Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Sepiolite Based Muds as an Alternate Drilling Fluid for Hot Environments

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Keywords: Sepiolite muds, Hot wells, High temperature, High pressure differential, HTHP rheometer, Barite-weighted mud

ABSTRACT

Drilling operations usually experience difficulties in hostile drilling conditions such as high temperature, high pressure, and extreme salinities. Such environments are encountered as drilling deep oil and gas wells, geothermal wells, and unconventional wells. Drilling hot wells experiences extreme difficulties in controlling drilling fluid properties. This fact comes into prominence particularly in geothermal fields. Safe and cost effective drilling in hot environments dictates the customization of a high performance drilling fluid.

This study is an experimentally attempt to design the properties of a new high performance water based drilling mud in order to function adequately in the aforementioned conditions. For this purpose, sepiolite clay obtained from Eskisehir district of Turkey has been used to formulate this new mud system. The properties of mud samples were evaluated with temperatures up to 400°F, pressure differentials up to 500 psi, salt content from fresh to 260,000 ppm using commercial additives. Rheological properties of samples were determined using both conventional viscometer by 16 hours of aging at elevated temperatures and high temperature and high pressure (HTHP) rheometer. Fluid loss properties of samples were measured with standard API filter press and HTHP filter press. In addition, the filtration properties were also investigated with a dynamic filtration apparatus. Both rheometer and dynamic filtration apparatus were used to customize the properties of sepiolite mud system to mimic real borehole conditions. Properties of barite-weighted sepiolite mud samples were also examined.

Results of the study reveal that sepiolite based muds provide good rheological properties up to 400°F. In addition, these muds are not sensitive to salt intrusion and yield better rheology with increasing salt content. Although sepiolite muds are known to have unacceptable high filtration rates, customized sepiolite muds in this study exhibit excellent filtration characteristics under both high temperature and pressure differential. Dynamic filtration rates less than 0.35 ml/min even for barite-weighted mud samples are obtained at 400°F of temperature and 500 psi of pressure differential. Rheological and filtration effectiveness of sepiolite muds in harsh conditions are experimentally demonstrated. In short, sepiolite muds might be a good alternative drilling fluid particularly in geothermal wells.

1. INTRODUCTION

The clay mineral sepiolite belongs to a group of magnesium silicate with a fibrous texture whose idealized formula can be written as $Si_{12}Mg_8O_{32}.nH_2O$. SEM image of sepiolite is shown in Figure 1. Some prominent properties of Sepiolite are also tabulated in Table 1.

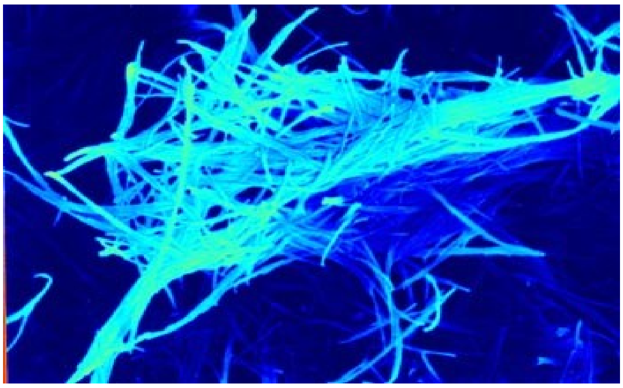

Figure 1: SEM image of a Sepiolite particle, (Osgouei (2010))

Sepiolite has a wide range of application areas such as pharmaceutical industry in the ceramic industry, agriculture, animal husbandry and farming sector by sector, catalytic applications of fiber reinforced cement production, rubber industry, bioreactors, industrial waste water treatment and flue gas waste removal, etc. (Sabah and Celik (1998)).

Clay sepiolite is proposed to be used in drilling fluid since it is not sensitive to high temperature. The yield of drilling mud prepared with sepiolite is higher than that of commercial bentonite. In addition, sepiolite suspensions provide sufficient rheological values at high temperature and/or high salinity. However, the important disadvantage of sepiolite suspension is to have very high API water loss, therefore it is not suitable for using in drilling operations without controlling rheological and filtration loss properties.

Table 1. Properties of sepiolite clay.

Particle Structure	Fibrous
Mohs' Scale	2.0-2.5
Surface Area	150-320 m²/g
Cation Exchange Capacity	30-50 meq/100g
Melting Point	1550 °C
Water Absorption	Wide
Oil Absorption	up to 80 % of its weight

Rheology is defined as the study of the deformation and flow of matter. Viscosity is a measure of the resistance offered by that matter to a deforming force. Shear dominates most of the viscosity related aspects of drilling operations. That is why viscosity of drilling fluids is the property that is most commonly monitored and controlled. Retention of drilling fluid on cuttings is thought to be the primary function of the viscosity of the mud and its wetting characteristics. Providing stable suspensions with high viscosity at low concentrations makes sepiolite a good candidate to be the main clay for a drilling fluid. Designing the drilling fluid and controlling its properties in oil, gas, and geothermal drilling operations is very crucial. If the drilling fluid cannot preserve its properties in hot environments, problems may occur in drilling operation and may be ended up with abandoning the well.

When the hydrostatic pressure of the drilling fluid is greater than the pore pressure, drilling fluid invades through the formation. Suspended solids attempt to flow in with the liquid fraction, but very quickly particles of the appropriate size (generally one-sixth to one-third the size of pore throats at the borehole) bridge the pores and begin to build a filter cake. In time, finer and finer particles fill the interstices left by the bridging particles and ultimately form such a tight web that only liquid (filtrate) is able to penetrate. Once this filter cake is established, the flow rate of fluid into the formation is dictated by the permeability of the cake. When mud is not being circulated, filter cake grows undisturbed (static fluid loss), and the rate of filtration after the cake is established is proportional to the square root of time. When the mud is being circulated, the filter cake grows to the point at which the shear stress exerted by the mud balances the shear strength of the filter cake (dynamic fluid loss). Under this condition, the cake has a limiting thickness and the rate of filtration after the cake is established is proportional to time. Often, spurt loss is greater under dynamic conditions. Whether static or dynamic, the particles that invaded the formation during the spurt loss phase may or may not ultimately help to form an internal filter cake, too.

Flocculation causes particles to join together to form a loose, open network. When a drilling fluid is flocculated (e.g., through the addition of salts), the filter cake that is built up at the wall of borehole contains some of that flocculated character, and the rate of filtration increases. High temperature causes clay particles to flocculate easily and result in unacceptable high viscosities and water losses. Conversely, thinners (deflocculants) used to disperse the clay flocculated, thereby decreasing cake permeability.

In geothermal drilling operations, clay bentonite which is conventionally used in fresh water based drilling fluids cannot deliver proper rheological and water loss properties at temperatures above 300°F. The flocculation of drilling fluids may result in unsuccessful drilling operation. Moreover, the excessive gelation of drilling fluid sourcing from high temperature may cause problems in logging operations as well. Similar behavior may be observed if the mud is too sensitive to saline environments. It is inevitable to search for another alternate drilling fluid system in hot and salty environments even though high salinity is not usually associated to geothermal fields.

From the drilling fluid point of view, high temperatures can be considered as those above which conventional drilling fluid additives begin to thermally degrade at an appreciable rate. The degradation leads to loss of product function, and system maintenance becomes difficult and expensive. The majority of drilling fluid treatment chemicals derived from natural products begins to degrade at temperatures between 250 and 275°F. However, many systems designed for hot wells are based on clay containing lignosulphonates and lignite that can exhibit temperature stability approximately up to 350°F. However, management of these drilling fluids above 300°F can be difficult and expensive.

Safe and cost effective drilling in hot environments dictates the customization of a high performance drilling fluid. In short, the sepiolite muds might be a good alternative drilling fluid particularly in geothermal wells.

2. BACKGROUND

Numerous investigators have studied to formulate a water-based mud system that can be used in the high temperature and the high saline environments, Carney et al. (1976, 1980 and 1982), Hillscher and Clements (1982), Moussa (1985), Guven et al. (1988), Zilch et al. (1991), Serpen et al. (1992), Serpen (1999), and Serpen (2000). Such mud can also be used in very deep oil wells that present similar temperature conditions to the geothermal environment. One common point among the investigators is that almost all mud samples prepared with sepiolite clay contain abundant different additives to obtain suitable viscosity and filtration properties that are necessary to accomplish safe drilling operations with minimum cost.

Drilling fluids prepared with sepiolite with no additives protect their structure at temperatures up to 300°F and performs better than bentonite and attapulgite when exposed to the same conditions (Carney and Guven (1980)). Sepiolite clay used in conjunction with saponite at higher temperatures exhibits better rheological properties. Sepiolite begins to convert to a smectite at 300°F, and this reaction is fully completed at 500°F. The new smectite in the fluid have a thin flakey morphology and they increase the viscosity and improve the filtration losses (Guven et al (1988)).

2.1 Rheological Properties

In their experimental work, Serpen et al. (1992) compared sepiolite mud with bentonite and attapulgite muds at ambient condition and showed that sepiolite mud gave better rheological and filtration properties for various salinities. The effect of grain size on the rheological properties of sepiolite slurries at ambient temperature were investigated by Carney et al. (1976) and revealed the considerable differences.

It is well known fact that the effects of mixing speed, the mixing time, and the grain size on rheological and filtration properties for the bentonite based muds have trivial effect at ambient condition and can easily be neglected. In contrast, in an experimental study, Altun et al. (2005) showed that the sepiolite based muds behave in an entirely unusual manner under specified conditions mentioned above. Better viscosities and filtration properties were obtained from the sepiolite muds when the mixing speed and mixing time were increased and grain size was decreased. Rheological properties of fresh water based, semi saturated, fully saturated sepiolite muds are investigated at the ambient conditions by exposing them to different aging periods.

The sepiolite muds prepared with fresh water have Non-Newtonian fluid behavior. Depending on increase in aging time, the fluids shear stress tends to increase. These muds have high yield point and gel strength with respect to salt saturated system. Generally, it is observed that fresh water sepiolite muds have higher rheological values than fully and semi saturated sepiolite muds. This situation confirms that shear stress value of sepiolite clay is inversely proportional with increasing salinity.

Another important observation is the effect of salt concentration on rheological behavior. Simply, higher the salt content in the mud, lower the shear stress. Salt content and aging period have significant effect on rheology of sepiolite muds. As shown in Table 2, increased salt content reduces the shear stress or apparent viscosity; in other words, higher the salt content, lower the yield of sepiolite clay. Shear stress recorded at 600 rpm of viscometer speed and 48 hours of aging decreases from 42 for fresh water mud to 32 for saturated mud. Total change referenced to fresh water mud has a value of 24 % and it is very important. The change in shear stress is more dominant at lower aging periods. Another important parameter effecting shear stress is aging period of sepiolite muds as indicated in Table 2, shear stress increases with increasing aging period; for instance, there is 11 % variation for fresh water mud case when the period of aging varies from 20 min to 48 hours. The aging effect gets higher when the salt content increases. As a result, unlike bentonite based muds, the rheological properties of sepiolite based muds are more dependent on aging period and salt concentration, (Altun et al. (2005)).

Table 2: Effects of aging and salt content on rheological behavior at ambient conditions (Altun et al. (2013)).

		Shear stress @ 600 rpm, lbf/100 sq ft				**Aging effect (%)**
		20 min	16 hrs	24 hrs	48 hrs	
Mud Type	Fresh water	38	38	42	42	**11**
	Semi -saturated	26	33	35	36,5	**40**
	Saturated	21,5	26	29	32	**49**
	Salt effect (%)	**43**	**32**	**31**	**24**	

2.2 Filtration Properties

Poor filtration property of sepiolite based mud is a well-known fact and has already been addressed by some investigators, such as Carney and Meyer (1976), Serpen et al. (1992), and Altun et al. (2005). High water loss problem is resolved to some degree by using polymers, such as Na-polyacrylates (cypan) and synthetic resin (resinex), Serpen et al. (1992).

A good filtration characteristic is expected from any mud used in a drilling well, particularly in high temperature environments. The problem gets worsen with increasing salt intrusion into the mud. As a result, both high salt content and high temperature make sepiolite muds unique among others in terms of high filtration rates. Thicknesses of mud cakes obtained from sepiolite muds ranging from 6 to 10 mm are too thick due and unacceptable due to high filtration rates.

It is also interesting that unlike bentonite muds, API standards do not specify any water loss value for the sepiolite muds. Moreover, the API water losses of the muds are much above the industry limits. If the drilling environment is exposed to sensitive formations, almost zero water loss is needed and should be achieved by means of additives.

The effect of aging period and salt content for sepiolite muds shown in Table 3 indicates that there is negligible effect of aging periods on water loss of sepiolite muds prepared with fresh water. Similar behavior is observed when the sepiolite muds are prepared with different salt content.

Table 3: Effect of salt content and aging on API water loss, (Altun et al. (2013))

		API water loss, ml			**Aging effect (%)**
		20 min	16 hrs	24 hrs	
Mud Type	Fresh water	108	108	108	**0**
	Semi - saturated	110	110	108	**2**
	Saturated	98	92	86	**14**
	Salt effect (%)	**9**	**15**	**20**	

2.3 Dynamic Filtration

As mentioned before, there are two kinds of filtration during drilling and completion operations. One is the static filtration after stopping the circulation of drilling fluids. The mud cake thickness increase gradually. On the other hand, the filtration rate decreases with time. Another is the dynamic filtration when the mud cake formed is eroded by circulating of drilling fluids. The erosion rate depends on the shear rate of the fluid at the face of the cake. If the shear rate remains constant, cake thickness and filtration rate reach steady state conditions, usually in a matter of hours. When the conditions change, a new steady state will be established. There is no proportional relationship between static filtration and dynamic filtration of different drilling fluids; therefore, the measurement of dynamic filter loss is particularly important.

FANN Model 90, a dynamic radial filtration apparatus, evaluates the filtration properties of a circulation fluid through a ceramic core. It can be also used in the industry for conducting filter cake formation and permeability analysis when drilling fluid optimization through shale sections. Dynamic filtration simulates the effect of fluid movement (shear rate) on the filtration rate and filter cake deposition in an actual well. In addition, the Model 90 can be heated and pressurized to provide the closest possible simulation of downhole conditions. The filter medium is a thick walled cylinder with rock like characteristics to simulate the formation. The filter medium is available in varying porosities and permeabilities.

The test determines if the fluid is properly conditioned to drill through permeable formations. Currently there are no standard methods for the interpretation of Dynamic Filtration Data. Some parameters that can be determined from the data obtained using the Model 90 are spurt loss volume, particle plugging of pores, dynamic filtration rate, and cake depositional index (CDI), (Osgouei (2010)).

Moreover, the values named above for CDI and filtration rate have been revised for a field mud, and the desired maximum recommendation values of CDI and filtration rate are given in Table 4 for the most oil well drilling fluid systems.

Table 4. Maximum recommended values for Fann Model 90, (Osgouei (2010))

Mud Weight, lb/gal (sg)	Rate, mL/min	CDI
9-12 (1.08-1.44)	0.22	25
12-15 (1.44-1.80)	0.18	20
15 or greater (1.80 or greater)	0.14	16

3. OBJECTIVE OF THE STUDY

It is obvious that there are no sufficient works on sepiolite based drilling fluids. In other words, all the attempts are failed in terms of controlling the rheological and particularly the filtration characteristics of sepiolite muds. Sepiolite is used in most of the work done before as additive to improve properties of main clay such as bentonite, saponite, and attapulgite. Thus, it is noticeable that consideration of sepiolite as the main clay of a drilling fluid system is sizeable contribution to fill the gap in the drilling industry. In conclusion, if rheological and water loss properties of sepiolite base muds are controlled by using additives, it can become a proper drilling fluid in high salinity and high temperature environments.

The main objective of this study is to use sepiolite as the main clay in a drilling fluid system by formulating sepiolite muds with commercial additives and to develop a suitable mud system in high temperature environment, particularly for geothermal fields.

4. METHODS AND MATERIALS

API RP-13B Standard procedures are employed throughout the experimental study to determine rheological and fluid loss properties. Also according to API Spec 13A, drilling grade sepiolite shall be deemed to meet the requirements of the international standard if a composite sample representing no more than one day’s production conforms to the physical specifications of Table 5, API-13A, (1990).

Table 5: Sepiolite physical specifications (API Spec 13A (1990)).

Suspension properties	Specification
Viscometer dial reading at 600 r/min	Minimum 30
Residue of diameter greater than 75 μm	Maximum mass fraction 8,0 %
Moisture, %	Maximum mass fraction 16,0 %

All mud samples prepared in this study are based on the formulation of 350 ml of fresh water that contains 20 g of sepiolite clay along with different concentrations of some additives in order to acquire the best performance from additives such as polymer A, polymer B, soda ash, caustic and glycol. In addition, properties of sepiolite muds examined in this work are also investigated for two different brine (NaCl) concentrations, 200 g/l and 400 g/l, respectively. Prepared muds are subjected to hydrothermal treatments in aging cells that is rolled in an oven at temperatures up to 400^{o}F for 16 hours. Rheological properties such as apparent viscosity, plastic viscosity, yield point, and gel strength of the sepiolite suspensions are measured at ambient condition using a coquette type Fann Model 35A viscometer before and after high temperature aging. Rheological properties of sepiolite muds are also investigated using Fann Model 50 SL HTHP rheometer at high temperatures (up to 400 ^{o}F) and high pressure (700 psi). Static filtration properties of the samples are measured by standard API filter press and HTHP filter press equipment. Formulation of sepiolite muds used in this study is based on the mixing order listed in Table 6.

Table 6: Compositions of unweighted and weighted sepiolite mud.

Substance	Quantity (lbm/bbl)	
	Unweighted	Weighted
Sepiolite	20	20
Soda Ash	0.1	0.1
Polymer - 1	4	4
Polymer - 2	5	5
Barite	-	150

Sepiolite clay samples were obtained from Sivrihisar -Eskisehir district of Turkey. The pieces of sepiolite clays were reduced to a smaller size using large crushers, and then it has been reduced to a size below 74 microns (200 mesh) by using rotary grinding. The mineral composition of the sample is given in Table 7. The XRF analysis of grinded sepiolite is given in Table 8. These results indicate that the sepiolite used in this study can assumed to be pure.

Table 7: Mineral composition of sepiolite sample.

Mineral composition (%3 by volume)								
Ankerite	Hydro magnesium	Brucite	Dolomite	Magnesium	Feldspate Groups	Quartz	Clay+Mica	
							Others	Sepiolite Groups
-	-	-	-	-	Trace amount	Trace amount	-	100

Some special materials are used as additives, all in technical grades, in order to control of sepiolite base mud properties especially for filtration control that is the major problems of drilling fluids prepared with sepiolite clays. Polymer-1 is a liquid polymer used to reduce the viscosity of the mud and functions extremely well in reducing high-temperature gelation. It is used to pretreat the mud system prior to drilling cement and stable at temperature above 400°F that may be used as a deflocculants to maintain low rheological properties in high temperature wells. Polymer-2 is a filtration control agent provides filtration control and secondary viscosity in water-based drilling fluids at temperature beyond 400°F. Caustic or soda ash is used to control of mud pH and water hardness.

Table 8: XRF analysis of sepiolite samples.

CaO % by weight	MgO % by weight	SiO_2 % by weight	Fe_2O_3 % by weight	K_2O % by weight	Na_2O % by weight	Al_2O_3 % by weight
4.37	23.22	52.31	1.23	0.35	<0.01	2.69

In this study, the experiments with sepiolite clay comprise three different groups. In the first group, water loss and rheological properties of fully saturated sepiolite muds (400 g sodium chloride in 1 liter distilled water) were investigated. The second group is semi saturated (200 g sodium chloride in 1 liter distilled water) sepiolite muds, and the third group includes the experiments made with fresh water. Mud samples are also investigated for barite-weighted sepiolite muds.

5. RHEOLOGICAL AND FILTRATION PROPERTIES OF SEPIOLITE MUDS CONTAINING ADDITIVES

Rheological properties of the base mud are measured in 80°F and 120°F after 16 hours aging periods for different temperatures. Results of rheological and water loss experiments of both weighted and un-weighted sepiolite base muds containing additives are given between Tables 9 and 10.

Bourgoyne et al. (1991) defines the range of plastic viscosity and yield point for an un-weighted bentonite mud is 5 to 12 cp at 120 °F and 3 to 30 lbf/100 ft^2, respectively. These ranges considered to evaluate the rheological results obtained from sepiolite muds, since there is no data specified in API standards.

The plastic viscosity values ranges of the un-weighted sepiolite muds vary between 11 to 25 cp measured at 120°F as shown in Table 9. These values are acceptable by considering high aging temperatures. Likewise, the yield point values ranging from 9 to 17 lbf/100 ft^2 are in acceptable interval for all samples. It is experienced that the apparent viscosity of muds first decrease until 350 °F, and then began to increase. Such situation is similarly observed in yield point. The increase in yield point is considerable while the variation of plastic viscosity above 300°F is not. This behavior is a distinctive property of sepiolite clays. It is a well-known fact that sepiolite begins to convert to a smectite at 300°F, and this reaction is totally completed at 500°F. The new smectite (thermally altered sepiolite clay, like saponite) in the fluid have a thin flakey morphology, and they increase the viscosity and improve the filtration losses (Bourgoyne et al. (1991)). Temperature effect on the rheology of un-weighted sepiolite muds are shown in Table 9. As expected, shear stress decreases with increasing aging temperature until 350°F, then tends to slightly increase with increasing temperature of 400^{o}F. If a mud is flocculated, increase in shear stress with higher temperature is inevitable. Increase in the shear stress is not caused by flocculation since it is not supported by substantial increase in the filtration rate; i.e., the mud still exhibits appropriate filtration rate at this temperature.

Similarly, the plastic viscosity values ranges of the weighted sepiolite muds vary between 16 to 33 cp measured at 120°F as shown in Table 10. These values are acceptable in as much as both the experiments are run at high aging temperatures and the mud samples are weighted. Likewise, the yield point values ranging from 11 to 29 lbf/100 ft^2 are in acceptable interval for all samples. As observed in the un-weighted system, the shear stress decreases with increasing temperature, then increases with increasing temperature at lower value of 300°F compare to that of un-weighted system. When the shear stress behavior is examined together with filtration rates, it is obvious that the mud is not flocculated yet. It can also be inferred from Tables 9 and 10 that when the concentration of inert materials (barite) is increased in the mud, higher shear stress values are observed. This increase in shear stress is dominantly caused by the increase in plastic viscosity. The more the content of inert solids in the mud, the more increase in the plastic viscosity rather than yield point as observed from the test results.

HTHP filter press tests are performed from ambient to high-temperatures to characterize water loss behavior at 100 psi pressure differential. As seen from Table 9 and 10, both weighted and un-weighted mud samples exhibiting very low filtrations collected at 7.5 min and 30 min have excellent fluid loss values, even at high temperatures. Note that the HTHP water loss slightly increases with increasing aging temperatures. API standards do not specify any water loss values for the sepiolite muds. Amount of filtration at 400°F is slightly high comparing to low temperatures due to the possible decrease in polymers efficiency around 400°F. However, the amount of water loss has an acceptable value at such high temperature.

Table 9. Rheological and filtration properties of un-weighted sepiolite mud aged at high temperature condition in fresh water system.

Aging temperature, °F		80		300		350		400	
Dial Reading	@ 600 rpm	71	59	59	43	40	31	46	36
	@ 300 rpm	46	38	38	28	26	20	32	25
	@ 200 rpm	35	30	29	22	20	16	26	20
	@ 100 rpm	22	19	19	14	13	11	18	12
	@ 6 rpm	5	4	4	3	3	3	6	4
	@ 3 rpm	4	3	3	2	2	2	5	3
Temperature of rheology measurement, °F		80	120	80	120	80	120	80	120
Plastic Viscosity, cp		25	21	21	15	14	11	14	11
Yield Point, lb/100 sq ft		21	17	17	13	12	9	18	14
HTHP water loss, cc (7.5/30min)		6.4/14.6		6.4/14.5		7.2/15.7		11.8/24.5	
Cake thickness, mm		2		2		2,5		3	

Table 10. Rheological and filtration properties of weighted sepiolite mud aged at high temperature condition in fresh water system.

Aging temperature, °F		80		300		350		400	
Dial Reading	600	95	107	56	43	61	46	64	52
	300	62	70	35	27	39	30	48	38
	200	51	55	26	20	30	23	34	30
	100	35	36	16	12	19	15	25	19
	6	8	8	3	3	4	4	6	5
	3	6	7	2	2	3	3	4	4
Temperature of rheology measurement, °F		120	80	80	120	80	120	80	120
PV		33	37	21	16	22	16	16	14
YP		29	33	14	11	17	14	32	24
Temperature of filtration measurement, °F		300		300		300		300	
HTHP water loss, cc (7.5/30min)@100 psi		2,9/6,5		3/7,6		4,0/9,0		7,2/15,5	
cake thickness, mm		3		3,5		3,5		4	

6. RHEOLOGICAL PROPERTIES OF SEPIOLITE MUDS AT HIGH TEMPERATURE AND HIGH PRESSURE

HTHP rheological properties of sepiolite slurry and sepiolite base muds have been tested using Fann Model 50 SL HTHP Rheometer to better characterize of the mud behaviors under more realistic conditions. A different low-yield sepiolite clay was used to prepare mud samples tested in the HTHP Rheometer. Samples are tested at a given pressure of 700 psi and temperatures ranging from 300°F to 400°F with slight increment of 5°F. The results are depicted in Figure 2. Sepiolite slurry refers to the mud containing only 20 lbm/bbl of sepiolite clay and 1 bbl of fresh water. The same composition (given in Table 6) was considered while preparing base mud samples using low-yield sepiolite clay.

Findings reveals that aged sepiolite slurry has higher viscosity values. This is an expected situation so that similar behavior was observed at experiments run with conventional viscometer (Fann Model 35). The viscosity increases when additives are added to sepiolite slurry. Aging at high temperature results in viscosity decrease in the samples with additives. The similar rheological behavior tendency was observed for both muds with and without aging. While amount of shear stress and consequently viscosity of prepared sepiolite base mud decrease up to 350°F, these muds experience rapid viscosity increasing after 350°F. The reason of this behavior might hidden in chemical interaction between sepiolite clay and used polymers. Further investigation can be carried out to figure out nature of this viscosity variation. The traditional viscosity measurement using conventional viscometer (Fann Model 35) was also performed on mud samples prepared using new low-yield sepiolite clay. The rheological properties of base mud sample aged at high temperatures (300-350-400°F) was determined at ambient conditions after cooling at room temperature. Compare to the results obtained from HTHP Rheometer, traditional viscosity measurements gives higher values as seen in Figure 2.

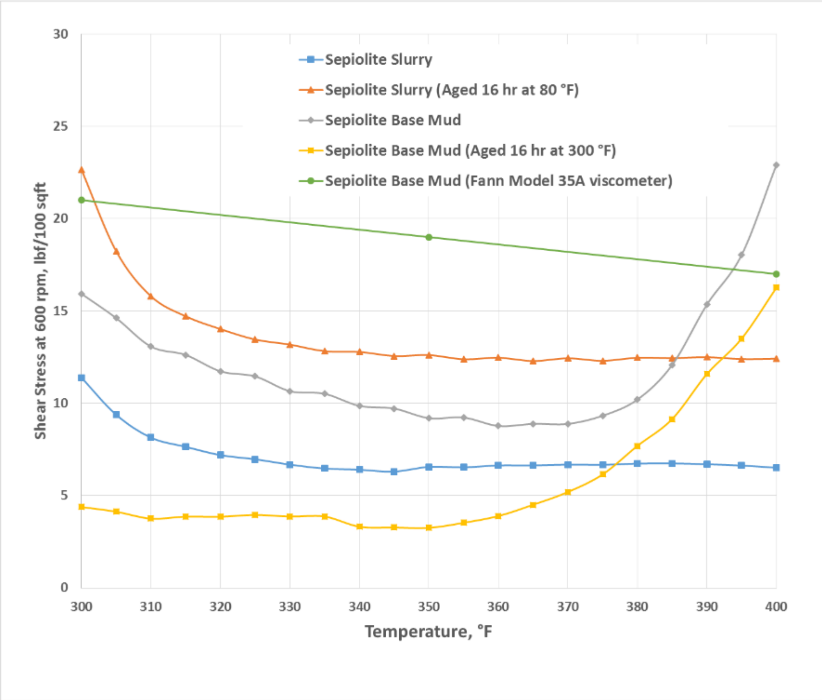

Figure 2. HTHP Rheological Properties of Sepiolite Muds

7. DYNAMIC FILTRATION PROPERTIES OF SEPIOLITE MUDS

200 lbm API Barite is added to base mud in order to get a mud with 11.5 lbm/gal density. The mud samples are subjected to dynamic filtration experiments. In addition, dynamic filtration of un-weighted sepiolite mud (density = 8.70 lbm/gal) is conducted in order to compare the results.

In order to obtain best performance in terms of particle plugging pores, and to compare dynamic fluid losses among clays with different grain sizes (three different sizes of clays) were selected. These three different particle sizes are below 20 microns, above 75 microns, and particles having grain size between 20 and 75 microns. After first experiments, the study attended with the particle size between 20 and 75 microns. Effective bridging of a reservoir depends upon both the particle size distribution of materials comprising the drill-in fluid and the pore throat diameters of the reservoir rock. A bridging material is chosen by matching its size to the diameter of formation pore throats. The industry-accepted rules for selecting size and concentration of bridging materials are based upon work carried out by A. Abrams (1977). The medium particle size of the bridging additive should be equal to or slightly greater than one-third the medium pore size of the formation. Once the mean pore diameter is known, the particle size distribution of the bridging solids must be measured and adjusted to meet the required specifications and included in the drill-in fluid formulation.

An alternative method of determining optimal particle size distribution is to use the ideal packing theory. The Ideal Packing Theory can be defined as the full range of particle size distribution required to effectively seal all voids, including those created by bridging agents' results in a tighter and less invading cake (Dick et al, 2000). In spite of this theory and considering to the results obtained from dynamic filtration tests, it is clear that drilling mud prepared with sepiolite having grain size between 20 and 75 microns provides better sealing and proper results in terms of filtration rate and cake deposition index while using a ceramic filter core having 35 micron (5.5 darcy) pore size. The results are given in Table 11.

Table 11: Summary of the test conditions and results of experiments.

Temperature, ^{0}F	Δp, psia	DFR, ml/min	CDI, ml/hr/hr	Spurt loss, ml	Particle size (d), micron
300	100	0.22	6.3	3.50	20< d <75
300*	100	0.32	0.75	13.60	20< d <75
300	100	0.25	12.6	2.60	75<d
300	100	0.26	6.95	3.00	20>d
350	100	0.27	6.98	3.70	20< d <75
400	100	0.34	6.75	3.25	20< d <75
300	500	0.33	3	4.40	20< d <75
200	100	0.12	5.47	2.90	20< d <75
*: Un-weighted Sepiolite base mud system					

While forming an external filter cake, fine solids are especially forced into the formation, building an internal filter cake. An internal filter cake plugs the near surface pore and reduces the formation permeability. Fine particles penetrate deeply into the pores and are not easily removed by back flushing. Invasion of larger particles is usually localized to near surface. Studies conducted by Bailey et al. (1999) show a strong correlation between invasion and damage. Because of that, minimizing of internal filter cake and quickly forming of external cake is very important for both fluid loss and formation damage control. A semi permeable slicker external filter cake can significantly reduce the invasion of the solids and the filtrate.

In all the tests, the internal filter cake is formed during the first 5 seconds, as can be seen in the results, once this internal filter cake is formed; the incremental filtration volume is minimal. These results also show no considerable increase in spurt loss. Data obtained from tests shows the proper filtration rate (0.22 – 0.27 ml/min) for sepiolite base muds at high temperature and 100 psi pressure (according to confirmation by FANN Company). Dynamic filtration results of weighted (20< d <75) mud at 300°F and 100 psi is given in Figure 3. Also in temperature of 300°F and 500 psi pressure, it is observed that amount of 0.33 ml/min in terms of filtration rate that is a reasonable value in high pressure condition for sepiolite base muds. Moreover it is observe that in the entire tests amount of low CDI (below 10 ml/hr/hr) that is a desirable value. Also, a decrease in the CDI value is observed with increasing pressure, which indicates a compressible filter cake. However, in temperature of 400°F at 100 psi pressure differential, we can see a little high filtration rate (0.34 ml/min) for the typical composition of mud. It can be improved with mud treatment, using of other concentration of additives. In the case of unweighted sepiolite mud, amount of filtration rate (0.32 ml/min) is higher than weighted mud at the same condition, also unweighted sepiolite mud have amount of very low CDI (0.75 ml/hr/hr) that indicates, external cake is not formed, as seen in the test process and unweighted system have a high amount of spurt loss (13.60 ml).

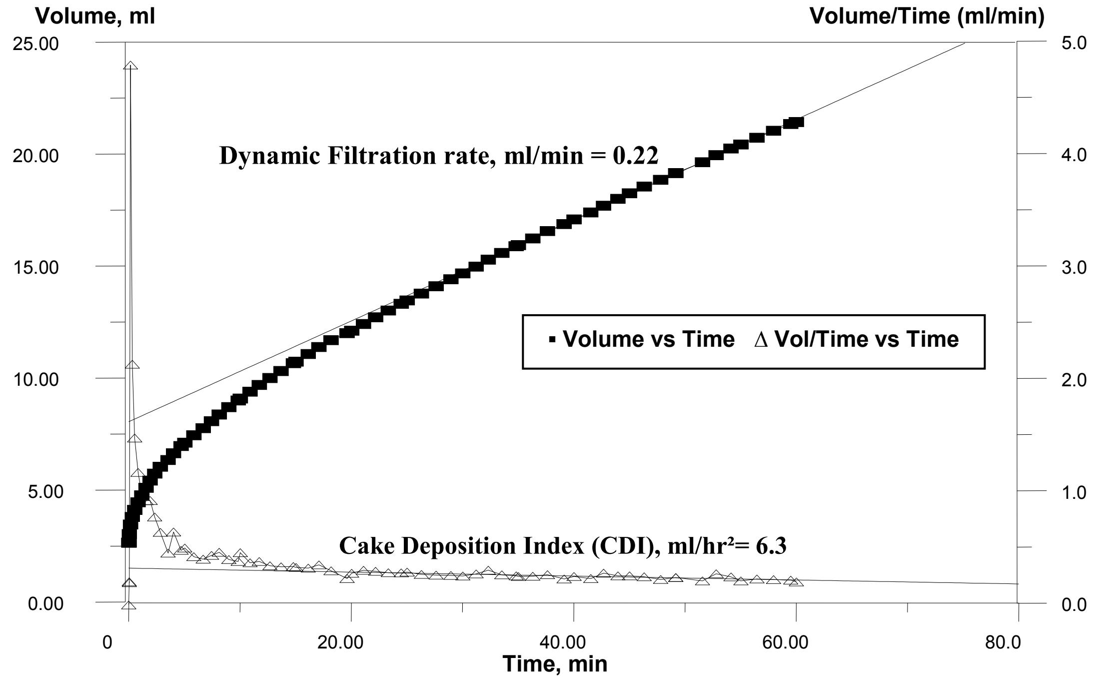

Figure 3: Dynamic filtration results of weighted (20< d <75) mud at 300°F and 100 psi.

8. CONCLUSION

In this study, rheological and filtration properties of drilling fluids prepared with sepiolite clay are experimentally investigated. Experiments are conducted with and without some commercial additives for different temperatures and pressures with varying salinity. In consequence, the following results are experimentally obtained:

- Since the relationship between shear stress-shear rates is not linear, the rheological properties of muds show a non-Newtonian behavior. All of the mud samples have pseudo plastic structure because apparent viscosity decreases with increasing shear rates.
- Aging period of muds has significant effect on rheological properties and slightly effect on water loss properties. Even though aging effect is not recognized by API standard for clay sepiolite, it is recommended that minimum of 16 hours of aging should be applied to get better rheological values.
- Examined sepiolite muds give relatively high gel strength values. The ratio of yield point to plastic viscosity of the mud (YP / PV) is typically about 3 indicating proper rheological characteristics.
- Mud samples prepared with fresh water result in better rheology. On the other hand, mud samples prepared with fully salt saturated result in better filtration rates.
- Amount of water loss and rates in sepiolite base drilling fluid can be controlled using different additives at high temperature and high pressure conditions. It is indicated that sepiolite muds exhibits have an acceptable water loss at 350°F and 500 psi pressure differential.
- Filtration properties of commercial drilling fluids used at high temperature (above 300°F) and especially with high salinity conditions are not reported in literature.
- Drilling muds prepared with sepiolite having average grain size 25<d<75 provides better sealing and proper results in terms of dynamic filtration rate and cake deposition index. Dynamic filtration rates are affected from the temperature variations. DFR increases with increasing temperature. Cake deposition index are similarly affected by the temperature variations. However, the temperature augmentations slightly increase CDI. As the pressure differential increases, DFR proportionally increases and CDI decreases, that indicate a compressible filter cake. On the other hand, CDI decreases at high pressure differential that indicates a compressible filter cake.
- Investigation on HTHP rheological properties of sepiolite muds indicates more realistic results compare to traditional method. It can simulate real conditions to evaluate effect of temperature on rheological properties. Aged sepiolite slurry has higher viscosity values. In the case of sepiolite base mud, HTHP Rheometer results yield that rapid viscosity increases initiates after 350°F and fastens after 380^{o}F. More investigation will be helpful to find out about this variation.

ACKNOWLEDGEMENT

Author of this work specially thanks the Scientific and Technological Research Council of Turkey (TUBITAK) and Turkish Petroleum Corporation for funding this research and for giving the permission to publish the findings of this study.

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