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Effect of Two Types of Fly Ash on Rheological and Filtration Properties of Water-Based Drilling Mud

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Abstract

In this study, the usage of class F fly ash (brown coal) and class C fly ash (lignite) with increasing concentration in water based mud mainly composed of bentonite dispersion was investigated at ambient conditions. Experimental results indicate that efficiency of the mud is significantly controlled by type of the fly ash tested and its concentrations. The results show that Class F fly ash enhanced filtration properties (filtrate loss and mud cake) of the mud and have no effect on the rheology including, yield point, viscosity whereas the class C fly ash increased the rheology parameters and degraded water loss into the formation and filer cake thickness dramatically. This study showed that class F fly ash displays superior performance than class C fly ash. Through this study, it was reveal that class F fly ash is a promising additive to improve the filtration characteristics of bentonite based drilling fluids, thereby contributing to reducing formation damage caused by drilling mud.

Keywords:
Bentonite, drilling fluid, fly ash, filtration, rheology
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Introduction

Drilling mud is an indispensable component of drilling process. It performs many important functions including cleaning bottom of the well, balancing formation pressure, minimizing formation damage, controlling corrosion, maintaining the stability of the well, suspending cuttings, ensuring adequate formation evaluation, as well as lubricating and cooling drilling string and bit. Currently, water-based fluids and oil-based fluids are two broad classes of drilling fluid used in

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petroleum industry (Caenn et al., 2011). Oil based muds have advantages over water based muds such as hole stability in water sensitive shales, thermal stability when drilling high temperature wells, lower drill pipe torque and drag for drilling deviated wells. However, water based muds are most widely used drilling fluid systems in worldwide, approximately 80 % of wells drilled by using water based muds (Oilfield Market Report, 2004), due to their relatively lower cost and negative environmental effect (Amani et al., 2012). As well known, bentonite mainly composed of montmorillonite is frequently used in the water based muds both to increase viscosity and to decrease water loss of drilling fluids. These functions of bentonite help to improve hole cleaning ability of drilling mud and decrease formation damage. On the other hand, various additives such as rheology and filtration modifiers are commonly employed in water based muds to obtain higher drilling fluid performance. Based on literature review, the common filtration control and rheology modifier additives (e.g., carboxy methyl cellulose (Sehly et al., 2015), Starch (Dias et al., 2015), xanthan gum (Benyounes et al., 2010), polyanionic cellulose (PAC) (Joel et al., 2012), guar gum (Hasan et. al., 2018). Moreover, it has been observed that nano additives in drilling fluids has been received much attention by researcher (Akhtarmanesh et al., 2019; Aramendiz et al., 2019). However, it is well known that the production of these kind of polymer and nano material expensive and time consuming.

Fly ash or flue ash is a waste obtained from pulverized coal combustion in coal-fired power plants. An ASTM standards (ASTM C618) defines mainly Class F and Class C considering their composition. The main difference between these two types of fly ashes is amount of SiO_2, Al_2O_3, and Fe_2O_3 they contain. While harder anthracite or bituminous coals produce Class F fly ash, lignite or sub-bituminous, which are the lowest grade of coal, produce Class C fly ash.

A great amount of coal has been used for energy production in worldwide. In 2015, the share of coal was 29% of the global total primary energy consumption and 3840 million tons oil equivalent (mtoe) was consumed each year. The percentage share of coal has expected to %24 by 2035, despite growing alternative energy resource. On the other hand, in 2035, the quantity of coal consumed for each year is expected to be 4032 mtoe (Bhatt et al., 2019). Such a huge quantity of fly ash can result in serious environmental problems, since it contaminates air, soil and water. To alleviate this problem, there is a need to use this large amount of ash effectively.

The usability of fly ash in many applications from concrete (Herath et al., 2020) to recovery of valuable metals (Wang et al., 2020), road construction (Bakare, 2019), composite materials (Praveenkumar and Gnanaraj, 2020) has been studied by researchers. However, possible utilization of fly ash in drilling muds has been received very little attention. Based on literature (Mahto and Jain, 2013) investigated utilization of fly ash in drilling mud consisting KCl and (Mahto et al., 2013) used fly ash to develop a non-damaging drilling fluid. The common deficiency in these two studies is that the type of fly ash used is not analyzed. Also, (Fliss et al., 2019) studied utilization of Class F fly ash in polymer water-based drilling mud and (Avci et al., 2019) analyzed the usage of two types of fly ashes, which are Class C and Class F, on gypsum/polymer water-based drilling fluid. However, there is no published data regarding utilization of fly ash in spud mud which is basic mud and it is used to start the drilling of a well. The goal of the study is to design a novel drilling mud by using fly ash in bentonite based mud and analyzing how different types of fly ash affect flow behavior of the mud at ambient conditions.

Materials and Method

Two different types of fly ashes and bentonite were employed in the study. Firstly, the brown coal fly ash was received from Tiszaújváros-Hungary. It is with gray color and its mean particle diameter (D_{50}) and specific surface area are 84.11 micrometer 1191.2 cm^2/cm^3, respectively, as shown in Fig.2. Secondly, lignite fly ash was received from Mátra Power Station Visonta-Hungary. It is with brown color. Also, its mean particle diameter (D_{50}) and specific surface area are 59.82 micrometer 1799.3 cm^2/cm^3, respectively, which were given in Fig.2. The fly ash samples were used as received without any treatment. Bentonite was used to prepare bentonite dispersion. Bentonite is mainly composed of montmorillonite mineral. The properties of bentonite that enable it to be used efficiently in drilling mud provide this clay mineral. Montmorillonite is a smectite group and has a 2: 1 layer structure.

Preparation of Drilling Fluid

Bentonite dispersion mixture (spud mud) was prepared with incorporating water to bentonite for 20 minutes by means of five-spindle multi-mixer. The dispersion was prepared by maintain clay-water ratio, which is 6% (w/v) bentonite. Thereafter, the mud was left to age for 16 hours to reach exact hydration of bentonite in accordance with API standards. Prior to usage of fly ash samples in the mud, the samples exposure 105 °C in an drying cabinet for 8 hours to reach constant mass by removing moisture from the samples. Fly ash produced from brown coal and fly ash produced from lignite powders was added into the bentonite suspension in various concentrations (1%, 3% and 5% by weight of mud). After addition of fly ash into the bentonite suspension, the suspension was stirred for ten minutes. Totally, seven mud samples were prepared by repeating this process.

Analysis of Rheology

Throughout this study API standards (API RP-13B) was taken into consideration. Before testing the rheology, the mud samples were stirred for 5 minutes to achieve same shear history. The rheological analysis was conducted with rotating viscometer (Fann-model 35A). The fundamental rheological parameters, which are gel strength, apparent viscosity (AV), yield point (YP) and plastic viscosity (PV) were investigated for analyzing of flow characteristics of the drilling muds. The rotating viscometer has coaxial-cylinder type and six different rotation speed including 600, 300, 200, 100, 6 and 3 (rpm). The viscometer sample cup was filled up to marked level with the mud that had just been mixed and submerged in the mud to the line on the rotor. Then the rotor was rotated at 600 rpm and when the pointer on the dial became steady it was recorded as a 600 rpm reading. After that, the viscometer was adjusted to a speed of 300 rpm and fixed value of the pointer was recorded as a 300 rpm reading. By following this process, dial readings were recorded under the other rotation speeds. Dial readings were recorded for each sample at the relevant speeds. 600 rpm and 300 rpm dial readings were used to calculate PV, YP and AV by using the relationship in following equation.

$$\text{AV, (cP)} = \theta_{600}/2 \quad (1)$$

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

$$\text{YP, (lb/100ft}^2\text{)} = \theta_{300} - \text{PV} \quad (3)$$

The rotating viscometer was also used for measurement of gel strength. Mud sample to be tested was stirred for 10 second at high speed (600 rpm) and motor was stopped again for 10 seconds the mud was kept stationary. Then, at 3 rpm the viscometer was operated and the maximum value measured at this speed was recorded as 10 seconds gel strength in lbs / 100 ft^2. By following this process 1 minute gel strength and 10 minutes gel strength were recorded considering stationary time 1 minute and 10 minutes, respectively.

Analysis of Filtration and Density

The water loss of suspension containing only bentonite and the fly ash added bentonite suspension was measured with API standard filter press. Firstly, screen and filtrate paper were placed and samples of 350 ml were poured to test cell. The tests were conducted under 100 psi pressure provided by N_2O gas for 30 minutes. By applying this pressure, the mud leaves the filtration liquid through the metal screen and filter paper. Meanwhile, mud cake is built on the filtrate paper. The volume of filtrate collected was noted in cubic centimeters after 1, 3, 7.5, 10, 15, 20, 25, 30 min. of testing. The experiment was terminated after 30 min. After that, the thickness of mud cake was also measured with vernier caliper.

The other main characteristics of the drilling mud are density/weight. It allows the formation pressure to be balanced and prevent influx into wellbore. Mud weight also prevents collapse of the well. For the determination of the mud density, the chamber is first filled with the drilling mud sample, and some mud is provided to expel through to hole in the lid to make sure the chamber is full. The mud balance consists of a container with a fixed volume on one side and the counterweight arm and the measuring weight acting on the arm. The value on the edge of the weight moved on the mud arm to the left hand side was recorded mud density value in lb/gal.

Results and Discussions

Characterization

Elemental composition of both types fly ash samples used were measured with Rigaku Supermini 200 type XRF spectrometer. The analysis results are given in Table 1. The results show that the chief differences between two samples is amount of silica, alumina and iron contained in them, as expected. According to ASTM standards, the fly ashes introduced were determined as Class F and Class C.

Table 1. Elemental analysis of two type of fly ashes and bentonite

Oxides	**Brown coal fly ash (wt%)**	**Lignite fly ash (wt%)**	**Bentonite (wt%)**
SiO_2	58.8	39.8	57.2
Al_2O_3	24.0	14.0	15.0
MgO	1.17	3.41	3.98
CaO	1.92	12.1	5.62
Na_2O	0.91	0.54	2.19
K_2O	1.53	1.61	1.19
Fe_2O_3	5.51	11.2	5.12
MnO	0.032	0.176	0.110
TiO_2	0.605	0.495	0.886
P_2O_5	0.053	0.346	0.220

Figure 1 shows the microstructure of brown coal fly ash (Class F) used in drilling mud, determined by Scanning Electron Microscopy (SEM). As can be seen from the figure, fly ash particles predominantly consist of spherical shapes, which are cenospheres (thin-walled, hollow spheres), solid spheres and unburnt carbon. Also, there are irregularly shaped particles consisting of softened minerals that do not melt completely in the fly ash structure (Yao et al., 2015). In addition, the surface texture of fly ash is smooth and dense, and has a highly porous structure.

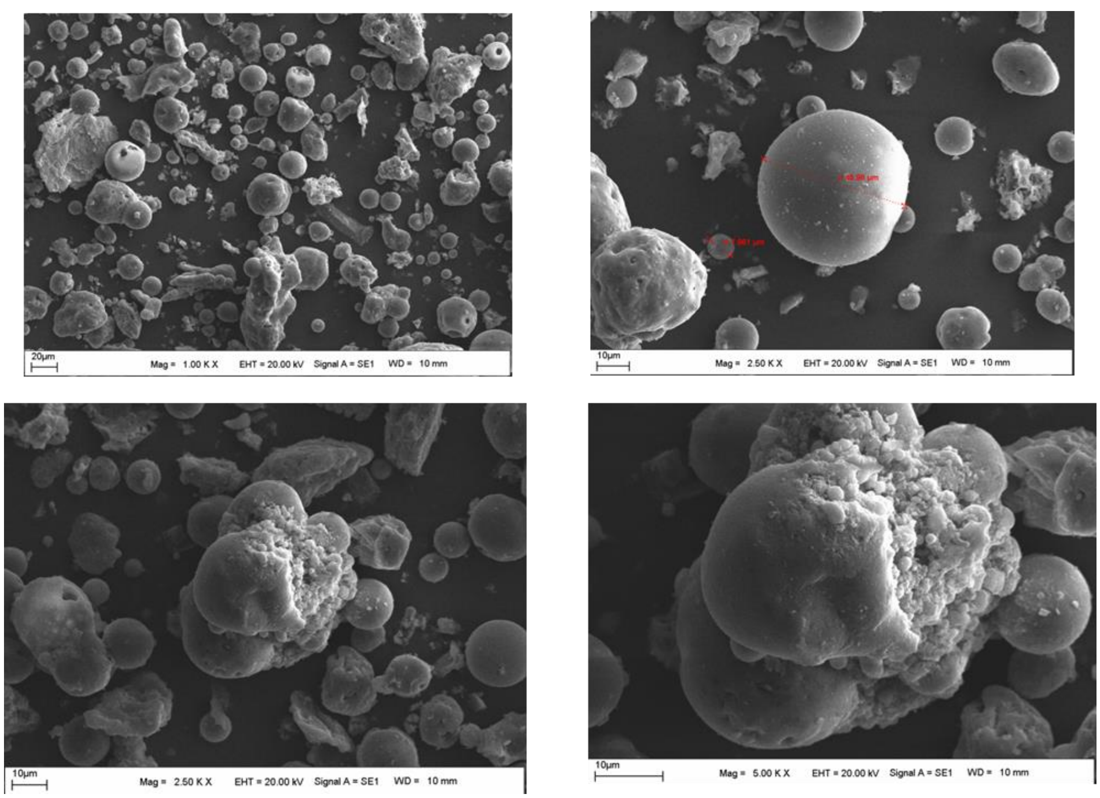

Figure 1. SEM images of brown coal fly ash (Yalman et al., 2021).

Additionally, particle-size analyzer HORIBA LA-950V2 laser diffraction equipment was employed to determine particle-size analysis of both fly ash samples and bentonite used and the particle size distribution data obtained was used to calculate their specific surface area (SSA) values with laser size software. As can be seen in Figure 2, the average particle size (D_{50}) of fly ash produced from brown coal and fly ash produced from lignite are 84.11 micrometer, 59.82 micrometer, respectively while average particle size (D_{50}) of bentonite is 1.79 micrometer. This indicate that the difference of particle size distribution of bentonite quite higher than those of fly ashes.

Samples	D_{10}, µm	D_{50}, µm	D_{90}, µm	SSA, cm^2/cm^3
Lignite Fly Ash	13.36	59.82	175.19	1799.3
Brown Coal Fly Ash	21.28	84.11	187.89	1191.2
Bentonite	1.02	1.79	3.15	36632

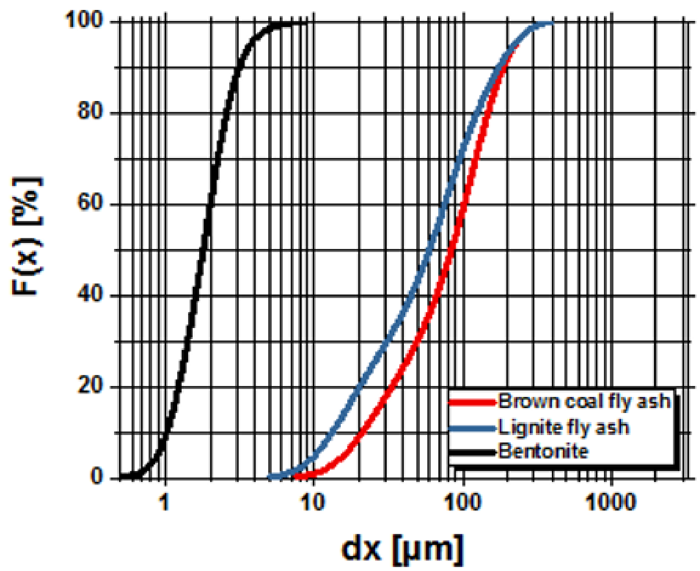

Figure 2. Particle size distribution for two type fly ashes and bentonite.

Rheology Results

Rheology of the water-based drilling muds was evaluated taking into account four parameters, which are yield point, plastic viscosity, gel strength and apparent viscosity, which were tested for 10 second, 1 minute and 10 minutes static period. Apparent (shear) viscosity is a rate of between shear rate and shear stress. Plastic viscosity is a parameter which arises due to mechanical friction between solid materials in the mud and varies depending on the size, shape and multiplicity of the solid material. The tendency of the plastic viscosity value to increase without the addition of any controllable solid material (bentonite, barite) is an indicator of the formation of solid matter in the mud system. Yield point of mud is based on attractive forces among colloidal particles within the mud and refers the stress needed to start the movement of the fluid and indicates of carrying capacity of the mud. From Figure 3, it is seen that the use of fly ash produced from brown coal have neglect effect on the both apparent viscosity, yield point and plastic viscosity of bentonite dispersion. Nevertheless, the addition of lignite fly ash increases the rheology parameters. The apparent viscosity and plastic viscosity increases with an increase in concentration of lignite fly ash, as it is shown in Figure 3 (a, b).

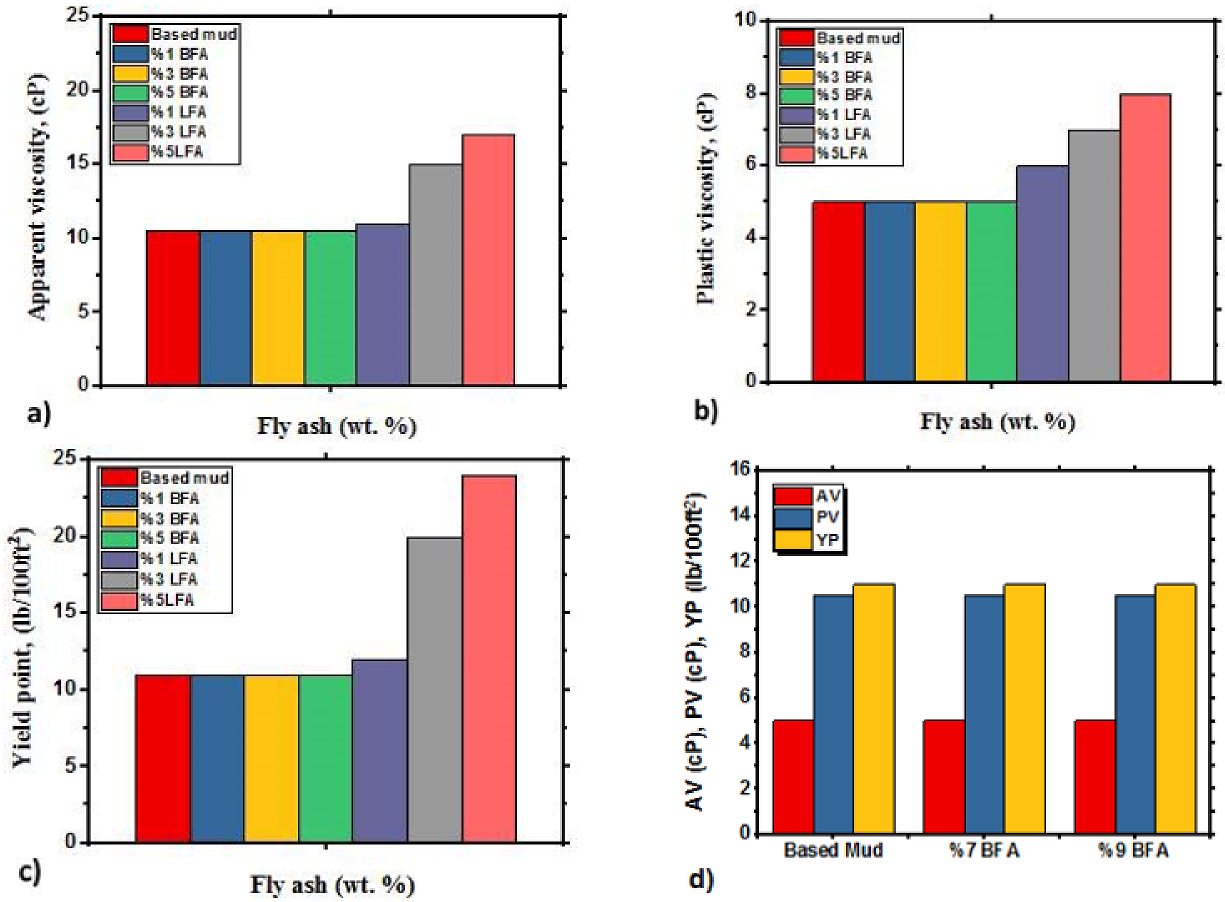

Figure 3. Variation of rheology of bentonite based mud with the fly ash type and concentration, a) Variation of apparent viscosity b) Variation of plastic viscosity c) Variation of yield point d) Variation of rheology with further increasing of brown coal fly ash.

This can be related to lower particle size of lignite fly ash. Same trend was also observed for the change of yield point with the addition of lignite fly ash (Figure 3c). It should be noted that the rate of increment for yield point is greater than those of apparent viscosity and plastic viscosity. Brown coal fly ash concentration was also further increased to 7 wt% and 9 wt% for a better understanding flow behavior of bentonite suspension with higher content of fly ash. Fig.3d shows the rheology results obtained with further increasing concentration of brown coal fly ash. When concentration of brown coal fly ash further is increased, no change was observed on apparent viscosity, plastic viscosity and yield point, similar to lower concentration.

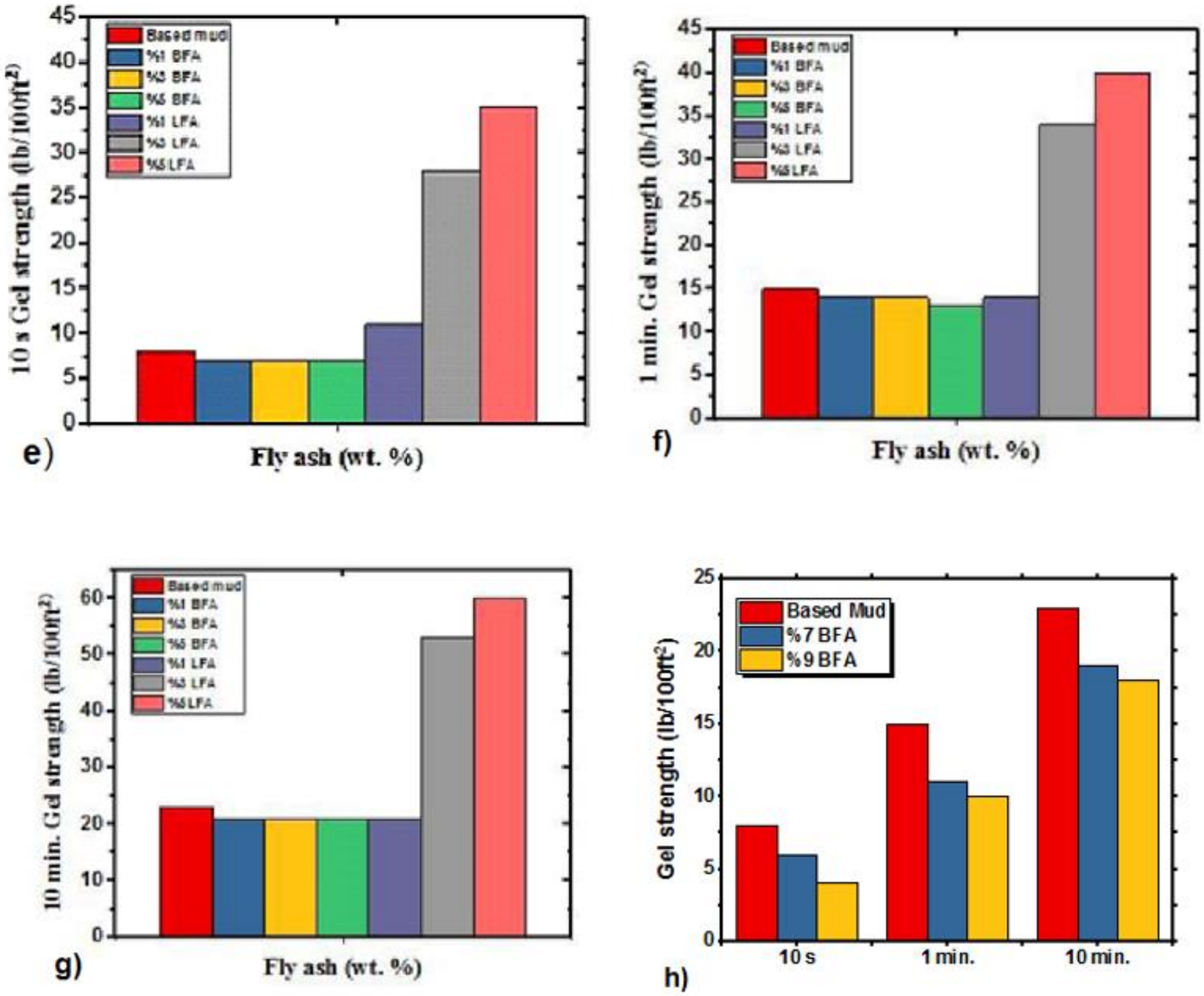

Figure 4. Variation of gel strength of bentonite based mud with the fly ash type and concentration, e) Variation of 10 s gel strength, f) Variation of 1 min. gel strength, g) Variation of 10 min. gel strength h) Variation of gel strength with further increasing of brown coal fly ash.

The important feature that distinguishes drilling mud from other fluids is that gel structures can be formed. This feature is of great importance in terms of drilling technique. Gel strength increases when the mud stays stationary. This makes it difficult for the cuttings to collapse downwards, and when the mud circulation stops for any reason, the cuttings in the hole with the mud are prevented from settling to the bottom and causing drill string sticking. Gel strength, which increases when circulation stops, should decrease when circulation begins. Otherwise, high pump pressures will be required to maintain circulation. The 10 s (Figure 4e), 1 min (Figure 4f) and 10 min gel strengths (Figure 4g) of spud mud slightly decreased with the increasing concentration of brown coal fly ash whereas the figures show that the gel strengths increased with increasing lignite fly ash concentration. It should be noted that the initial, 1 min. and 10 min. gel strength of the samples containing lignite fly ash considerably higher than those of samples with brown coal fly ash. On the other hand, it was seen that further increasing concentration of brown coal fly ash has a greater impact on gel strength, compare to lower concentration. The 10 s, 1 min. and 10 min gel strength decreased with the further increasing concentration of brown coal fly ash (Figure 4h). The thixotropic of bentonite suspension decreased by about 13% with 7 wt% brown coal fly ash. This indicate the utilization of brown coal fly ash decreases the thixotropic of spud muds and the employment of brown coal fly ash may provide to low pumping pressure to initiate circulation after prolonged periods of rest and also mitigate the risk of formation fracture and lost circulation issues.

Filtration and Density Results

The fluid loss is a highly significant parameter for drilling fluid hydraulic. When mud prepared by mixing water and clay, most of the water is absorbed by the clay and a suspension is formed. Some of the water is free in this suspension and can be filtered off through a filter paper. While this water, called "filtration water" is filtered, a mud cake forms on the filter paper.

The porous formations forming the surface of the borehole resemble filter paper and the water in the mud infiltrates and enters them. If the formations contain such as clay, shale, marl, etc. are swollen with water, less filtration water is desired. In addition, since the low amount of filtration water will mean less cake thickness, it should be below a certain value in terms of not narrowing the annulus cross section. The filtrate volume of bentonite mud for both absence of fly ash and presence of two types fly ashes under the pressure of 100 psi versus time is given in Figure 5. Figure 5a-c shows the difference of effects of fly ashes when they are used at the same concentration. Fig.5d demonstrates the filtration volume recorded of the samples at the end of 30 minutes. It was observed that as concentration of brown coal fly ash increases, the amount of invasion water decreases whereas the water loss increases considerably with the increasing lignite fly ash concentration. The reduction in API water loss of drilling mud observed was about 11% at a concentration of 5 wt% brown coal fly ash. Figure 7 shows that the mud cake thickness of samples decreased and exhibited the lowest mud cake thickness when brown coal fly ash was added. The filter cake reduction was found 10% for fly ash produced from brown coal with the concentration of 3 wt%. However, the thickness of filter cake increased when lignite fly ash was added for 3 and 5 (wt%) concentrations. On the other hand, Figure 6 demonstrates that the water loss also decreased with further increasing concentration brown coal fly ash with both 7 wt% and 9 wt% concentrations. However, lower filtration was obtained with 7 wt% concentration (Figure 6e). While 30 minutes API fluid loss decreased by approximately 28% with 7 wt% concentration, it decreased by 15% with 9 wt% concentration of brown coal fly ash. Fig.6f shows that further increasing concentration brown coal fly to 7 wt% more enhanced cake thickness than lower concentration. The filter cake reduced by 15% with 7 wt% concentration whereas 9 wt% concentration caused to an increase in the thickness. The reduction of drilling mud water loss and mud cake thickness can be attributed to the binding effect of fly ash. The mitigation fluid loss and building thinner mud cake may minimize the serious drilling problems including pipe sticking, wellbore instability and formation damage.

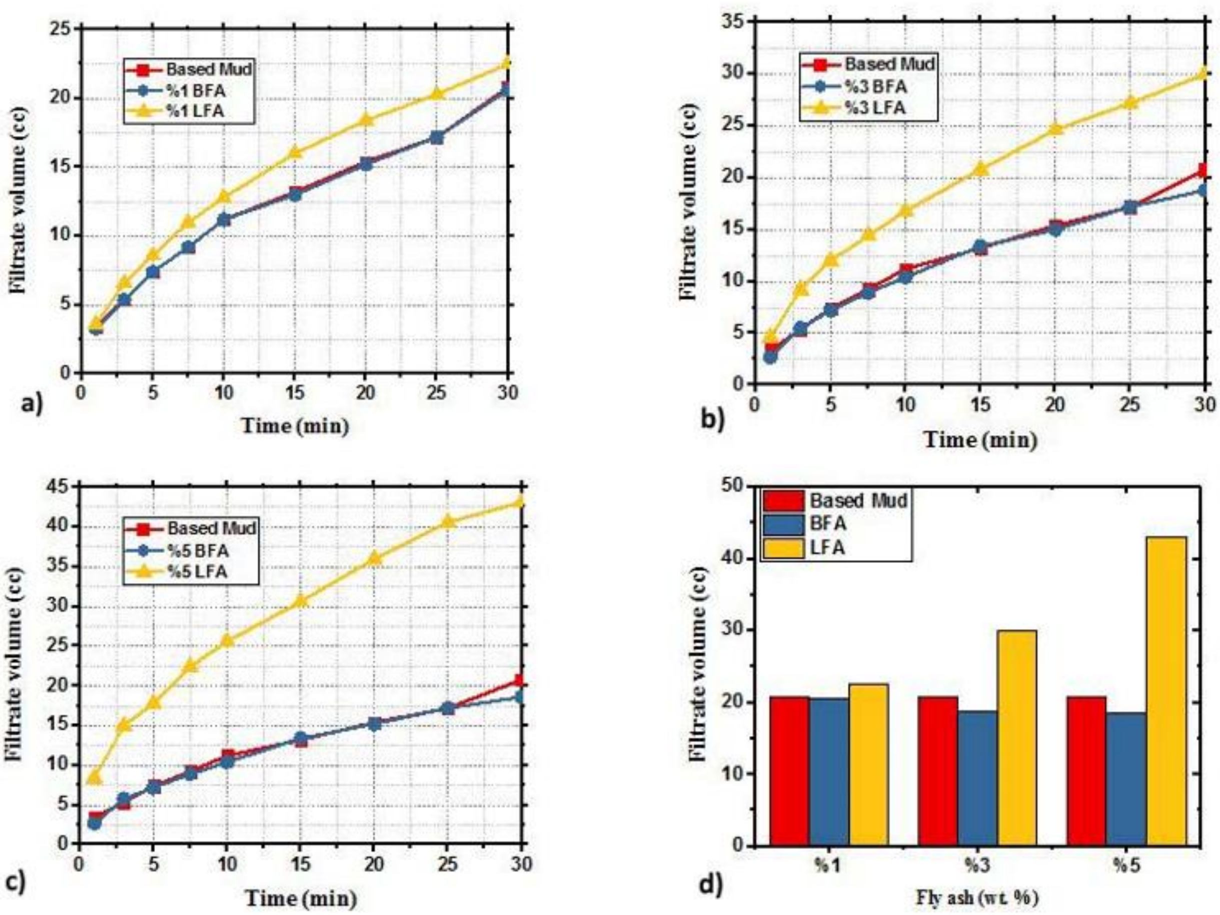

Figure 5. Variation of fluid loss of bentonite based mud with the fly ash concentration, a) Fluid loss versus time for 1.0 wt% concentration, b) Fluid loss versus time for 3.0 wt% percent concentration, c) Fluid loss versus time for 5.0 wt% percent concentration, d) Fluid loss at 30 min for all tested suspensions.

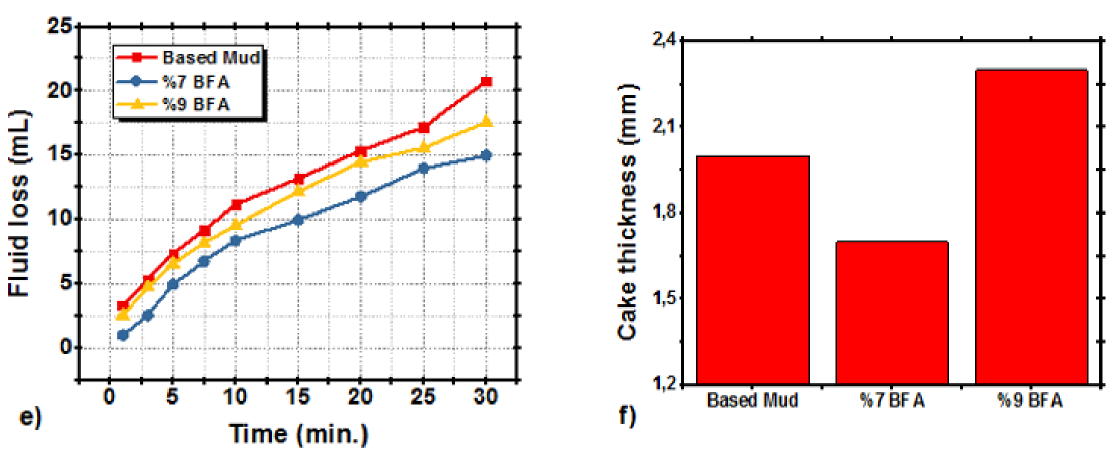

Figure 6. Variations of filtration with further increasing brown coal fly ash e) Fluid loss f) Cake thickness.

Density is one of the most fundamental characteristic of drilling mud. Hydrostatic pressure of the drilling mud enables the mud to fulfill one of its most important functions, controlling the formation pressure. The density of mud is a one of parameter in determining the hydrostatic pressure of the mud column. Figure 8 shows that as concentration of two types fly ashes increases the density of bentonite based mud increases. The other noticeable is that the density of samples with lignite fly ash is higher than samples with brown coal fly ash. This is probably due to higher particle density of lignite fly ash.

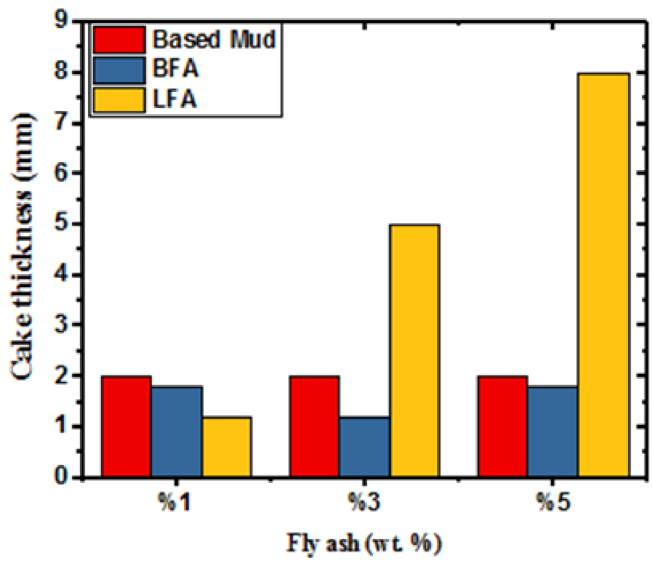

Figure 7. Cake thickness of spud mud with the increasing concentration and type fly ash.

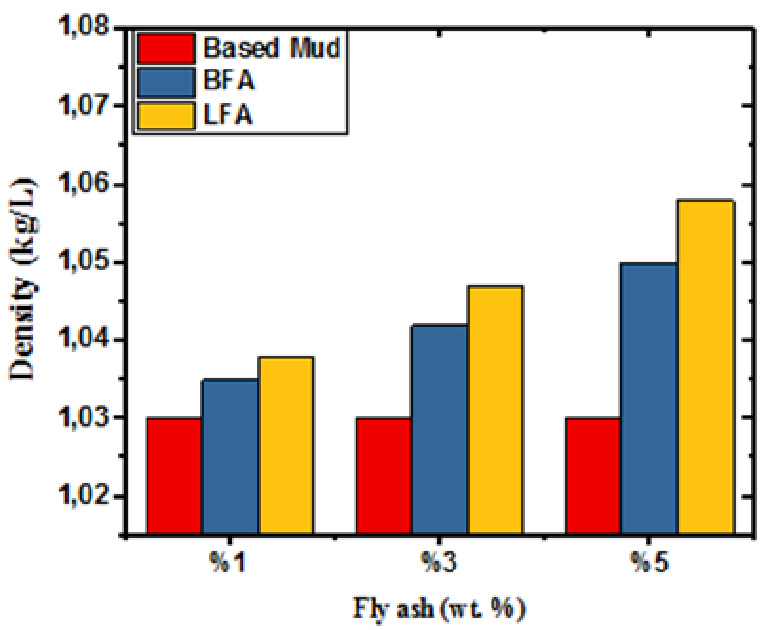

Figure 8. Density of spud mud with the increasing concentration and type fly ash.

A novel water based drilling mud was designed with the use of fly ash at ambient conditions. Laboratory work was performed by studying the density, rheology, filtration and filter cake thickness of water based bentonite muds with brown coal and lignite fly ashes. In the light of results obtained, it was concluded that the performance of brown coal and lignite fly ashes depend on their concentration used and brown coal fly ash has an optimum concentration for a given system. The optimized brown coal fly ash had no effect on the rheological parameters. On the other hand, this developed system with Class F fly ash at the 7 wt% concentration exhibited reduction in fluid loss with 28% and filter cake thickness with 15% compared with the reference mud, which are favorable characteristics to reduce formation damage. Reduction on the fluid loss obtained in the study is greater than the value obtained from the study performed by Saengdee & Terakulsatit (2017). When the authors used 1% sugarcane bagasse ash in drilling mud, they had a 6% reduction in water loss. Reduction rate on the mud cake thickness is also higher than the data reported in the literature. In the study performed by Okon et al., (2014) and Agwu et al., (2019), thicker filter cakes were obtained in contrast to the decrease in the mud cake thickness. When Okon et al., (2014) used 10 ppb rice husk in the drilling mud mud cake thickness increased from 1 mm to 1.5 mm. On the other hand, when Agwu et al., (2019) used 5 gram saw dust, filter cake thickness raised from 1 mm to 2.6 mm.

Although the use of lignite fly ash improved the rheology of the drilling mud, it degraded filtration properties and filter cake thickness dramatically. Experimental results showed this developed mud system with brown coal fly ash could be considered as an alternative mud system to conventional mud for mitigation formation damage of water-based bentonite muds.

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Author Contributions

All author contributions are equal for the preparation research in the manuscript.

Conflict of Interest

The authors declare that they have no competing interests.

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