotating at high speeds (500 - 2.500 rpm) and a very precise gap between the pipe and the well wall (approximately 2 - 4 mm). The rotation of the drill string at high speeds creates a centrifugal effect on the circulating mud coming out of the water swivel.

Depending on the bearing capacity of the diamond drill rigs and the drawworks power, in order to reach the targeted depth, the drill string of PQ (114.3 mm), HQ (89.9 mm), NQ (69.9 mm) and BQ (55.5 mm) diameters are usually used (Özbayoğlu, 1983) and the design of the well is made according to the depth to which the casings will be lowered. In deep and problematic formations, the upper levels of the well are usually drilled with a PQ (or HQ) drill string,

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*Corresponding author: Bülent TOKA, tokabulent@yahoo.com

and PW (outer diameter - 139.7 mm) or HW (outer diameter - 114.3 mm) diameter pipes are lowered to this range when the planned depth is reached. In order to lower PW pipes, the well is enlarged with a drill, usually in the diameter range of 6 ¼″ (158.7 mm) or 6 ¾″ (171.4 mm). In the event of certain drilling related problems (mud leakage, collapse and spillage) occuring in the formations such as alluvium and sandstone at the upper levels of the deep wells to be drilled, it is recommended to lower $6^{5/8}$″ (168.3 mm) diameter protection pipes before the PW pipe. Following the PW pipes, HW, NW(88.9 mm), BW (73.0 mm), and AW (57.1 mm) casings are lowered into the well, in the order mentioned and according to the design plan or encountered problems related to the well. In case the well cannot be finished with BQ rods at the planned depth because of drilling problems, the drilling is tried to be completed at the desired depth with the AQ (44.5 mm) drill string.

In drilling works, it is desirable to have high core efficiency and penetration rates. While having knowledge related to the lithology of the area affects the core efficiency, high penetration rates allow for a more economically viable drilling activity. Choosing the suitable drilling mud composition for lithology increases the core efficiency and minimizes the drilling problems related to the formation that affect the penetration rates.

Since solid control equipment is not generally used in diamond drilling, the formation pieces are mixed into the mud and negatively affect the quality of the fluid. Therefore, it becomes difficult to control the properties of the mud which leads to the occurance of problems related to the well. Negative changes in mud properties decrease the penetration rates and core efficiency, cause collapses in the well, narrowing between the drill pipes and the well wall, and ineffective cleaning of the well inside. In addition, solid-contaminated mud causes cake formation (solid material deposition) that narrows the inner surface of the drill pipes under the water swivel. In this case, sometimes the whole entire drill string needs to be pulled up, as the inner tube catcher (sampler) cap cannot be lowered into the well or the core barrel cannot be taken out. For all these reasons, it is important to prepare and control the drilling mud suitable for the formation.

The most important of the main problems swelling, flow into the welll and spilling of active formations (water sensitive) such as clay and shale, poses to be the most important problem encountered in core drilling. Moreover, the unconsolidated formations such as claystone, siltstone, sandstone, conglomerate show the characteristic of flowing into the well with the deterioration of the physical balance in the well. In the clay types contained in clay and shale formations, sodium montmorillonite (smectite) is the most sensitive to water. Among the clays, sodium montmorillonite has the highest cation exchange and water-bearing capacity (Luckham and Rossi, 1999). The API non-treated bentonite, which provides viscosity and filtration control in drilling mud preparation, is also sodium montmorillonite. The chemical and physical properties of mud are used to control problematic formations (Toka, 2017). While the chemical balance is set up between the mud and the formation in drilling of active clays that swell with water, the physical balance has an important role in formations that tend to spill and flow. Inhibited or petroleum-based muds are used to provide chemical stability. The balancing mud density is also needed to provide a mechanical balance between the formation and the mud.

In the mud design of core drillings, the mud systems containing low solid (polymerized) are generally selected instead of bentonite muds. For this reason, the solid materials contained in bentonite increase the rate of in-pipe caking in bentonite-based mud systems. Therefore, high molecular weighted carboxymethyl cellulose (HV CMC), high molecular weighted polyanionic cellulose (PAC R), xantham gum (known as XCD in the market), and partially hydrolyzed polyacrylamide (PHPA) are added to the fluid system to increase the viscosity of the drilling fluid as bentonite amount is reduced in drill fluid compositions to decrease the in-pipe caking ratio. At the same time, the synthetic PHPA and semi-synthetic polyanionic cellulose (PAC) having the property of cutting encapsulation are also used to prevent swelling of active clay formations with water (Cario and Bagshaw, 1978; MI Drilling Fluids Engineering Manual, 1998). In order to hold in the water loss of the fluid, the low molecular weighted carboxymethyl cellulose (LV CMC), low molecular weighted polyanionic cellulose (PAC LV), and modified starch are added to the system. The compatible work of modified starch with xantham gum, which is a branched polymer, improves the dynamic carrying capacity (yield point) of the mud and the ability to suspend cuttings (gel strength) in the static state (Darley and Gray, 1988).

2. Geological Structure and Formation Characteristics of Çorum - Amasya Fields

Borehole drilling activities for coal exploration were carried out in Sungurlu (Terziköy and Mecitözü) of Çorum province and Suluova region of Amasya province. While the Terziköy and Mecitözü formations are composed of brittle mudstone (shale) (Figure 1a), claystone, siltstone, and sandstone, the Suluova formation consists of unconsolidated claystone, siltstone, sandstone, and conglomerate (Figure 1b). In some wells, the acidic gas intrusions into the drilling mud were observed and the mud showed the characteristics of pH buffer solution. In addition, the mud leaks at different depths were observed in Suluova boreholes, followed by increases in pump pressure, and when the pressure relief line was opened to reduce the pressure, the mud that escaped from the drill pipes came back to the mud pools.

3. Material and Method

Drilling works were carried out with METASON with a drilling capacity of 2.000 m and SONMAK diamond drilling rigs with a capacity of 1.000 m.

Non-treated bentonite, HV CMC, XCD, PAC LV, LV CMC, modified starch, NaCl (density increasing water-soluble salt), and caustic soda (pH regulator) were used as mud additives.

For the physical measurement of the mud, the 6-speed viscometer, marsh funnel, filter press, and mud balance were used. For the chemical properties of the mud, the total hardness, P_f/M_f, and chlorine contents were continuously monitored (P_f: phenolphthalein alkalinity of the mud filtrate, M_f: methyl orange alkalinity end point of mud filtrate). The rheological values of the fluid (TS EN ISO 13500, 2010) were calculated according to the formulas given below.

$$AV = \frac{\theta_{600}}{2} \quad (1)$$

$$PV = \theta_{600} - \theta_{300} \quad (2)$$

$$YP = \theta_{300} - PV \quad (3)$$

where AV (apparent viscosity, cP), θ_{600} (value read at 600 rpm in the viscometer), θ_{300} (value read at 300 rpm in the viscometer), PV (plastic viscosity, cP) and YP (yield point, lb/100 ft^2).

Some of the mud compositions (Toka et al., 2016) selected according to the laboratory test results to determine rheological and filtration properties of the drilling fluid within the scope of the drilling mud research and development project of the Department of Drilling of the General Directorate of Mineral Research and Exploration were tested in this field (Table 1).

The most important reason for choosing the bentonite + CMC composition for this drilling is its low cost, suitable rheological and filtration values for the core drilling works as seen in Figure 2. This mud with its high gel strength value of 10' (17 lb/100 ft2) is expected to infiltrate into the voids of unconsolidated sandstones and conglomerates, provide reinforcement and prevent the flow of the formation into the well.

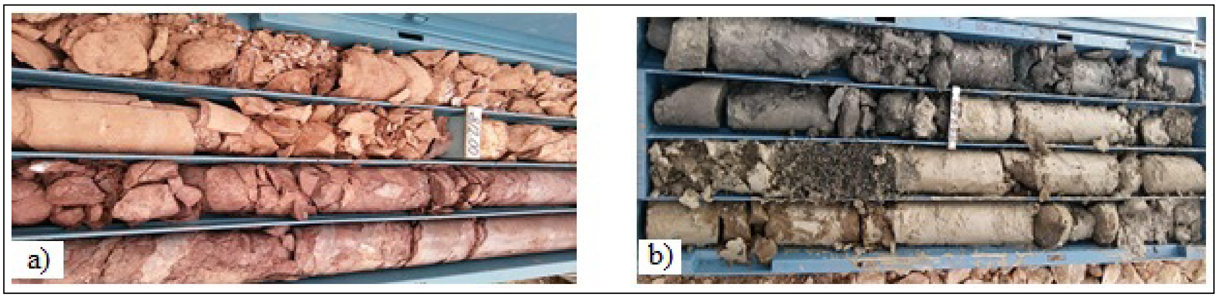

Figure 1- a) Brittle mudstones encountered in the Terzili and Yörüklü areas and b) unconsolidated sandstones, claystones and siltstones in the Suluova field.

Table 1- Mud compositions selected according to the laboratory test results to determine rheological and filtration properties of drilling fluid within the scope of drilling mud research and development project.

Mud Composition	Composition Additives
Bentonite + CMC composition	10 ppb (28.5 kg/m^3) Non-treated bentonite + 0.7 ppb (2 kg/m^3) LV CMC + 0.6 ppb (1.7 kg/m^3) HV CMC
Bentonite + Modified (M.) starch + XCD composition	10 ppb (28.5 kg/m^3) Non-treated bentonite + 0.9 ppb (2.6 kg/m^3) M. starch + 0.7 ppb (2 kg/m^3) XCD
Salt composition	NaCl saturated drill fluid preparation water + 2 ppb (5.7 kg/m^3) M. starch + 1 ppb (2.85 kg/m^3) PAC L + 1 ppb (2.85 kg/m^3) XCD

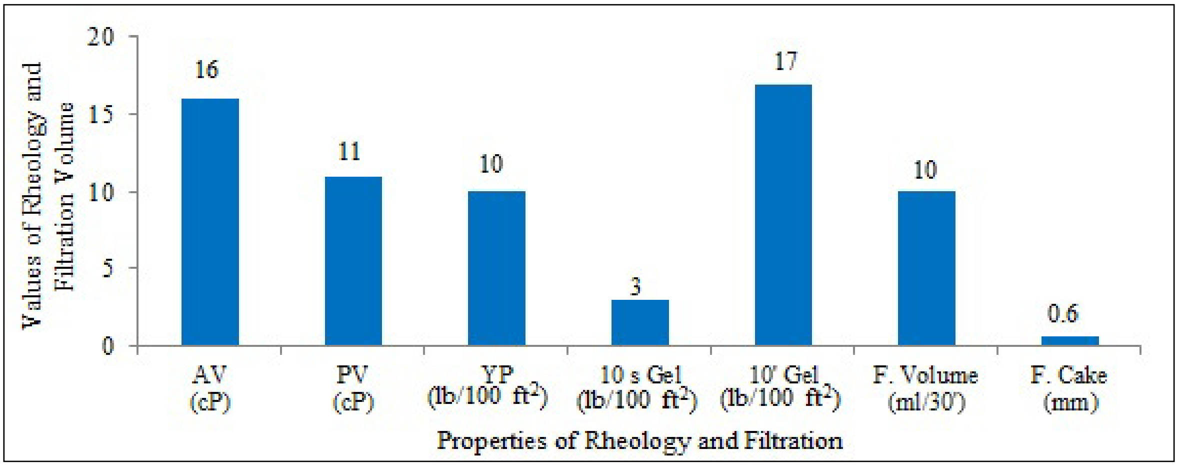

Figure 2- Rheological and filtration properties of bentonite + HV CMC + LV CMC based drilling fluid.

The mud composition consisting of modified starch, XCD, and non-treated bentonite was tested instead of this mud due to the viscosity decrease in the some zones where bentonite + CMC mud was used. Since 10 s and 10' gel strength (4 - 8.5 lb/100 ft^2) of this composition determined in the laboratory were close to each other and the YP value, which provides the dynamic carrying capacity, is higher than PV, this mud type was also tested in the drilling (Figure 3).

When the mechanical balance between the drilling fluid and the well wall was spoiled (when there were debris and spills in the well) the salt mud system, as one of the protected fluid types, was adopted in

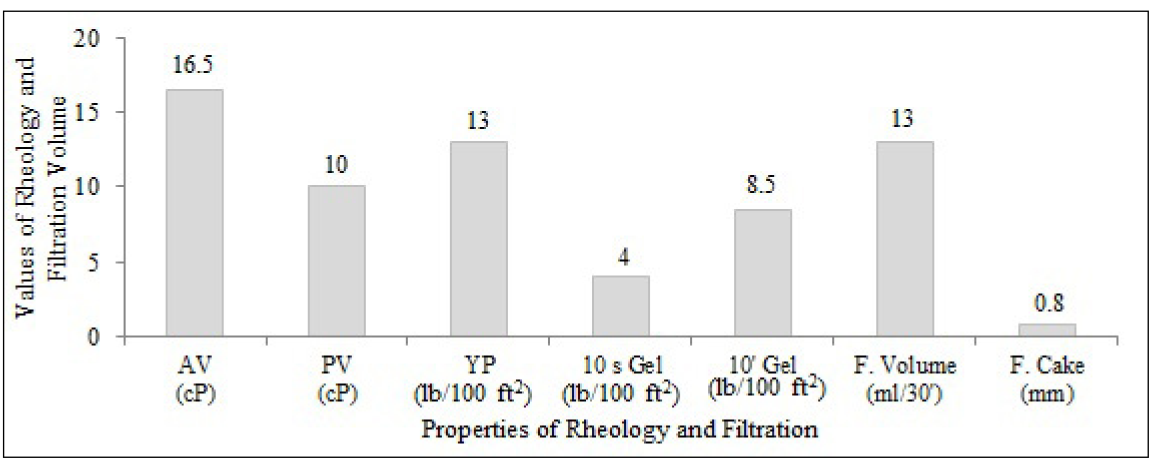

Figure 3- Rheological and filtration properties of bentonite + modified starch + XCD based drilling fluid.

order to increase the physical force (density) that the mud would exert on the well wall and provide extra inhibition. According to the observations on the field, since the cutting formations do not swell with water, the NaCl, which is more economical than KCl, was selected to prepare salt mud. The rheological properties of salt (NaCl saturated drilling fluid preparation water) + XCD + PAC L + modified starch composition according to laboratory tests are given in Figure 4. This mud type was also used as the yield point and gel strength, which express the carrying capacity of the cuttings under dynamic and static conditions, are at appropriate values, and increase the density of the fluid up to approximately 1.2 g/cm^3.

4. Field Studies and Evaluations

Since lithology, geological and tectonic structures, and formation behaviors of the field are not fully known, great difficulties are experienced in determining the mud composition and design of the well. Since the formation behavior of coal exploration drillings in Çorum - Sungurlu and Amasya - Suluova regions is not known, well problems were encountered during drilling. Problems related to the well increased, the mud compositions were changed according to the behavior of the well and efforts were put forward in order to achieve in-hole balance. In cases where it was not possible to balance the well with mud and the risk of jamming of the drill string increased, the well was brought under control by lowering the casing pipes into the problematic zones. Due to the variable depth of the well in deep exploration, the design of the well was started with the largest diameter pipes (PW).

Borehole processes which has the lowest cost were initiated with the bentonite + CMC mud composition as given in Table 1. The rheological and filtration properties of the mud were rearranged by reducing the amount of bentonite to 8 - 15 kg per 1 m^3 of mud and increasing the amount of polymer (Table 2) depending on the in-pipe caking (Figure 5). Efforts were put into keeping the viscosity of the circulating mud at around 13 - 20 (Table 3). Observations showed that between the aforementioned values, working with a pump flow rate of approximately 40-45 l/min for the HQ drill sing provided effective well cleaning. Since the increase in rheological values will also increase the pump fuel consumption (Toka and Şahin, 2006), the water + LV CMC was added to the mud depending on the water loss value, the cuttings accumulated in the channels were regularly discarded, the fresh mud was added to the mud system and solid control was carried out by adding desilter in order to prevent rheological values of the mud from increasing further. The rheological and filtration properties of the fresh mud added to the

Table 2- Bentonite + HV CMC + LV CMC mud composition.

Mud Additives	Concentration (kg/m^3)
Non-treated Bentonite	8 - 15
LV CMC	2 - 3
HV CMC	1.5 - 2
Caustic Soda	0.25 – 0.50

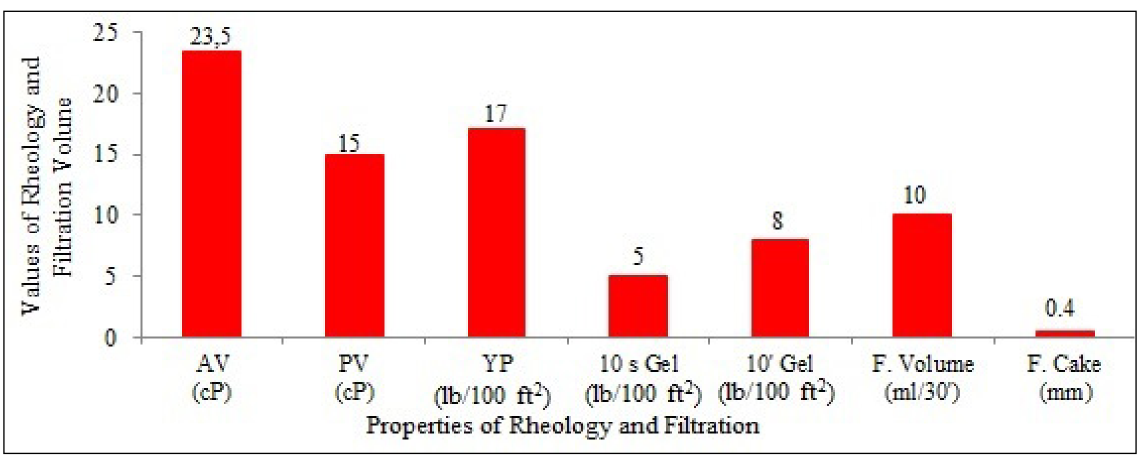

Figure 4- Rheological and filtration properties of drilling fluid containing NaCl saturated drilling fluid preparation water + XCD + PAC L + modified starch (F. Cake: filtrate cake).

Figure 5- The in-pipe caking and the rate of caking seen during the cleaning of the inside of the pipe.

system were kept at low values in order to reduce the rheological and filtration properties of the circulating mud and to remedy the mud. The AV value of the fresh mud added to the circulating mud was 11 - 12 cP and the water loss rate was adjusted between 10 - 15 ml/30′ (Table 3).

Table 3- Bentonite + HV CMC + LV CMC mud composition; average values of circulating and fresh mud.

Mud Properties	Circulating Mud	Fresh Mud
Mud Density (g/cm^3)	1.08 - 1.15	1.01- 1.02
Funnel Viscosity	36 - 42	32 - 35
AV (cP)	15 - 20	12 - 15
PV (cP)	9 - 12	10 - 12
YP (lb/100 ft^2)	10 - 13	5 - 6
10 s -10′ Gel Strength (lb/100 ft^2)	3 - 17 / 7 - 20	0 - 2
Water Loss (ml/30′)	8 - 12	10 - 12
Filtrate Cake Thickness (mm)	0.5 - 1.5	0.3 - 0.4
Ca (mg/l))	80 - 100	-
Pf/Mf	0.2 - 0.7	-
pH	9 - 10.5	-

The mud type containing bentonite + HV CMC + LV CMC showed an increase in rheological and gel strength when used in Terzili and Yörüklü areas, while it showed a decreasing trend in the formations in Suluova area. When it tended to decrease, the mud type was changed and the bentonite + modified starch and XCD composition determined in the laboratory (Table 4) was adopted. The composition of this mud is given in Table 4 and its physical and chemical properties are given in Table 5. This mud type provided very good rheological properties in such formations to carry the cuttings dynamically and keep them suspended in the static state.

Table 4- Bentonite + modified starch + XCD mud composition.

Mud Additives	Concentration (kg/m^3)
Non-treated Bentonite	8 - 15
Modified Starch	2 - 4
XCD	2 - 3
Caustic Soda	0.25 - 0.50

Table 5- Bentonite + modified starch + XCD mud composition; average values of circulating and fresh mud.

Mud Properties	Circulating Mud	Fresh Mud
Mud Density (g/cm^3)	1.07 - 1.10	1.01 - 1.02
Funnel Viscosity	40 - 48	34 - 40
AV (cP)	15 - 20	12 - 17
PV (cP)	14 - 16	8 - 10
YP (lb/100 ft^2)	11 - 14	8 - 14
10 s -10′ Gel Strength (lb/100 ft^2)	6 - 14 / 10 - 20	3 - 6
Water Loss (ml/30′)	8 - 12	10 - 12
Filtrate Cake Thickness (mm)	0.5 - 1	0.3 - 0.4
Ca (mg/l))	80 - 100	-
Pf/Mf	0.2 - 0.7	-
pH	9 - 10.5	-

In these two selected mud compositions, the density of mud was allowed to increase and the high-density value of mud was aimed to be preserved as long as the formation cuttings mixed into the system did not increase in-pipe caking. The reason for this is to provide the physical balance between the density of the mud and the well. Therefore, in order to maintain the physical balance in the well, complete removal and replacement of the old mud was avoided and the channels were consistently cleaned while adding fresh mud to the system to sustain the properties of the mud. By means of this method, the density of the mud was kept between 1.10 - 1.12 g/cm^3.

When the physical balance was spoiled in the well and the formation flowed and spilled into the well, in order to increase the density of the mud, the salt mud of which the composition is given in Table 6, was adopted in Terzili, Suluova, and Mecitözü areas. The other reasons for switching to salt mud, which is an inhibitory system, are that the water-insoluble thickening additives (barite, calcite) will increase in-pipe caking and the evaporates (gypsum, anhydrite) and acidic gases (H_2S) contained in the formation would adversely affect the performance of bentonite

Table 6- NaCl + modified starch + PAC L + XCD mud composition.

Mud Additives	Concentration (kg/m^3)
NaCl	140 - 160
PAC L	3 - 4
Modified Starch	6 - 8
XCD	2 - 3
Caustic Soda	0.50 - 1
Corrosion Inhibitor	as much as necessary

and negatively charged polymers. As can be seen in Table 7, the density of fresh mud was prepared to be between 1.08 - 1.11 g/cm^3 in Mecitözü drilling, and the density increased up to the range of 1.16 - 1.18 g/cm^3 with the clays and the cuttings mixed into the mud. It was planned to increase the mud density by adding more salt to the system and ensure the physical balance in the well in case of problems in the operation at this selected density. The reason for keeping the properties of the fresh mud added to the system low is to allow the mud to be improved by reducing the rheological properties of the circulating mud with rheological values increased.

Table 7- NaCl + modified starch + PAC L + XCD mud composition; average values of the circulating and the fresh mud.

Mud Properties	Circulating Mud	Fresh Mud
Mud Density (g/cm^3)	1.16 - 1.18	1.08 - 1.11
Funnel Viscosity	37 - 42	32 - 35
AV (cP)	15 - 20	10 - 15
PV (cP)	10 - 15	10 - 14
YP (lb/100 ft^2)	10 - 16	8 - 16
10 s -10′ Gel Strength (lb/100 ft^2)	4 - 7 / 8 - 15	3 - 5
Water Loss (ml/30′)	10 - 16	10 - 14
Filtrate Cake Thickness (mm)	0.75 - 1	0.5 - 0.8
Ca (mg/l))	800 - 1200	-
Cl (mg/l)	55000 - 60000	-
Pf/Mf	0 / 0.6	-
pH	7	10 - 11

The most important feature of all mud types used in these fields is their high gel strength. The reason for choosing a mud system with high gel strength is the opinion that the gelled mud penetrating into the formations (such as sandstone and conglomerate) on the well wall acts as reinforcement by filling the cracks and gaps. As can be seen in Figure 6, the gelled mud filling the voids by consolidating the formation obstructed the mud from flowing into the well together with the pressure exerted by the mud column on the formation.

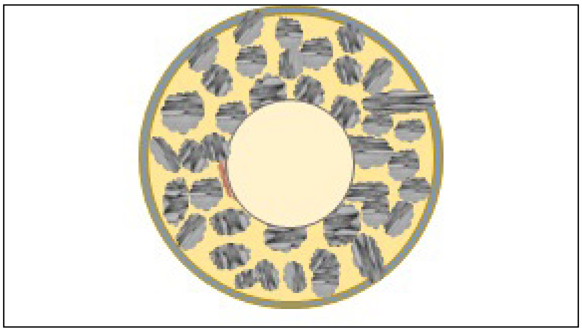

Figure 6- Invasion of the unconsolidated formation by the high gel mud.

The decreases in pH values were experienced in some wells. Increasing the pH value by adding caustic soda to the system did not work, and since the pH value behaved like a buffer solution, the studies were carried out around pH 7. Since the bentonite content in the mud system is very low, it was observed that working at a low pH value did not have a significant effect on the rheological and filtration properties of the mud. The reason why the pH value of the mud decreased and could not be increased was due to the formation or the acidic gases contained therein.

During studies, the core samples representing the formation were kept in circulating mud, fresh mud, and water (Figure 7). Their behaviors were examined and the mud was altered according to the changes observed. While core samples did not show

Figure 7- Keeping the core samples in mud and water and observation of the properties such as dispersion and swelling.

any change in the mud samples used, some samples showed dispersion and fragmentation in water. Zones where samples dispersed in water were located by closely monitoring the water loss of the mud, aimed to preserve formation and cutting integrity.

In core drilling, the shale shakers are generally not used for solid control. Therefore, the silt separator (desilter) shown in Figure 8 was operated regularly according to the PV and sand content of the mud in order to remove the drilling cuttings from the mud and control mud properties. The cuttings accumulated in the channels were regularly ejected and approximately 2 - 3 m^3 of fresh mud was added to the system per day. When the proportion of sand in the mud reaches 1 - 1.5%, with these measures taken the percentage of sand in the mud system was kept to a maximum of 0.8 - 1.0%. Thus, the in-pipe caking close to the surface was minimized.

Figure 8- Desilter.

One of the important problems encountered in the Suluova field is that after the loss of complete circulation in a short interval, the pump pressure increased and when the pressure relief line was opened and the pressure was wanted to be reduced, the mud that escaped to the formation flowed out of the well through the rods and returned to the tanks. It was thought that this problem, which occurs at two different depths, may have two causes. The first is the clogging of the annulus with the collapse of unconsolidated formations due to the deterioration of the physical balance in the well during the removal of the inner tube from the well, and then the cracking of the weak formations by the drilling mud pumped into the well. The second is the presence of formation fluid (gas) traps at levels where the problem occurs, and the settlement of mud in the formation cavity after the gas is separated. The escape direction of the mud being from the pipe rather than the annulus indicates that the formation is settling and during this settlement, the formation closes the sensitive sized gap between the drill (or core barrel) and the well wall. Following the occurrence of this event, an observation was made for about two hours, during this process, the mud was re-pumped into the well and as there was no change in the return of the mud, the exit maneuver was performed to control the drill and drill string. Lowering of the drill string into the well resulted in an unrepeated, one time collapse of the well. Observations made raised the assumption that there was a high probability of fracture of the formation of a jammed formation fluid trap at these levels bas a result of unconsolidated formation collapsing and occluding the annulus.

5. Results

● Low cost bentonite + HV CMC + LV CMC composition with high 10′ gel strength demonstrated good core drilling performance in the first stage of the well and for unproblematic formations.

● Bentonite + modified starch + XCD composition with its capacity to form a good gel in a static state and carry cuttings in a dynamic state, provides well balancing in unconsolidated formations.

● Salt-based drilling mud, which is used to maintain the physical balance in the well and minimize the formation of in-pipe caking, exhibited a positive performance in the zones where spillage problems were faced.

● By using desilter in core drilling, keeping the percentage of sand in the mud between 0.8 - 1.0% maximum, regular cleaning of mud channels and adding fresh mud to the system daily ensured the preservation of the physical balance in the well and the control of the mud properties.

● Mud compositions with a yield point between 10 - 20 lb/100 ft^2 seems sufficient for core drilling at recommended circulation rates for cleaning of the pieces in the well.

● In an event of increasing pump pressure following a loss of circulation and fluid ejection through the set; ascending the drill string (or pulling into the casing pipe) and descending it again into the well until the circulation is achieved, would assist the re-establishment of the balance and lower the risk of drill string jamming.

Acknowledgements

Mud compositions that can be applied for core drilling, within the scope of drilling mud research and development project, in the Mud Laboratory of the Department of Drilling of the General Directorate of Mineral Research and Exploration (MTA) were determined by Oil and Natural Gas Engineer Nuray TOKA (MSc) and were consulted for new mud compositions applied.

The fieldwork was carried out together with the Mining Engineer Bülent TOSUN, Mining Engineer Hayati ÖZKAYA, the local staff trained for mud measurement and monitoring, and the permanent drilling technical staff.

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