Comparative evaluation on rheology performance and thermal stability of ester based drilling fluids

A R Mohamad Daud¹*, S Abdullah¹, A Azizi¹ and E Ariyanto²

¹Faculty of Chemical Engineering, Universiti Teknologi MARA 40450 Shah Alam, Selangor, Malaysia
²Global Research and Technology Center, Scomi Oiltools Sdn Bhd, Shah Alam Selangor, Malaysia

*ahmad2057@uitm.edu.my

Abstract. Drilling fluid plays an important role in ensuring smooth drilling operations. Application of ester based drilling fluid (EBDF) is desirable as it shows comparable performance to the conventional oil based drilling fluid (OBDF) as well as environmental friendly. The ester used as a base in the EBDF is usually derived from vegetable oils such as palm oil. In this study, methyl laurate (ML), methyl palmitate (MP), and isopropyl laurate (IPL) esters were used as a base in the EBDF formulation. Subsequently, their physical and rheological properties were determined. In addition, thermal stability of the EBDF was tested to estimate the maximum operating temperature for the EBDF application. Isopropyl laurate (IPL) based EDBF was found to have better rheological properties at standard test condition as compared to the other two esters used. The IPL based EBDF also showed improved viscosity at 90°C. Thermal stability test conducted on the IPL drilling fluid indicated that it is stable up to 150°C.

1. Introduction

The Drilling fluid is a circulating fluid employed in rotary drilling operations primarily for suspension of drill cuttings, to maintain downhole pressure, heat transfer and facilitate the drilling operations [1]. The removal of the drill cutting to the surface is accomplished by adjusting the mud viscosity to the desired value depending on the type of wellbore. Drilling fluid column also provides hydrostatic pressure which helps control the formation pressure. This is achieved by adjusting the mud density to a desired value [2].

There are several types of drilling fluids which have been developed and tested with varying degree of success. They are oil based drilling fluid (OBDF), water based drilling fluid (WBDF) and synthetics based drilling fluid (SBDF). The OBDF is basically consists of suitable oil, asphalt, water, emulsifier, surfactant, lime, weighting material and chemicals additives. The OBDF has been widely used because of its superior lubricating performance and stability at high temperature. Its application often results in high operation costs and maintenance. In addition, the discharges of the OBDF have been found to be harmful to the environment which limits the usage of the OBDF [3]. On the other hand, the WBDF is favored due to its environmental friendly features (water used in replacement of synthetic oil as fluid base), providing direct disposal route of the cuttings to the environment [4]. However, the WBDF lacked in performance and was found to be unstable at high temperature.
The SBDF offers excellent performance similar to the OBDF and deemed harmless to the environment. Its biodegradable characteristic makes it more desirable than any other conventional drilling fluids. The SBDF is non-polar, less toxic, neither conducts electricity nor dissolves in ionic compound and often recycled than being disposed to the environment as well economical [5]. An example of SBDF which receives a lot of interest is an Ester based drilling fluid (EBDF). They are basically derived from vegetable oils and they are well known for their biodegradability [2,6,7]. Other advantages of the EBDF include faster drilling capability, superior lubricity, reduce drilling costs and provide excellent hole cleaning [6,8].

Different types of esters used as drilling fluid’s base will result in different flow and filtration characteristics of the fluid. Therefore, it is crucial to select an ester that encourage better performance in terms of rheological properties. The drilling fluid’s rheology is commonly characterized by plastic viscosity (PV), yield point (YP) and gel strength (GS). These characterizations are important in designing fluid’s circulating systems to accomplish target objectives in any drilling operations. This study aims to investigate the impact of ester addition on fluid rheology and thermal stability.

2. Methodology

2.1. Formulation of ester based drilling fluid

Three types of palm oil based esters were used as a base in this study. They are methyl laurate (ML), C_{17}H_{34}O_{2}, methyl palmitate (MP), C_{13}H_{26}O_{2} and isopropyl laurate (IPL), C_{15}H_{30}O_{2}. The ester:brine ratio by volume used was 90:10 for all EBDF formulated. Each formulation is prepared in batches of 350 mL or 1 lab barrel. The mixing time and additives used were stated in table 1. All samples were mixed using Hamilton Beach Mixer in about 60 minute to ensure that the formulation is homogenous and particles remain suspended after mixing. The formulations has to be prepared in exact order using specific amount to avoid settling and inhomogeneity of the drilling fluid.

| Mixing Order | Component/Additives                  | Mixing Time (min) |
|--------------|--------------------------------------|-------------------|
| 1            | Ester Base                           | -                 |
| 2            | Primary Emulsifier                   | 2                 |
| 3            | Secondary Emulsifier                 | 2                 |
| 4            | Viscosifier                          | 10                |
| 5            | Fluid Loss Control Agent             | 2                 |
| 6            | Emulsifier Activator (lime)          | 2                 |
| 7            | Drill water + Brine Phase Salinity (Calcium Chloride, CaCl) | 15                |
| 8            | Weighting agent (Barite)             | 5                 |

2.2. Characterization of EBDF

Density Test - The Baroid Mud Balance was used to determine the density of the drilling fluids. It will be balanced by a fixed load at the opposite side, with a rider moving alongside a scale. The drilling mud density will be measured in pounds per gallons (ppg).

Rheology Test - The fluid rheology was tested using Fann Viscometer. It was used to determine the plastic viscosity (PV) at fixed speed, yield point (YP) and gel strength at 10 seconds and 10 minutes. 350 mL of EBDF was used for each measurement. The PV and YP can be calculated using the following equations:

\[
\eta_{PV} = R_{600} - R_{300}
\]

\[
Y_{ph} = R_{300} - \eta_{PV}
\]

where \( \eta_{PV} \) is plastic viscosity, \( R_{600} \) and \( R_{300} \) are dial readings at 600 rpm and 300 rpm and \( Y_{ph} \) represent the yield point.
2.3. Thermal stability.
Drilling fluid was subjected to heat at different temperature ranging from 50°C to 200°C. Each sample contains 20 mL of drilling fluid and heated for 30 minutes in an oven at 50°C, 100°C, 150°C and 200°C.

3. Results and discussion
3.1. Formulation of EBDF
The formulations for all the drilling fluids prepared for this study were based on the formulation presented in table 1. All the additives used in the formulation have their own specific functions important for drilling operation. They have to be measured in exact measurements. The emulsifier and viscosifier play an important role in ensuring that the barite component does not settle after mixing. Settlement of the barite will cause instability to the drilling fluid hence affecting the rheological performance of the drilling fluid. The ester:brine ratio by volume chosen in these runs was 90:10 considering the lower the brine content to ester the lower the viscosity of the drilling fluid would be. This feature will improve rheological properties of the drilling fluid.

3.2. Characterization of EBDF
Overall rheological results of the EBDF formulated in this work are compared to published EBDF data as presented in table 2.

| Rheological Properties | IPL | ML | MP | Palm oil ester |
|------------------------|-----|----|----|---------------|
| Density (ppg)          | 9.8 | 9.8| 10 | 10            |
| PV (cp)                | 20  | 20 | 22 | 21            |
| YP (cp)                | 14  | 19 | 19 | 7             |
| 10s / 10 min GS (lb/100ft²) | 9/12 | 9/10 | 8/9 | 9/12 |

*Data published by Ismail and Foo [1]*

3.2.1. Density measurement.
The density measured for all the three EBDF was almost similar to the published density of palm oil based EBDF. The density was not greatly influenced by the addition of the esters although the molecular weight for all the esters differs. The molecular weight of ML, MP and IPL are 214.34 g/mol, 270.45 g/mol and 242.22 g/mol respectively. In the drilling operation, the density factor affected the hydrostatic head that prevent influx of formation fluid. It must be properly controlled to avoid loss circulation and damage to the formation. The knowledge of density is also important in determining whether the drilling fluid (mud) needs to be weighted up. In this work, the formulation used was designed to form low mud weight to avoid an increase in viscosity.

3.2.2. Rheological properties.
Rheological test was performed at standard temperature of 50°C. Rheology is the deformation and flow characteristics of all form of matter. Rheological measurements include viscosity and gel strength help determine the flow of the fluid under various conditions. This information is crucial in designing circulating systems that is required to accomplish certain desired objectives in drilling operations [9,10]. Results for three fluid rheology properties are presented below.

**Viscosity** – Viscosity is a measure of fluidity of the prepared drilling fluid characterised by its resistance to gradual deformation by shear or tensile stress. Viscosity measurements of each EBDF is shown in figure 1. The trend shows that viscosity of the fluids increases with the rotation speed which
follow the Bingham plastic model of fluid behaviour [11]. The model is more to low shear rate viscosity. The viscosity between ML and IPL shows slightly lower values compared to MP. This is reflected by the molecular weight values whereby the MP has the highest MW. Generally, lower viscosity enhances rheological performance of the drilling fluid. Another important viscosity measurement is plastic viscosity (PV) which refers to the linear shear-stress behaviour observed after the initial shear stress threshold or yield point has been reached. PV measures drilling cuttings suspension and hole cleaning ability of the drilling fluid and therefore a lower value of plastic viscosity is desirable. The value of PV for a drilling fluid is highly affected by its viscosity. As can be seen in figure 2, both ML and IPL have lower PV compared to MP at 20 cp. Thus, it can be concluded that IPL and ML are better candidates for EBDF.

**Figure 1.** Viscosity of EBDFs as a function of speed.

**Figure 2.** Comparison of plastic viscosity obtained at $R_{600}$-$R_{300}$ (rpm) for EBDFs prepared.

**Yield Point** - YP indicates the ability of the drilling fluid to bring drill cuttings to the surface. It also contributes to the degree of hole cleaning efficiency. Higher YP value will give better performance for the EBDF. It can be seen from figure 3 that the YP value for IPL is slightly lower at 14 cp than 19 cp for both ML and MP. These values are higher than the published data for IPL based drilling fluid as reported by Ismail and Foo [1]. However, direct comparison is not possible considering the factors contributing to yield point which include IPL concentration, brine water content and gelling agent used in the formulations of drilling fluid are different than in the present formulation.

**Figure 3.** Comparison of YP between different types of EBDF.

**Gel Strength** - Gel strength measurement represents the drilling fluid ability to suspend drill cuttings and drill pipe when the drilling operation is temporarily halted. Higher gel strength resulted in higher pump pressure and too low gel strength resulted in inefficient suspension of the cuttings. Figure 4 presents the values of gel strength measured for all the EBDF. Small increases in gel strength with
time (GS-10 s and GS-10 min) confirm the thixotropic property of all EBDF tested [12]. The IPL EBDF shows similar gel strength of 9/12 to the published palm oil based EBDF by Ismail and Foo [1]. Overall, the characterization of EBDF results showed that they are comparable in terms of density, viscosity and PV properties. However, IPL showed superior gel strength performance showing adequate increase in gel strength property which is an important parameter when the drilling fluid is in motionless mode or when the drilling operation is temporarily suspended. Although the IPL showed lower YP than the ML and MP EBDF, this property only affects its performance at low shear rate and can be rectified by changing the concentration of brine water and gelling or emulsifier. Therefore, it can be concluded that IPL shows a potential to be considered as candidate for a base fluid in EBDF.

3.3. Rheology of IPL based EBDF at elevated temperature

IPL drilling fluid was chosen and tested for rheological performance at higher temperature of 90°C (200°F). This is to determine the influence of temperature on the IPL EBDF rheology. Figure 5 compares the viscosity of IPL drilling fluid at 50°C and 90°C. As expected, the viscosity of IPL drilling fluid at 90°C is lower than that of 50°C. Lower viscosity enhances the fluidity or flowability of the drilling fluid and therefore results in better rheology of the drilling fluid. The PV of IPL drilling fluid reduces with temperature. Based on figure 6, the plastic viscosity of IPL drilling fluid at 90°C was determined as 10 cp whereas at 50°C 20 cp was recorded. The results illustrated better PV of IPL drilling fluid at 90°C as reflected by the lower values of viscosity at this temperature. Figure 6 also illustrated an increase in YP from 14 cp to 20 cp as the temperature increases from 50°C to 90°C respectively. Higher YP indicates better hole cleaning efficiency for the drilling fluid.

Figure 7 presents the GS of IPL drilling fluid at 50°C and 90°C. The figure shows that the GS of the drilling fluid slightly decreased at 90°C while showing slight increase when measurement was extended from 10 s to 10 min. Low GS is undesirable as it will decrease the ability of the drilling fluid to suspend solids leading to broken gelling problem. Overall, the IPL-EBDF showed better rheological performance at higher temperature.

![Figure 5. Viscosity of IPL drilling fluid as function of speed obtained at 50°C and 90°C.](image1)

![Figure 6. PV and YP of IPL drilling fluid contained at temperature of 50°C and 90°C.](image2)

![Figure 7. Comparison of Gel Strength of IPL drilling fluid determined at 50°C and 90°C.](image3)
3.4. IPL thermal stability
The IPL drilling fluid was further subjected to heat treatment at temperatures ranging from 50°C to 200°C for 30 minutes. Thermal stability test was conducted to identify the well operating temperature range suitable for the IPL drilling fluid application. Figure 8 shows the physical appearance of the IPL drilling mud after being subjected to heat at different temperatures. Water content for the IPL drilling fluid decreases as the temperature increases. The visuals show that at 150°C, a layer of cake was formed at the bottom while at 200°C, the IPL drilling fluid has transformed to near solid. Water content affects the performance and rheological of the drilling fluid [13] and therefore, it is important for drilling fluid to have sufficient water content to ensure successful drilling operations. In general, the IPL drilling fluid showed thermal stability up to 150°C. Beyond this temperature the physical appearance of IPL drilling fluid has changed from flowing fluid to semi solid or cake indicating that the IPL drilling fluid estimated maximum well temperature of 150°C.

![Figure 8. IPL drilling fluid appearance at (a) 50°C (b) 100°C (c) 150°C (d) 200°C](image)

4. Conclusions
EBDFs were successfully prepared and tested for rheological performance and thermal stability. The formulation of the EBDF prepared in this work showed comparable physical and rheological performances to the published EBDF data. Among the esters tested, the IPL drilling fluid exhibited good overall rheology characters. Rheological properties of the IPL drilling fluid obtained at higher temperature of 90°C is better when compared to the properties at standard test condition of 50°C indicating its suitability for higher well operation temperature applications. Thermal stability test conducted indicated that the estimated maximum temperature suitable for the IPL drilling fluid application was 150°C.

Acknowledgments
The authors would like to thank the Faculty of Chemical Engineering, UiTM for providing the laboratory facilities and the Ministry of Higher Education, Malaysia for financial support through RAGS research grant 600-RMI/RAGS 5/3 (67/2012). The authors also gratefully acknowledged technical assistance and testing equipment provided by GRTC Scomi Oil Tools Sdn Bhd.
References
[1] Ismail A R and Khor S F 2001 Feasibility Study Of Palm Oil Esters As Based Fluid In Drilling Operation Universiti Teknologi Malaysia.
[2] Caenn R and Chillingar G V 1996 Drilling fluids: state of the art. *Journal of Petroleum Science and Engineering* **14**, 3-4 p. 221-30.
[3] Xie S Jiang G Chen M Deng H Liu G Xu Y Wang J and Qiu K 2011 An environment friendly drilling fluid system *Petroleum Exploration and Development* **38**, 3 p. 369-78.
[4] Conlette O C 2011 aerobic degradation of synthetic-based drilling mud base fluids by gulf of guinea sediments under natural environmental conditions *Life Science Journal* **8**, 2 p. 569-76.
[5] Shah S N Shanker N H and Ogugbue C C 2010 Future challenges of drilling fluids and their rheological measurements *InAADE fluids conference and exhibition* Houston Texas.
[6] Kania D Yunus R Omar R Rashid S A and Jan B M 2015 A review of biolubricants in drilling fluids: recent research, performance, and applications. *Journal of Petroleum Science and Engineering* **135**, p. 177-84.
[7] Abdullah S Azizi A Yahya E Sauki A Ghazali N A Jamaludin S K Daud M and Rafizan A 2015 The effects of particle size and viscosity on settling behaviour and rheological performance of isopropyl laurate drilling fluid *InAdvanced Materials Research* **1113**, p. 161-167.
[8] Ghalambor A Ashrafizadeh S N and Nasiri M Z 2008 Effect of basic parameters on viscosity in synthetic-based drilling fluids *InSPE International Symposium and Exhibition on Formation Damage Control*. Society of Petroleum Engineers.
[9] Nwosu O U and Ewulonu C M 2014 Rheological behaviour of eco-friendly drilling fluids from biopolymers *Journal of Polymer and Biopolymer Physics Chemistry* **2**, 3 p. 50-4.
[10] Patel A D 1998 Choosing the right synthetic-based drilling fluids: drilling performance versus *InSPE India Oil and Gas Conference and Exhibition* Society of Petroleum Engineers.
[11] Majid N F Katende A Ismail I Sagala F Sharif N M and Yunus M A 2018 A comprehensive investigation on the performance of durian rind as a lost circulation material in water based drilling mud *Petroleum*.
[12] Ismail A R Khamis A and Khor S F 2001 Performance of mineral binder ester oil based drilling fluid system *Canadian International Petroleum Conference* 2001-004.
[13] Hemphill T 1996 Prediction of rheological behavior of ester-based drilling fluids under downhole conditions *International Petroleum Conference and Exhibition of Mexico* Society of Petroleum Engineers.