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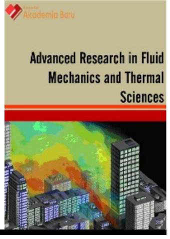

Development of High Temperature Pressure (HTHP) Water Based Drilling Mud Using Synthetic Polymers, and Nanoparticles

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ABSTRACT

It is important to understand the aspects influencing water based mud (WBM) rheology in order to maintain a firm control over rheological properties of high temperature high pressure (HTHP) and high density water based mud. This paper focuses mainly on the rheological properties of water-based drilling fluid under high pressure and high temperature condition. This work focuses on the design, optimization and formulation of a HTHP water-based drilling fluids in accordance with the required specification such as rheological properties and fluid loss. To meet the aforementioned drilling fluid properties, the research was limitless to the use of clay, polymers, and nanoparticles. Polymers provide excellent rheological and fluid loss properties to water base muds but degrade at high temperature. The experimental method used was generally mixing of water base mud with certain formulation and then performing mud testing. The experimentation were conducted according to "Recommended Practice on Standard Field Procedure for Testing Drilling Fluid" API RP 13B and "Recommended Practice 13I Standard Field Procedure for Laboratory Testing Drilling Fluid" API 13I to meet the American Petroleum Institute (API) requirements and obtain trustworthy results. The main laboratory tests involved in this project are mud preparation, static rheology test, pH and HTHP static filter press. A bentonite clay and high temperature synthetic polymers have been successfully tested at 400-degree F with excellent rheological and filtration properties. The base mud formulation consists of the commercial chemicals provided by Scomi Oiltools, Malaysia. The base mud formulation has a stable rheology and excellent fluid loss properties at 400 F. A very thin and impermeable filter cake has been obtained with minimum fluid loss at a temperature of 400 F. Researchers have successfully used nanoparticles for providing excellent rheology, thermal stability and fluid loss control. Two nanoparticles namely, Carbon nanotubes (CNT) and Zinc Oxide were tested on the base WBM system to analyze their effects on HTHP rheology, fluid loss, and filter cake quality. A very positive result has been obtained using Carbon nanotubes (CNT). The use of CNT in WBM increased HTHP rheology by 14% and reduced fluid loss by 25%. Moreover, this research provides solutions to the problems related to HTHP WBM development like clay gelation, solid sagging, and low-end rheology. The aforesaid problems have been fixed by using high temperature polymeric deflocculants, polymeric viscosifier, and bentonite extender respectively.

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HTHP, rheology, fluid loss, carbon nanotubes (CNT), sag

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1. Introduction

High Temperature and Pressure (HTHP) condition are experienced in wells that have downhole temperatures greater than 300 oF and pressure of 10,000 Psi and higher. The most predominant problem that can affect drilling fluids in HTHP conditions, is the thermal degradation of the water based mud system, and inducing changes in its properties under HTHP conditions. Oil-based mud have the ability to resist thermal degradation and withstand severe downhole condition like HTHP. However, oil based mud imposes a negative impact on the environment and it is not economically viable compare to the other type of mud systems such as WBM. Hence, drilling into formations with HTHP requires an eco-friendly WBM drilling fluid possessing stable rheological and enhanced fluid loss properties [8].

The main function of bentonite in WBM is to elevate viscosity and reduce filtration loss to wellbore walls. Bentonite can be classified into either Ca-bentonite with low swelling capacity or Na-bentonite with high swelling capacity [1]. According to Shan Wenjun *et al.*, [3], the clay property will be greatly affected with increasing temperature due to hydration and coalescence of Bentonite clay particle in high temperature condition. Clay gelation process in WBM requires special attention at temperatures higher than 300 F. The mud loses its shear-thinning property especially under static aging condition and cause excessive gel strengths. To avoid excessive mud viscosities and gel strengths, bentonite concentration used should be minimum. Bentonite concentration should not be exceeded more than 3 lb/bbl when formulating HTHP WBM [2].

A successful HTHP well drilling requires an appropriate control on drilling mud rheology. As Johann [2] stated that “if concentration of Bentonite or clay materials exceeds acceptable levels and results in viscosity problems, polymeric deflocculants can be used as a last resort to control rheology.” In the past, high solids dispersed drilling fluid systems for HTHP drilling contained lignosulfonate and lignite for rheology and fluid loss control. The conventional lignite/lignosulfonate high- solid dispersed muds function at alkalinity (pH 9) and require high dosages of lignite/lignosulfonate at temperature above 360 F because of thermal degradation. Chrome lignite degradation by-product is CO_2 which flocculates clay and Bentonite, causing high yield point and gel strength [2]. The recent development of synthetic short chain polymeric deflocculants improved the temperature stability and low dosages compared to conventional lignite/lignosulfonates. They are temperature-stable above 400 F.

Nanotechnology and surfactant has contributed to novel developments in petroleum industry in the past few decades. The rheology at HTHP condition is affected by breaking bonds between mud particles at high temperature [6]. Nano based drilling fluid greatly reduces frictional resistance between drill pipe and wellbore wall by forming a lubricating film at wall and pipe interface. Shale formation consists of reactive clays, which stick to the drill bit and centralizer, causing balling effect. Nano based mud could be a better choice in drilling operation in reactive shale because of it hydrophobic film forming characteristic [12]. Due to the presence of large quantity of very minute particles with high surface area, thermal conductivity, high temperature stability, high mobility, and thermal conductivity, effective interaction with internal and external surfaces of rock, nanoparticle-based drilling fluids are anticipated to play a key role in future and current high temperature and high pressure drilling operations [11]. Multiwall Carbon Nanotube (MWCNT) has been successfully used by Abduo *et al.*, [8] to improve HTHP rheological stability and fluid loss.

2. Experimental Procedure

The methodology is divided into several steps, as shown in Figure 1. The specifications of HTHP drilling mud were set according to the field experience by drilling fluid engineers of Scomi Oiltools Sdn. Bhd. The two steps involved are before hot rolling (BHR) and after hot rolling (AHR). BHR consists of Bentonite (Drill-Gel) pre-hydration for 16 hours, mixing of fresh water base mud, rheology and pH test, and hot rolling. The tests involved after hot rolling (AHR) are same as BHR with an extra HTHP fluid loss test.

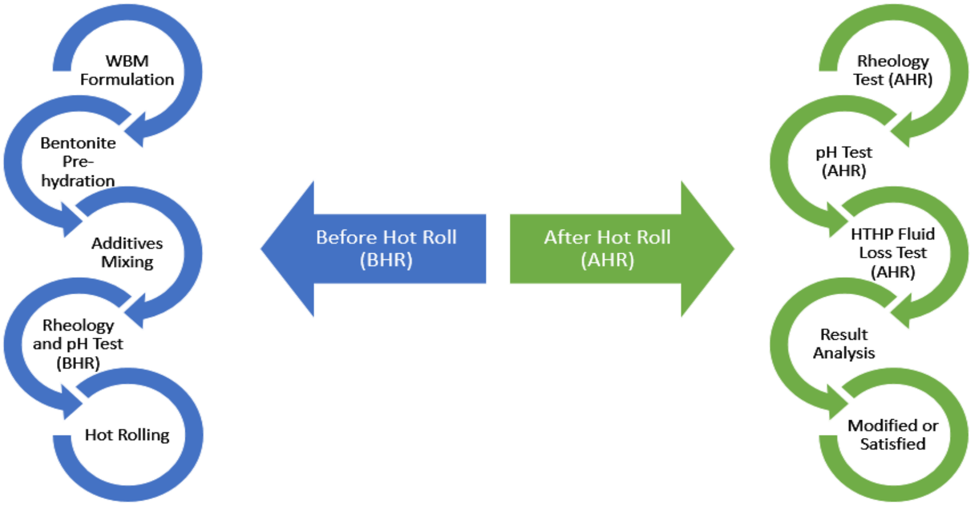

Fig. 1. Experimental flow

2.1 Drill-Gel Pre-Hydration

Pre-hydrated Drill-Gel was prepared by adding 35 lb/bbl of Drill-Gel and 1 lb/bbl of caustic soda to 0.97 bbl of water. The mixture was stirred at high speed for 30 minutes using Hamilton beach mixer. It was then kept for 16 hours at room temperature for better hydration.

2.2 Additive Mixing

The order of chemicals mixed is shown in table 1. The way of adding chemicals and mixing time for each chemical is an important aspect in water base mud mixing. The polymers were added very slowly, and more mixing time was given to each polymer for better hydration. A relatively higher mixing time was also given to Drill-Bar and Drill-Gel.

2.3 Rheology Test

Rheology test represents the flow behaviour and hole cleaning efficiency of drilling mud. This test is used to record rheology parameters like yield point (YP), plastic viscosity (PV), and gel strength using Fann viscometer-model 35SA. For HTHP mud the tests were done at 150 F according to API standards.

Calculation involved

$$PV_{cps} = 600_{rpm} - 300_{rpm} \tag{1}$$

$$YP_{lb/100ft^2} = PV - 300_{rpm} \tag{2}$$

2.4 pH Test5

pH meter was used to find the pH of drilling fluid. pH plays an important role in water base mud and affects mud properties. Water-base drilling fluids are generally maintained in the 8 to 12 pH range for improved chemical solubility and performance, as well as for anti-corrosion of drilling and completion tools (Scomi).

Table 1
Chemicals used and their function

Additive	**Function**	**Base (lb/bbl)**	**Base + CNT (lb/bbl)**	**Base+ZnO (lb/bbl)**
Drill Water (bbl/bbl)	Base fluid	0.523	0.523	0.523
Caustic Soda	pH modifier	To pH 10	To pH 10	To pH 10
Soda Ash	control hardness	0.7	0.7	0.7
Hydro-Defoam HT	Foam remover	1	1	1
Hydro-Therm LV	HT Fluid Loss Polymer	6.2	6.2	6.2
Hydro-Therm R	HT Fluid Loss Polymer & Rheology modifier Polymer	1.8	1.8	1.8
Hydro-Zan	Rheology modifier	0.7	0.7	0.7
Sodium Chloride	Salinity	74.42	74.42	74.42
Hydro-Plast	HT fluid loss, shale stability	4	4	4
Hydro-Seal R	Bridging material, lubricity	4	4	4
Hydro-Sperse RS	HTHP Rheology stabilizer	2	2	2
Carbon nanotubes	Rheology & fluid loss improver	-	0.5	-
Zinc Oxide	Rheology improver and H_2S scavenger	-	-	0.5
Drill-Bar	Weighting agent	Up to 14 ppg	Up to 14 ppg	Up to 14 ppg
Drill-Gel	Viscosifier and Fluid loss control	8	8	8
Magnesium Oxide	pH buffer	1.5	1.5	1.5
Ox-Scav L	Polymer extender	1	1	1
Hydro-Buff HT	Polymer extender, HT rheology improver	1.5	1.5	1.5

2.5 Hot Rolling

Hot rolling is a process, which simulates a wellbore mud circulation in the laboratory using a roller oven and mud aging cell. The purpose of hot rolling is to check how the mud properties will change after a mud circulation at certain temperature. The mud samples were hot rolled at 380 F and 400 F for 16 hours under 200 Psi pressure.

2.6 HTHP Fluid Loss Test

High temperature and high-pressure filter press is used at high temperatures and high pressures to find the fluid loss. This test can be performed at original down-hole temperature giving realistic values of fluid loss. All the HTHP fluid loss tests were performed using Ofite HTHP filter press with threaded cells (500 mL) at temperature 380 to 400 F and 500 Psi differential pressure.

The paper represents an optimized formulation for HTHP dispersed water base mud. The base formulation is an enhanced system of polymers, clay, and dispersant with improved mud properties at elevated temperatures. The base is further improved by formulation with nanoparticles like Carbon Nanotube (CNT) and Zin Oxide. The normal field specifications that were established to describe the performance of the ideal fluid included a Plastic Viscosity (PV) of less than 50 cP, Yield Point (YP) in a range of 18 to 30 lb/100ft^2 and HTHP fluid-loss of less than 20 ml at 380-400 ^{o}F, and 500-psi differential pressure on hardened paper. The rheological properties were measured according to API standards using fann 35SA viscometer at 150 F (66 ^{o}C).

3. Results and Discussion

3.1 Formulation of Base

The water base mud was initially formulated with Drill-Gel as viscosifier and without Hydro-Sperse RS. The rheological properties after hot rolling at 380 F for 16 hours increased to high and unacceptable range (above 30 lb/100ft2). The plastic viscosity (PV) and yield point (YP) were too high for practical application (PV above 50 cP). This increase in rheology is caused by high temperature clay gelation phenomena. Shan Wenjun *et al.*, [3] attributed this to the clay property which is greatly affected with increasing temperature due to hydration and coalescence of clay particles under high temperature condition.

The same formulation was then mixed with a polymeric deflocculant known as Hydro-Sperse RS. Hydro-Sperse RS stabilized the rheology by dispersing the clay at high temperature. The polymer uncoiled and attained a straight chain configuration when dissolved in water due to mutual repulsion of same charged groups along the chain. Hydro-Sperse RS efficiently improved the action by stimulating clay platelet disaggregation. Un-hydrated clay platelets are aggregated by edge to face and face to face electrostatic bonding as shown in Figure 2.

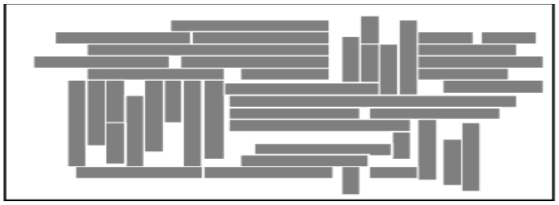

Fig. 2. Clay platelet aggregation before hydration

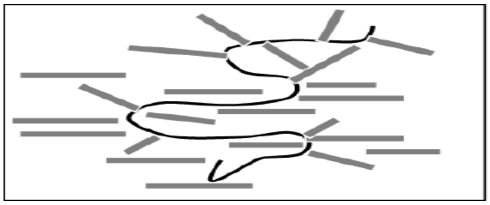

Fig. 3. Short chain anionic polymers enhances disaggregation

When water contacts polymer becomes uncoil and adsorbs on clay where polymer‘s negative charge neutralize positive charge of clay. This causes platelet disaggregation because polymer overcomes the bond strength of the macrostructure as shown in Figure 3. It becomes more effective compared to untreated clay because a larger fraction of clay gets activated for hydration [9]. The Figure 4 below shows the rheology curves with and without Hydro-Sperse RS. Another analysis in this research is the contribution of Hydro-Sperse RS to HTHP fluid loss. The optimum concentration for the lowest fluid loss was deduced to be 2 lb/bbl as shown in Figure 5. This can be explained as Hydro-Sperse RS disperse clay particles causing the formation of a thin and impermeable filter cake which in turn reduces fluid loss.

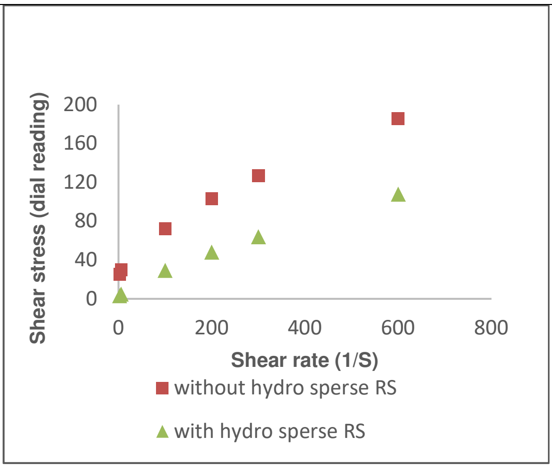

Fig. 4. Effect of Hydro-Sperse RS on Rheology after hot rolling

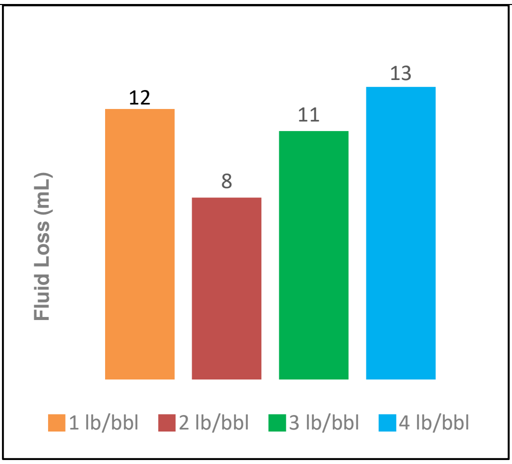

Fig. 5. Effect of Hydro-Sperse RS on Fluid loss

Fig. 6. Barite sagging due to low LSRV

The low end rheology or low shear rate viscosity (LSRV) refers to 3 and 6 rpm dial reading of Fann viscometer. The low wellbore annular shear rate is best approximated by 6 rpm reading, equivalent to a shear rate of 10.2 sec^{-1}. The 6 rpm reading for drilling fluids is important for cleaning the hole and suspend the cuttings. LSRV values are the main inhibitive mechanism for barite sagging at dynamic condition. These properties should be maintained within the range for a particular set of wellbore condition (Scomi). The use of Hydro-Sperse RS stabilized the rheology (PV and YP) at high temperature but reduced the low end rheology (LSRV). The decrease in LSRV resulted in severe sagging of solids as shown in Figure 6. The LSRV was successfully elevated by using Hydro-Zan and Hydro-Buff HT. Hydro-Zan polymer is stable up to 250 F and degrades at temperature higher than 250 F. The synergy of hydro-zan and Hydro-Buff HT is explained as Hydro-Zan efficiently stabilized LSRV until a temperature of 250 F, while above that, Hydro-Buff HT is responsible for stabilization of LSRV and overall rheology because of its high temperature stability. This strategy efficiently eliminated solid sagging at high temperature. The overall testing results are shown in Table 2.

Table 2
Drilling fluid properties at 380-400 F

Drilling Fluid	Temperature (^{o}F)	Plastic viscosity (cP)	Yield point (lb/100 ft^2)	10 sec Gel (lb/100 ft^2)	10 min Gel (lb/100 ft^2)	HTHP Fluid loss (mL)	Cake thickness (1/32 inch)
Base	150 ^{o}F (BHR)	56	46	7	34	-	-
	150 ^{o}F (AHR 380 ^{o}F)	41	18	3	7	8	3
	150 ^{o}F (AHR 400 ^{o}F)	41	22	4	7	9	4
Base + CNT*	150 ^{o}F (BHR)	60	55	10	36	-	-
	150 ^{o}F (AHR 380 ^{o}F)	55	31	5	11	6	2
	150 ^{o}F (AHR 400 ^{o}F)	47	25	5	8	8	3
Base+ZnO	150 ^{o}F (BHR)	56	46	8	35	-	-
	150 ^{o}F (AHR 380 ^{o}F)	46	21	4	10	9	4
	150 ^{o}F (AHR 400 ^{o}F)	42	20	4	7	9	4

(*) Carbon Nanotubes

3.2 Rheological Properties

Rheology of drilling fluid dictates successful drilling as well as hole cleaning. At HTHP conditions, the conventional water base mud system loses its rheology and results in major drilling problems. High temperature weakens or breaks the bonds among the mud particles and cause a severe drop in rheology. For this reason, the results after hot rolling (AHR) will be closer to reality and more meaningful at these conditions. It can be seen from Figure 7 that rheology is higher for mud sample with nanoparticles. The concentration of both Carbon nanotubes (CNT) and Zinc Oxide nanoparticle is 0.15% by weight. A small concentration of both nanoparticles improved the rheology of mud at 400 F. The rheology can be broadly explained in terms of PV, YP and gel strength as follows.

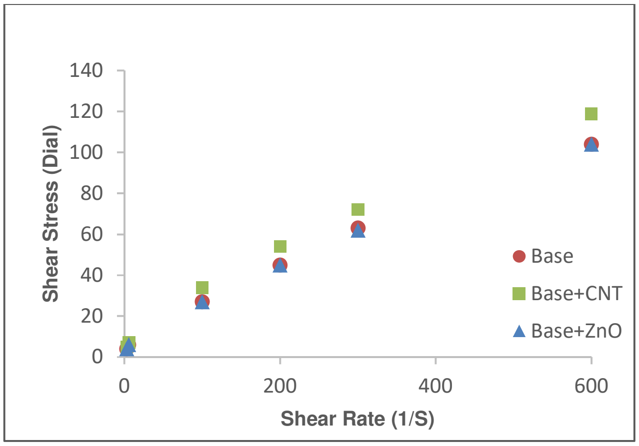

Fig. 7. Rheology curve for all samples at 150F (AHR@400F)

3.3 Plastic Viscosity (PV)

Drilling fluids usually consist of dispersed solids in continuous phase of fluid. PV (Plastic viscosity) is caused by mechanical friction of solids which constitute to total flow resistance. From Figure 8, it can be seen that PV increases for both samples containing nanoparticles compared to base sample. Many factors like increasing percent volume of solids, constant percent volume of solids, and decreasing particles size in drilling fluid increases plastic viscosity. Small particles size has high surface to volume ratio, which causes increased frictional drag (Scomi). The PV is higher for Carbon nanotube fluid compared to ZnO because its particle size is very small compared to ZnO and hence has a high surface to volume ratio.

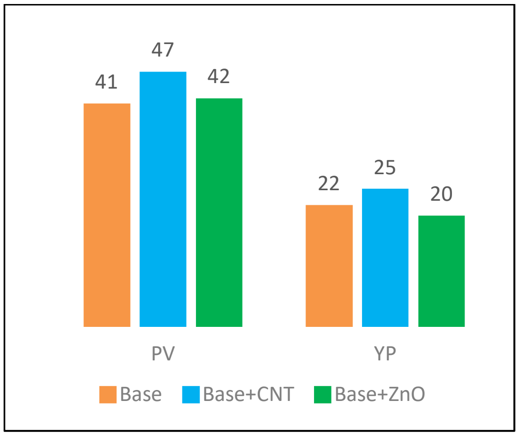

Fig. 8. PV & YP after hot rolling at 400F

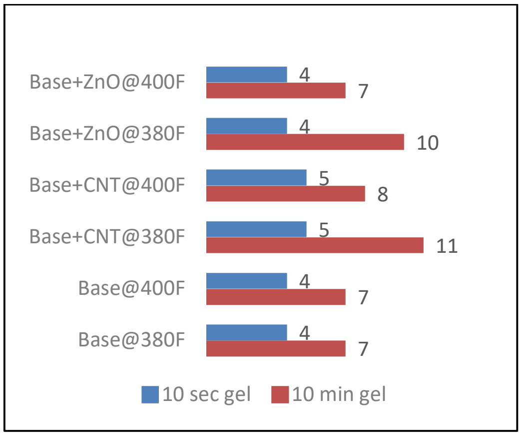

Fig. 9. Gel strength

3.4 Yield Point (YP)

The electrochemical attractive forces in the mud particles cause flow resistance and is termed as yield point. The surface of dispersed particles in mud can have positive, negative, or neutral charge. These charges cause electrochemical attractive or repulsive forces under dynamic condition, giving rise or drop to yield point respectively [7]. From Figure 8, it can be seen that YP of base sample is thermally stable up to 400 °F. Table 2 shows the drop in YP for all the samples after hot rolling at 380 and 400 °F. The YP or rheology for all the samples are in a stable range after hot rolling. Adding Carbon nanotubes and Zinc Oxide nanoparticle further increased and stabilized the solid carrying capacity (YP). Carbon nanotubes efficiently increased and stabilized yield point of the base mud sample. This increase in YP is due to increasing quantity of solid particle and complex interactions among carbon nanoparticles and other additives. ZnO loses a proton in aqueous medium when pH is high and obtain a net negative surface charge [10]. This negative charge is responsible for interaction of ZnO with other charged particles and hence modify YP of the mud system. The most stable YP is given by carbon nanotubes compared to zinc oxide and base.

3.5 Gel Strength

Gel strength is the power of forces of attraction in drilling mud at static condition. Figure 9 shows that gel strength for all the samples are in a range of 4 to 11 lb/100ft^2. These gels are considered as low gels and hence are desired in mud engineering perspective. High strength of attractive force cause high gelation, and vice versa. Flocculation of solids in the mud causes excessive gelation which results in high mud pump pressure to break the gel after a shutdown period. These gels are neither progressive nor high flat gels as these are undesired in the drilling industry (Scomi).

3.6 HTHP Filtration Properties

The combination of synthetic fluid loss polymers, dispersant, and clay enhanced the fluid loss properties of the base mud sample up to 400 ^{o}F. The fluid loss can be seen in Figure 10. Dispersant and fluid loss polymers are negatively charged low molecular weight polymers of short chain length. These negatively charged polymer adsorbs on positively charged clay platelets causing neutralization of charges. This creates an overall negative charge and deflocculation occurs. The dispersion or deflocculation of clay particles result in the formation of a thin and impermeable filter cake. The formation of thin and impermeable filter cake resists excess fluid loss to wellbore formation. The synthetic fluid loss polymers used in this water base mud system also work as secondary viscosifier. The lower fluid loss can also be explained by the fact that a viscous base fluid of mud reduces fluid loss. This proves that the used polymers are stable up to or perhaps above 400 ^{o}F. The addition of Carbon nanotubes to the base further enhanced the fluid loss properties. Carbon nanotubes not only reduced fluid loss but also filter cake thickness at high temperature and high pressure. The filter cake is shown in Figure 11. Carbon nanotubes reduced the fluid loss by physically plugging the nano-sized pores of the filter cake (A.I. El-Diasty). This resulted in a thin impermeable filter cake with reduced fluid loss compared to other two samples. Zinc oxide did not show any improvement in fluid loss.

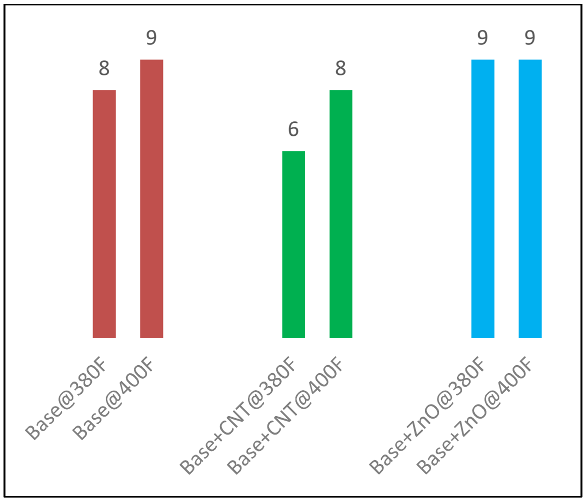

Fig. 10. HTHP fluid loss in mL at 380-400 F

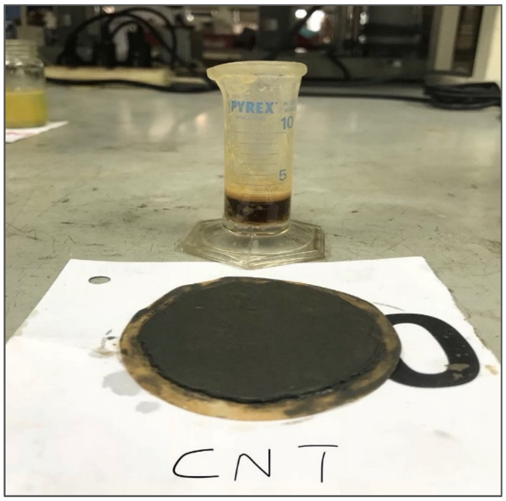

Fig. 11. Filtrate and filter cake of base+CNT at 380F

4. Conclusion

In the current era, HTHP well drilling is a norm and needs a fluid with thermally stable rheology, fluid loss and other mud properties. This study shows that a conventional water base mud system can be optimized by using engineered synthetic polymers, dispersants, and clay to efficiently withstand a high temperature up to or above 400 °F. The base formulation itself has optimized rheological stability and excellent filtration properties at 400 °F. It is also concluded that Carbon nanotubes comparatively helped in thermal stability, rheological and filtration properties of water base mud at high temperature and high pressure. Zinc Oxide nanoparticles showed a small improvement in rheology with an exclusive benefit of being hydrogen sulphide scavenger.

5. Recommendation

The additives involved in the base formulation are Scomi Oiltools commercial chemicals with optimized rheology stability and superior filtration properties at ultra HTHP conditions. These novel chemicals and formulation can be readily applied to currently deep HTHP wells around the globe. This water base mud system can be made high performance inhibitive water base system like KCl/Polymer system, glycol or formate system for drilling reactive shale formations. It is also recommended to analyse acid or surfactant treated carbon nanotubes in water base mud.

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