Application of Ester based Drilling Fluid for Shale Gas Drilling

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Abstract. Water based mud is the most commonly used mud in drilling operation. However, it is ineffective when dealing with water-sensitive shale that can lead to shale hydration, consequently wellbore instability is compromised. The alternative way to deal with this kind of shale is using synthetic-based mud (SBM) or oil-based mud (OBM). OBM is the best option in terms of technical requirement. Nevertheless, it is toxic and will create environmental problems when it is discharged to onshore or offshore environment. SBM is safer than the OBM. The aim of this research is to formulate a drilling mud system that can carry out its essential functions for shale gas drilling to avoid borehole instability. Ester based SBM has been chosen for the mud formulation. The ester used is methyl-ester C12-C14 derived from palm oil. The best formulation of ester-based drilling fluid was selected by manipulating the oil-water ratio content in the mud which are 70/30, 80/20 and 90/10 respectively. The feasibility of using this mud for shale gas drilling was investigated by measuring the rheological properties, shale reactivity and toxicity of the mud and the results were compared with a few types of OBM and WBM. The best rheological performance can be seen at 80/20 oil-water ratio of ester based mud. The findings revealed that the rheological performance of ester based mud is comparable with the excellent performance of sarapar based OBM and about 80% better than the WBM in terms of fluid loss. Apart from that, it is less toxic than other types of OBM which can maintain 60% prawn’s survival even after 96 hours exposure in 100,000 ppm of mud concentration in artificial seawater.

1. Introduction
It is estimated that there are large reserves of unconventional gas reservoirs throughout the world such as coalbed methane, shale gas and tight gas sand. Generally, reservoir that contains only free gas as the hydrocarbon source is called as gas reservoir. Gas in the reservoir can be classified as ‘dry’, ‘wet’ or ‘condensate’. The condition is depends on its composition, pressure and temperature at which the accumulation occurred [1]. Shale gas is generally stored in the form of free compressed gas in open pores and cracks. It is stored as adsorbed gas on the surfaces of kerogen or clay minerals. Besides that, the gas has been stored as diffused gas within solid organic matter [2].

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Nowadays, drilling in shale gas formation is expanding rapidly especially in the south central of United States. Some examples of shale gas fields in United States are Barnett shale, Appalachian basin and Rocky Mountain basin. While outside the United States, there is no commercial shale gas projects currently exist but the work for exploration of new shale gas reservoirs is continues to growth [3]. Drilling fluid is used in order to assist the drilling of borehole into the earth. A proper formulation of drilling fluid will enable operator to drill into a desired geological aim at low cost. Drilling fluid should be able to enhance penetration rates, reduce hole problems and minimize damages of formation.

The primary functions of drilling fluid are to control formation pressure, transport cuttings and maintain stable wellbore. Force exerted by a fluid column is called hydrostatic pressure and it depends on the mud density and true vertical depth. Drilling fluid controls subsurface pressure by this hydrostatic pressure. One of the essential functions of drilling fluid is cleaning the drilling hole. During drilling operation, cuttings must be removed from the wellbore. Drilling fluid will be circulated down through the drill bit and it will transport cuttings up through the annulus to the surface. Generally, drill solids have a specific gravity (SG) of 2.3 until 3.0 SG and assuming the average is 2.5 SG. When the mud used during drilling operations is lighter than the drill solids, the drill solids will be slipped downward through the mud [4]. Drilling fluid can be categorized into water-based, oil-based and synthetic-based mud. Each type of based mud has its own advantages and disadvantages. Generally the uses of drilling fluid depend on the well condition.

The formation which is water-sensitive may require oil-based and synthetic-based mud. A proper formulation of OBM can prevent water movement from the mud into the shale. Despite of its effectiveness, oil-based mud can give negative impact to environment when the pollutant is discharged and subsequently dispersed to the sea. The cuttings from oil-based mud do not disperse as much as water-based mud when it is discharged under water. It will form piles of cuttings that blanket parts of seabed. This condition may affect the bottom-dwelling organisms close to the rig [5,6]. The aim of this research is to formulate a synthetic based mud for shale gas drilling. Ester is used as the drilling fluid based.

2. Methodology

The methodology for the measurement of drilling fluid properties was constructed based on American Petroleum Institute (API) Recommended Practice 13B. The recommended practice provides standard procedures for determining the physical and rheological properties of oil-based mud. The measurable properties are drilling fluid density, viscosity, gel strength and filtration test. Other formulation and tests were conducted based on past literature.

2.1. Formulation of Ester based Mud

Three different formulations were designed to determine the best combination of Ester based mud at different oil-water ratio. The formulated ester based mud consists of ester as the base fluid, emulsifier, viscosifier, salt as salinity, lime as alkalinity, fluid loss control additive and weighting agent. The density of the samples was kept constant which is about 10.7 ppg and the formulations are shown in Table 1. Among the three formulations, the best formulation was selected based on the comparison of rheological performance of sarapar-based mud and water-based mud which was designed about the same density. The formulation of SBM and WBM were prepared as in Table 2.
Table 1. Formulation of Ester Based Mud

| Component               | 70/30 (ml) | 80/20 (ml) | 90/10 (ml) |
|-------------------------|------------|------------|------------|
| Ester                   | 245.00     | 280.00     | 315.00     |
| Water                   | 105.00     | 70.00      | 35.00      |
| Primary Emulsifier      | 10.00      | 10.00      | 10.00      |
| Secondary Emulsifier    | 3.00       | 3.00       | 3.00       |
| Viscosifier             | 5.00       | 5.00       | 5.00       |
| Calcium chloride        | 26.25      | 17.50      | 8.75       |
| Lime                    | 10.00      | 10.00      | 10.00      |
| Barite                  | 195.00     | 195.00     | 195.00     |

Table 2. Formulation for other types of mud

| Sarapar-147            | 280.00 ml  |
|------------------------|------------|
| Primary Emulsifier     | 10.00 g    |
| Secondary Emulsifier   | 3.00 g     |
| Viscosifier            | 5.00 g     |
| Lime                   | 10.00 g    |
| Water                  | 70.00 ml   |
| Calcium chloride       | 17.50 g    |
| Barite                 | 195.00 g   |

| Water          | 330.00 g |
|----------------|----------|
| Starch         | 4.20 g   |
| Xantham Gum    | 2.00 g   |
| Potassium Chloride | 9.90 g   |
| Sodium Hydroxide | 4.00 g   |
| Barite         | 185.00 g |

2.2. Rheological Test

Prior to rheological test, mud was mixed using high shear blade mixer. The rheological test was then carried out using Fann viscometer to find the plastic viscosity (PV), yield point (YP) and gel strength of the mud samples in Table 1 and 2. Yield Point (YP) is the stress required to move drilling fluid. It is used to determine the ability of mud to lift cuttings out of the annulus. Plastic viscosity (PV) is a measurement of resistance of fluid to flow. For PV and YP analysis, the sample was stirred at 600 rpm. The reading was stabilized at 600 rpm before proceed to 200, 100, 6 and 3 rpm speed respectively. The results from viscometer reading were used to measure PV and YP value using Eq. 1 and Eq. 2.

Plastic Viscosity, Centi Poise (CP) = Reading at 600rpm – Reading at 300rpm (1)

Yield Point, (lb/100ft²) = PV – Reading at 300rpm (2)

Gel strength was measured at time 10 seconds and 10 minutes. It is the shear stress of drilling mud that is measured at low shear rate after the mud had been static for certain time period. The properties are important to investigate the ability of drilling mud to suspend cuttings and weighting
material when circulation is stopped. For gel strength analysis, the sample was stirred at 600 rpm for 30 seconds before taking 10-second gel strength at 3 rpm. The mud was stirred again at 600 rpm and let it undisturbed for 10 minutes. Then, the gel strength reading for 10 minutes was taken at 3 rpm.

2.3. **API Filter Press Test**

Filter press test was carried out in order to determine the fluid loss of mud at ambient temperature and 100 psi pressure. The equipment used is API filter press that consists of filtration cell, OFI special hardened filter paper, low pressure supply and measuring cylinder. The apparatus must be assembled correctly before the test is carried out. The filter paper must be ensured in a good condition. Mud sample must be put into the cell until it is ¾ full. Pressure of 100 psi was applied to the cell and the fluid loss reading was taken in measuring cylinder every three minutes period of time until it reached 30 minutes.

2.4. **Shale Dispersion Test**

The test was designed to simulate a shale dispersion scenario when drilling into shale gas zone. The test was started by drying the shale sample in the oven at 60°C. Then, the shale sample was screened through 6.73 mm and 2.38 mm sieve sizes respectively. The shale sample retained on 2.38mm sieve screen was weighed and put into a glass jar containing sample of mud for 48 hours. After 48 hours, the mud containing shale was poured onto the sieve screen. Then, the shale samples retained at 2.38 mm sieve screen were washed and blotted. The samples were then dried in the oven at 60°C. The percent of sample recovery was calculated using Eq. 3:

\[
\% \text{ Recovery} = \frac{\text{Weight of sample retained}}{\text{Initial weight of sample}} \times 100\%
\]  

(3)

2.5. **Toxicity Test**

The purpose of the test is to investigate the impact of ester based mud on marine life. Local marine life namely tiger prawn (*Penaeus Monodon*) was used. The Lethal Concentration (LC$_{50}$) was identified in which mud concentration killed 50% of exposed prawns after 96 hours of exposure. The LC$_{50}$ value less than 100 ppm is considered as toxic material. The formulated mud was diluted with a ratio of 1:9 (mud : artificial seawater, v/v). It was mixed for about 30 minutes before settling for one hour. The mixture was used to make different concentrations of toxicant environment for the prawns such as 100, 1000, 10000 and 1000000 ppm respectively. Ten prawns were exposed to each concentration for 96 hours and the observation was done throughout the period. The methodology used for this test was done according to past literature work [6].

3. **Results and Discussion**

3.1. **Rheological Properties for Different OWR**

Rheological properties are important to determine the effectiveness of drilling fluid in order to carry out its main functions. Table 3 shows the comparison of rheological properties of ester based mud at different oil-water ratio (OWR). From the results obtained, it was observed that the mud with oil-water ratio of 80/20 is the best candidate for the selection. It shows good rheological properties as the mud has a medium range of viscosity which is not too thick as compared with 70/30 OWR and not too thin as 90/10 OWR mud system. Besides, the plastic viscosity and yield point values of the 80/20 mud system are about the range of commonly used drilling mud with the plastic viscosity/yield point ratio of between 0.8 to 1.5 [7]. Even though the 70/30 OWR mud system has the lowest fluid loss (Figure 1), but the viscosity was too high and unstable to be used in drilling operation. The system cannot tolerate more contaminants and restrict extra loading of weighing material for higher mud density [8]. Mud with high gel strength is not favorable in drilling operation as it requires high
pumping pressure in order to break circulation after the mud is static for long period. The required 10 min gel strength is typically less than 20 lb/100ft² in which the 80/20 and 90/10 systems passed the limit [7]. The knowledge of gel strength development with time is so important to detect any possible rheological problem in a mud system [9]. Progressive gels are undesirable condition occurred when there is wide different range between the 10-second and 10-minute gel readings. Besides, high-flat gels are also undesired circumstance in which both the 10-second and 10-minute readings are high with no significant difference. Progressive gel can be seen in 70/30 mud system and it was waived for selection. Excessive gel strength may increase the swabbing and surging effect during tripping process of drillpipe. Yield point is used to determine the ability of mud to lift cuttings out of the annulus. From Table 3, YP values decrease dramatically with decreasing of water ratio. The mud with high YP can carry cuttings better than mud with similar density but lower YP [9]. The finding shows YP value of 80/20 mud system was higher than 90/10 mud system. Thus, 80/20 OWR system is the best candidate and was used in the next experiments.

### Table 3. Rheological properties for different OWR

| OWR    | 70/30 | 80/20 | 90/10 |
|--------|-------|-------|-------|
| 600 rpm| 95.0  | 51.0  | 35.0  |
| 300 rpm| 69.0  | 36.0  | 27.0  |
| PV     | 26.0  | 15.0  | 8.0   |
| YP     | 43.0  | 21.0  | 19.0  |
| Gel 10 s | 18.0  | 9.0   | 5.0   |
| Gel 10 min | 24.0  | 16.0  | 6.0   |
| Mud Weight (ppg) | 10.7 | 10.7 | 10.7 |
| Fluid Loss @ 30min (ml) | 2.8 | 3.9 | 5.4 |

### Figure 1. Fluid Loss for Different OWR

3.2. **Comparison with Other Types of Mud**

One of the objectives of this research is to design drilling fluid for shale gas drilling using ester as the base fluid. The research is focusing on the performance and compatibility of ester to act as the base fluid. The performance of ester-based fluid was compared with other base fluids i.e. water-based mud (WBM) and sarapar-based mud which are usually used for drilling wells and the results are shown in Table 4.
Table 4. Rheological properties for three different types of mud

| Types of Mud          | Ester-based | Sarapar-based | Water-based |
|-----------------------|-------------|---------------|-------------|
| 600 rpm               | 51.0        | 63.0          | 55.0        |
| 300 rpm               | 36.0        | 45.0          | 39.0        |
| PV                    | 15.0        | 18.0          | 16.0        |
| YP                    | 21.0        | 27.0          | 23.0        |
| Gel 10 s              | 9.0         | 14.0          | 15.0        |
| Gel 10 min            | 16.0        | 21.0          | 17.0        |
| Mud Weight (ppg)      | 10.7        | 10.9          | 10.6        |
| Fluid Loss @ 30min (ml)| 3.9        | 3.5           | 17.8        |

From Table 4, the performance of all three muds is nearly same. However, the PV of ester-based mud is slightly lower than sarapar-based and water-based. A low PV value shows the capability of the mud to assist drilling rapidly which will reduce the time consumption for drilling a well. Overall, the rheological properties of ester-based mud did not show significant different as compared to sarapar-based mud. Sarapar is commonly used drilling mud base in drilling industries. As such, it proved that ester can also be used as an alternative for drilling fluid base. Nevertheless, large amount of fluid loss (17.8 ml) was found in WBM as observed in Figure 2. It can be postulated that the WBM is not suitable for shale gas drilling as the filtrate will react with shale and may cause shale swelling. Fluid loss performance in ester based and sarapar based mud is about the same and competitive.

![Fluid Loss vs Time](image)

**Figure 2.** Fluid loss for different types of mud

3.3. **Shale Dispersion Test**

There have been numerous techniques were constructed to develop this test at different condition and feasibility [10]. In this paper, a new method was proposed to simulate shale-mud reaction in the borehole. Small size of shale cutting was used to promote larger surface area for the reaction and prevent the aggregation effect. Table 5 shows the percent recovery of shale cuttings in ester-based mud is slightly higher than the sarapar-based mud. It can be claimed that the higher recovery was associated with lesser reactivity of mud with shale. The findings revealed that ester based mud can reduce about 2.25% of shale reactivity as compared with sarapar based mud and is more effective when dealing with water-sensitive shale. It can also prove that the added Emulsified brine phase (calcium chloride) acts synergistically with ester based mud to preserve cuttings integrity and reduce water activity by creating osmotic forces in order to prevent adsorption of water by shale [5,8].
Table 5. Shale dispersion test

|                        | Ester     | Sarapar   |
|------------------------|-----------|-----------|
| Weight of sample used, | 16.34     | 14.69     |
| (Size between 2.38 mm  | (Size      | (Size     |
| to 6.73 mm)           | to 6.73   | to 6.73   |
| Weight of retained    | 15.89     | 13.95     |
| sample, gram (On      | (On 2.38  | (On 2.38  |
| 2.38 mm sieve screen) | mm sieve  | mm sieve  |
| Percent of Recovery, % | 97.25     | 95.00     |

3.4. Toxicity Test
Toxicity test was carried out in order to observe the effect of ester-based mud towards the environment. Past research had been carried out to investigate the toxicity of diesel mud and palm oil mud. The methodology of the past research was used in this experiment [6]. The results from this experiment were compared with the past research result as shown in Table 6.

Table 6. Survival of prawns from toxicity test

| Mud Concentration | Ester Mud | Palm Mud[6] | Diesel Mud[6] |
|-------------------|-----------|-------------|---------------|
| 100,000 ppm       | 60        | 70          | 0             |
| 10,000 ppm        | 100       | 100         | 0             |
| 1,000 ppm         | 100       | 100         | 0             |
| 100 ppm           | 100       | 100         | 30            |

The result shows the comparison of prawn’s survival when exposed to different types of mud and concentrations. Ester-based and palm oil based mud show slightly different result than diesel mud. The prawns started to die when exposed to 100,000 ppm concentration. After 96-hours period of time, four prawns had been observed dead and result in 60% of survival. When compared with past research, ester-based mud has nearly same percentage of survival with palm oil mud. The palm oil mud has 70% of prawn’s survival after 96 hours of exposure in mud. The expected LC₅₀ value could be more than 100,000 ppm which can be considered as non-toxic. In contrast, diesel mud shows the highest toxicity result with zero percent of survival starting from 1,000 ppm concentration. It could achieve LC₅₀ value less than 100 ppm and can be considered as toxic material. Nowadays, some of the countries have banned the use of Oil based Mud for their E&P activities such as USA, United Kingdom, Holland, Norway, Nigeria, European countries, Saudi Arabia, and Qatar [8]. In some areas, the use of oil based mud is permitted if the used mud and cuttings are disposed in an approved disposal site. This research contributes to the preliminary knowledge of using ester based drilling fluid as a green drilling fluid for shale gas drilling.

4. Conclusion
As for conclusion, the best ester mud formulation has OWR of 80/20 which contains 80% ester and 20% water. The rheological properties of ester-based mud have no significance different with sarapar-based and water-based mud which is suitable to be used as a base fluid for drilling process. Minimal fluid loss can be observed in ester based formulation as compared to water based mud although nearly the same as sarapar-based mud. Ester based mud could be the most excellent mud to be used in shale gas drilling as it is less dispersed in shale as compared to sarapar based mud. Moreover, it was proved
to be non-toxic with the expected LC$_{50}$ of more than 100,000 ppm of mud concentration. It can be concluded that ester can be an alternative base fluid for drilling fluid especially for gas shale drilling.

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