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Development of novel inhibitive water-based drilling muds for oil and gas field applications

Emine Yalman [a,b,*], Gabriella Federer-Kovacs [b], Tolga Depci [a], Hani Al Khalaf [b], Volkan Aylikci [c], Mustafa Goktan Aydin [a]

[a] Department of Petroleum and Natural Gas Engineering, Faculty of Engineering and Natural Sciences, Iskenderun Technical University, 31200, Iskenderun, Hatay, Turkey
[b] Department of Petroleum Engineering, Faculty of Earth Science, University of Miskolc, 3515, Miskolc, Hungary
[c] Department of Metallurgy and Materials Engineering, Faculty of Engineering and Natural Sciences, Iskenderun Technical University, 31200, Iskenderun, Hatay, Turkey

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ABSTRACT

The aim of this study is to develop inhibitive drilling fluid systems generated from waste materials that can contribute to the reduction of potential well instability problems caused by drilling fluid based on rheological and filtration properties. In this study, a comprehensive experimental work was carried out to assess suitability of fly ash and rice husk ash, which are quite a large amount of waste, in inhibitive water based-drilling fluids at ambient temperature. To this end, inhibitive drilling fluids systems were formulated with various concentrations (0, 1, 3, 5, 7, 9, 12.5, 15 (wt%)) of fly ash and rice husk ash with 0, 2, 4, 7, 9, 12.5, 15 (wt%) concentrations in the two type of inhibitive drilling fluid systems and combined use of fly ash and rice husk ash with their optimum concentrations determined was analyzed in the inhibitive drilling fluid in order to determine the drilling fluid with the most favorable characteristics based on rheological and filtration properties including apparent viscosity (AV), plastic viscosity (PV), yield point (YP), gel strength, fluid loss and mud cake thickness. In addition, grinding impact of fly ash particles in the inhibitive drilling fluid system was determined in the development of the drilling fluid by employing mechanically ground fly ash for 30, 60 and 120 min in a tumbling ball mill. Finally, fly ash and rice husk ash were characterized based on X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR) and Scanning Electron Microscopy (SEM). Experimental results show that developed drilling fluids with fly ash and rice husk ash not only enhanced rheological properties but also improved the filtration properties by increasing the rheological parameters and decreasing fluid loss and mud cake thickness. With the developed drilling fluids, AV, YP and PV increased by 35%, 32%, 28%, respectively with fly ash for the 12.5 wt% concentration while the parameters increased by 19%, 27%, 14%, respectively with the 4 wt% rice husk ash. Gel strengths of the fluids slightly increased compared to reference fluid and were in acceptable range. On the other hand, developed drilling fluid resulted in a 10% and 12% reduction in fluid loss for fly ash and rice husk ash at 12.5 wt% and 4 wt% concentrations, respectively, as well as a 54% and 63% reduction in mud cake thickness. In addition, the results reveal that developed drilling fluid with sieved fly ash yielded superior flow behavior compared to drilling fluid formulated with ground forms of fly ash. Consequently, based on the study, non-damaging and inhibitive drilling fluid systems were developed by using waste material fly ash and rice husk ash, and hence enhancing performance of drilling operation as well as reducing the risk of amount of wastes disposed to the environment and the potential of issues such as formation damage, wellbore instability caused by drilling fluid and associated challenges.

1. Introduction

Drilling fluid plays a vital role in the success in drilling operation and represent 15–18% of the total cost of oil well drilling (Khodja et al., 2010a,b) and is generally classified as water-based drilling fluid and oil-based drilling fluid according to their phase type and chemical

* Corresponding author. Department of Petroleum and Natural Gas Engineering, Faculty of Engineering and Natural Sciences, Iskenderun Technical University, 31200, Iskenderun, Hatay, Turkey.
E-mail address: emine.avci@iste.edu.tr (E. Yalman).

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properties (Melbouci and Sau, 2008). The drilling fluid performs many critical tasks which are essential for efficient drilling process. The main functions fulfilled of drilling fluids include removing drilled cuttings from the hole, controlling subsurface pressure, cooling, and lubricating drilling tools, maintaining the stability of wellbore, controlling corrosion and suspending drilled cuttings when drilling is paused (Aboulrous et al., 2016; Khodja et al., 2010a,b). The drilling fluid must have certain rheological and filtration properties to perform these critical duties, due to the change in flow characteristic of drilling mud in downhole conditions depending on mainly temperature, pressure and formation being drilled. Therefore, various chemicals, different additives and polymers have been mixed into the drilling mud to keep flow properties such as mud weight, gel strength, viscosity and filtration at desired levels (Moghaddam and Saadatabadi, 2020; Skalle, 2011; Khodja et al., 2010a,b). As conventional drilling mud additives increases the drilling cost, recently there has been gaining interest in application of cheap, easily available and environmentally friendly additives that could be an alternative to existing conventional additives (Avci et al., 2019; Aboulrous et al., 2016).

Wellbore instability is one of the key problem encountered during drilling operation and occurs depending on many factors. The properties of the drilling fluid and its interaction with the formation are one of the parameters that cause well instability problems (Nmegbu and Ohazuruike, 2014; Zeynali, 2012; Patel et al., 2007; Labenski et al., 2003). Stuck pipe, drill bit balling up, a decrease in the production capacity of the well, drilling fluid contamination, low quality logging and cementing are the largest source of trouble caused by well instability and formation damage (Yang et al., 2020; Azar and Samuel, 2007; Patel et al., 2007; Lake, 2006; Yu et al., 2001; Labenski et al., 2003; Steiger and Leung, 1992; Van Oort et al., 1994). These critical challenges cause excessive nonproductive time and increase the cost of drilling operations (Diaz-Perez et al., 2007; Van Oort, 2003). The wellbore instability problems have been mainly occurred in shale (mainly clay) formations represent 75% of drilled formation worldwide due to dispersion and hydration of shale formations in conventional water based drilling fluid (Yue et al., 2018; Guancheng et al., 2016; Khodja et al., 2010a,b; Azar and Samuel, 2007; Lake, 2006; Chen et al., 2003). Oil based drilling fluids are often used to drill through shale section to help address these drilling challenges because of advantages over water-based fluids with respect to drilling performance. The oil based drilling fluids generally exhibit superior wellbore stability features than water based drilling fluid by decreasing risk of stuck pipe, providing lubricity, increasing rate of penetration. However, there have been several concerns for oil based drilling fluids. These are mainly high cost with respect to build the fluid, logistic problems, environmental compliance, high gas solubility that can make detection of a gas influx more difficult. Thus, environmental regulation and associated concerns have restricted their usage in worldwide. Therefore, there is a great need for a low cost and environmentally friendly water based drilling fluid able to meet those problems during drilling the well.

Fly ash (FA) is a coal waste product consisting of particles from coal-fired power plants along with flue gases (Chepaitis et al., 2011; Ahmaruzzaman, 2010). The chemical properties of fly ash largely depend on the coal from which it is obtained and its combustion properties (Mozgawa et al., 2014). The American Society for Testing Materials defines two types of fly ash, Class C and Class F, according to the chemical composition of fly ash (ASTM C618, 1997). Class F fly ash is typically produced by burning harder, old anthracite and bituminous coal, while Class C fly ash is obtained by burning young lignite or lower bituminous coal (ASTM C618, 2008). In the past, fly ash produced from the combustion of coal was simply entrained in flue gases and emitted into the atmosphere. However, with the increase in industrialization, the rising fly ash production started to cause environmental and health problems. Today, more than 65% of the fly ash produced from coal power plants worldwide is dumped in landfills and ash ponds. On the other hand, rice husk, which is a by-product of rice production, is generally used as fuel in areas where green technology is available (Subashi De Silva and Priyamali, 2020; Liu et al., 2016). Rice is consumed as a staple food in many countries. This results in the production of large amounts of rice husk. 20% of the rice husk used as a fuel source in many countries turns into rice husk ash. In this context, as a result of the production of 500 million tons of rice in a year, 100 million tons of rice husk emerges, and 20 million tons of ash is produced by burning (Jongpradist et al., 2018). Therefore, the fly ash and rice husk ash (RHA) cause pollution by covering large areas in the environment.

Based on a review of current literature, it is seen that a large number of studies have been carried out to evaluate and utilization of fly ash (Yao et al., 2015; Fungaro and Silva, 2014; Parande et al., 2011; Ahmaruzzaman, 2010) and rice husk ash (Prasara-A and Gheewala, 2017; Rahman et al., 2014; Parande et al., 2011; Vempati et al., 2006) in various applications. However, a little attention has been paid to application of fly ash and rice husk ash on the flow behavior of drilling muds. Mahto and Jain (2013) studied the effect of fly ash on inhibitive drilling fluid containing potassium chloride while Mahto et al. (2013) developed a preventative drilling fluid system using fly ash that does not damage the formation. In addition, Avci et al. (2019) investigated the utilization of different class of fly ash (Class F and Class C) in gypsum/polymer drilling fluid while Fliss et al. (2019) studied ability of fly ash with particle size smaller than 63 μm in bentonite drilling fluid containing polymer. All of these studies were based on a single type of drilling mud, and neither the effect of ground fly ash was studied nor its rheological and filtration properties were optimized. On the other hand, Biltayib et al. (2018) analyzed usage of rice husk ash in spud mud that composed of bentonite and water and to date there are no published data on the application of rice husk ash in water based inhibitive drilling fluid.

In this study, an attempt has been made to study the usability of fly ash and rice husk ash in water-based inhibitive drilling fluids possessing different compositions through a comprehensive experimental work. In addition, the behavior of mechanically ground fly ash with tumbling ball mill in the drilling fluid has been studied. The aim of this study is to measure the flow properties of drilling muds formulated on the basis of laboratory tests and thus to determine the most favorable drilling fluid. To the best of the authors' knowledge this is the first approach to both developing an inhibitive drilling fluid system using fly ash and rice husk ash simultaneously, as well as studying the effect of ground fly ash in the drilling fluid.

2. Experimental work

All experiments conducted in this study were performed in the laboratory accordance with American Petroleum Institute (API) recommended practice API-RP-13B-1. Fig. 1 demonstrates the steps were taken in order to develop water based inhibitive drilling fluid systems with enhanced characteristics.

2.1. Materials

Fly ash and rice husk ash are the main materials used as additive in the study. The fly ash is procured from power plant of Tiszaújváros/Hungary while the rice husk ash was obtained from a food company Edirne/Turkey.

2.2. Chemical and morphological characterization

Elemental analysis (as oxides) of fly ash and rice husk ash was carried out with Rigaku Supermini 200 type XRF spectrometer and their FT-IR analysis was identified using PerkinElmer Spectrum Two. Their phase composition and surface morphology were determined by X-ray powder diffraction using Rigaku Miniflex 600 with Cu Kα (40 kV, 15 mA, $\lambda = 1.54050$ Å) radiation and LeO EVO 40 scanning electron microscope, respectively. In addition, their particle size distribution was measured

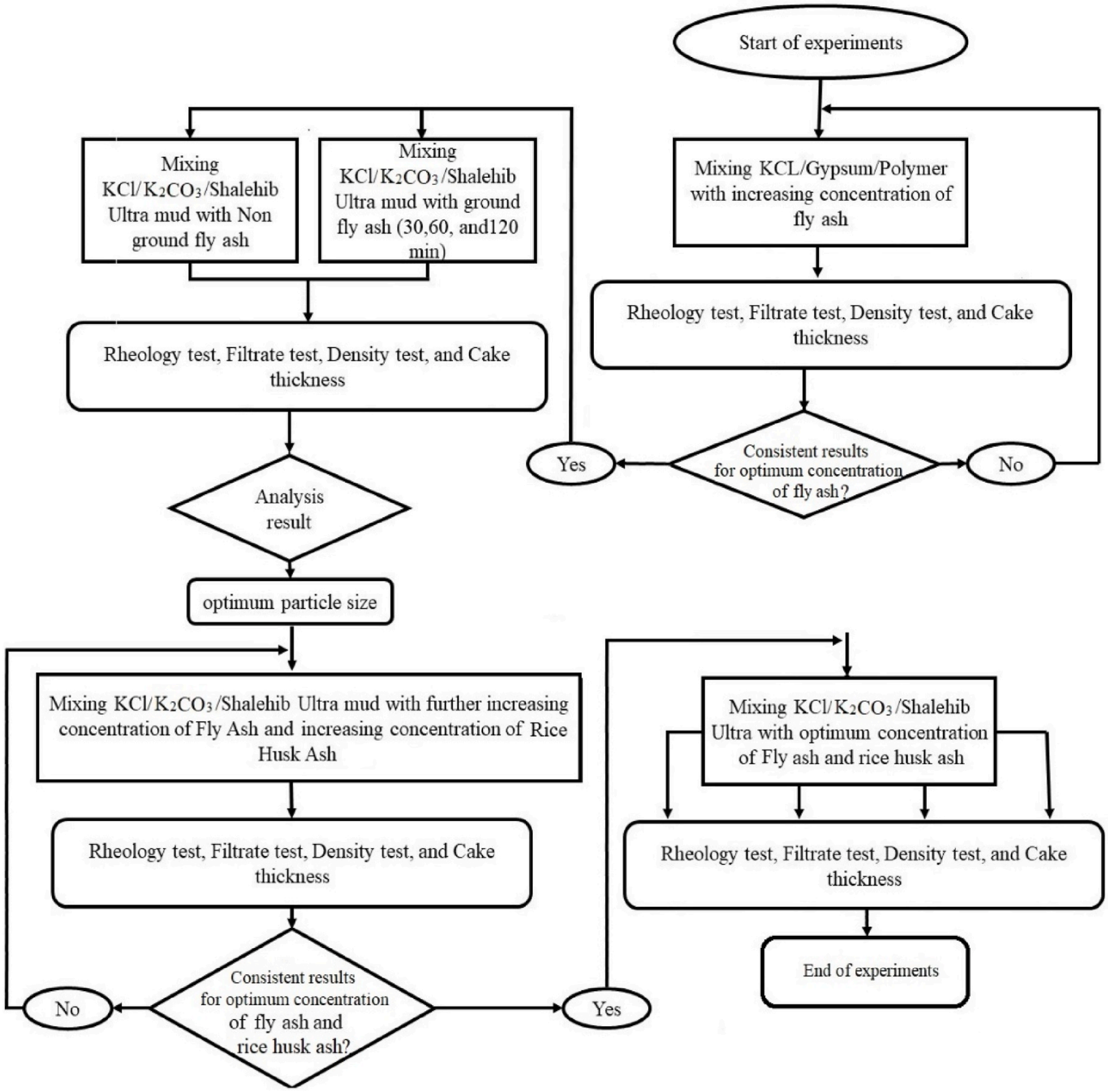

Fig. 1. Flowchart of the experimental analysis conducted.

with a HORIBA LA-950V2 laser diffraction particle size analyzer and their specific surface area (SSA) was calculated by the laser sizer software using particle size distribution data.

2.3. Preparation of drilling fluids systems

Two kind of inhibitive drilling fluid samples having different composition were prepared as control systems. These are KCl/gypsum/polymer and KCl/K_2CO_3/Shalehib Ultra Mud. These mud systems are typical field standard formulation of currently used in some drilling operations. Table 1 shows compositions of the KCl/gypsum/polymer and KCl/K_2CO_3/Shalehib Ultra Mud and functions of product used in formulations, respectively.

In the study, formulation of drilling fluid systems with fly ash and rice husk ash were carried out by dividing into four stages given in Table 2. Initially, drilling fluid samples were formulated with raw (non-grinding) fly ash with concentrations ranging from 1 wt% up to 9 wt% as additive to the KCl/gypsum/polymer drilling fluid. This step was adopted as Stage-I. In the Stage-II, drilling fluid samples were designed with different particle size of fly ash at the optimum concentration found in Stage-I by introducing into the KCl/K_2CO_3/Shalehib Ultra Mud. The different particle sizes were obtained by grinding raw fly ash with conventional laboratory ball mill for 30, 60 and 120 min. In the Stage-III, fluid samples containing rice husk ash at the increasing concentration ranging from 2 wt% to 15 wt% and fly ash with optimum particle size found in the stage-II at the further increasing concentration ranging from 7 wt% to 15 wt% based on KCl/K_2CO_3/Shalehib Ultra Mud. In the Stage-IV, combined drilling fluid system was formulated by employing rice husk ash with optimum concentration and fly ash with optimum particle size and concentration to the KCl/K_2CO_3/Shalehib Ultra Mud. Drilling fluid system developed in this section were coded as given in Table 3.

2.4. Rheological determination

The rheology of formulated drilling fluid systems was measured by using (a rotational viscometer model 35A) manufactured by Fann company, Houston, Texas by considering apparent viscosity, plastic viscosity, and yield point as well as gel strength. This device is equipped with six speeds: 3, 6, 100, 200, 300 and 600 (rpm). To measure the viscosity firstly, the sample cup of viscometer was filled with samples to be analyzed for 350 mL. Then, the cup was placed on the viscometer

Table 1
Formulation of the drilling muds.

Functions of product	Concentration of products for KCl/gypsum/polymer drilling mud (g/l)	Concentration of products for KCl/K_2CO_3/Shalehib Ultra mud (g/l)
Alkalinity Controller	0.5	–
Viscosifier-1	30	–
Inhibitor	25	–
Bactericide	1	0.5–1.0
Defoamer	1	–
Secondary fluid loss controller	4	–
Viscosifier-2	1	–
Corrosion inhibitor	1	2.0–3.0
Viscosifier-3	2	–
Lubricant	5	–
Ionic Inhibition	–	35–40
Chloride-Free Ionic Inhibition	–	5–10
Rheology/LSRV	–	2.5–3.0
Fluid Loss Control	–	10.0–12.0
Shale Inhibition	–	20.0–25.0
Density/ Bridging	–	40.0–50.0
Density/ Bridging	–	40.0–70.0
Density/ Bridging	–	40.0–70.0
Oxygen Scavenger	–	0.5–1.0

Table 2
Classification of samples formulated.

Samples		Stage-I	Stage-II	Stage-III	Stage-IV
Fly ash	Concentration (wt%)	1, 3, 5, 7, 9	9	7, 9, 12.5, 15	9
Rice husk ash		–	–	2, 4, 7, 9, 12.5, 15	4
Mud Type		KCl/ gypsum/ polymer	KCl/ K_2CO_3/ Shalehib Ultra Mud	KCl/ K_2CO_3/ Shalehib Ultra Mud	KCl/ K_2CO_3/ Shalehib Ultra Mud

Table 3
Code of samples for Stage-IV.

BM	Base Mud
12.5FAM	Base Mud+12.5 wt% FA
4RHAM	Base Mud+4 wt% FA
CM	Combined mud: Base mud+12.5 wt%FA+4 wt%RHA

after making sure that the rotor is properly installed. Finally, viscometer was turned on and dial readings was recorded at the speeds of 600, 300, 200, 100, 6 and 3 (rpm) while the ensuring that the samples are stirred for 10 s at 600 rpm before each speed change to gain same shear history each sample. After recording the values of the readings for all speeds, the following equations were applied to compute the rheological parameters:

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

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

$$\text{Yield point (YP) in } \left(\text{lb}/100\text{ft}^2\right) = \theta_{300} - \text{PV} \quad (3)$$

Gel strength of the designed drilling fluid systems was measured by reading maximum deflection observed at speed of 3 rpm after the rest period for at 10 s, 1 min and 10 min. At the beginning of each gel strength measurement, the samples were stirred for 10 s at 600 rpm.

2.5. Determination of fluid loss

The formulated samples were subjected to a fluid loss test to determine their filtration property. Fluid loss of the samples was determined by using a standard API filter press under 100 + 5 (psi) nitrogen pressure at room temperature for 30 min. Filtrate of the samples was collected in a graduated cylinder and recorded in mL unit at the end of 30 min. Subsequently, cake thickness of the test fluids was measured with a vernier caliper (Wang et al., 2021a, 2021b).

2.6. Determination of density

The studied samples were also subjected to density measurement and their density test was carried out by using Model 140 Fann Mud Balance to determine the mass of a given volume of liquid. For the measurement, Fann Mud Balance cup was filled with the studied mixture and the cup was closed with its lid, making sure that some drilling fluid does not escapes from the top hole of the lid, which means that it is completely filled. Subsequently, rider was moved along to balance arm up to the bubble located between the two line on the balance arm. Finally, the density was read off from the ruler on balance arm was recorded in lb/gal unit.

3. Results and discussion

3.1. Fly ash and rice husk ash characterization

The rice husk ash or fly ash both of them actually have been used as a cross linking agent to link the other particles in drilling sample. The difference between the fly ash and rice husk ash could be attributed to the percent of alumina and silica content. XRF analysis of fly ash and rice husk ash was given in Table 4. As can be seen from the table, since the value of total amount of SiO_2+Al_2O_3+Fe_2O_3 present in fly ash is more than 70% and the percent of CaO is less than Fe_2O_3, the fly ash used in the study was determined as Class F (Ahmaruzzaman, 2010). On the other hand, SiO_2 comprise 97.3% wt of rice husk ash.

The X-ray diffraction analysis (XRD) of the fly ash and rice husk ash were given in Fig. 2. The XRD pattern of rice husk ash samples the peaks of SiO_2 demonstrated that the crystalline form known as cristobalite phase. Also, other phases identified with XRD analysis are tridymite and anorthite. The fly ash is also characterized by a different phase composition. The identified phases are quartz, mullite, hematite, Ca4O16C8H8 (Rood et al., 2006), tridymite and aragonite and this pattern shows that the highly crystalline nature of the investigated sample. This property of the sample could be the reason of the mineral contents also proven by the high peak intensity. The peak list of each phase in fly ash and rice husk ash can be seen in Table A.1 and Table A.2, respectively.

Table 4
The chemical analysis of fly ash and rice husk ash.

Oxides	Fly ash (wt%)	Rice husk ash (wt%)
SiO_2	57.9	97.3
Al_2O_3	24.8	0.2
MgO	1.05	0.51
CaO	1.64	0.65
Na_2O	0.83	0.13
K_2O	1.49	2.68
Fe_2O_3	5.03	0.14
MnO	0.030	0.195
TiO_2	0.594	0.011
P_2O_5	0.046	0.429

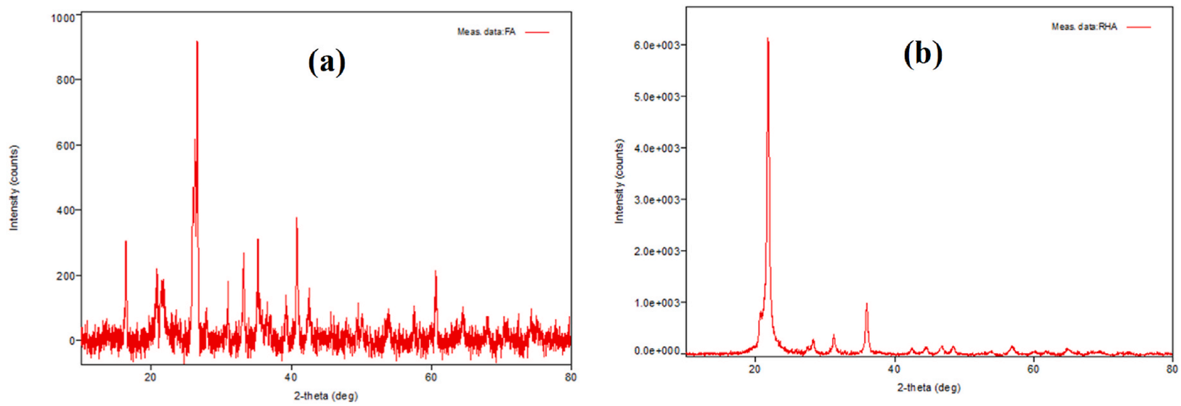

Fig. 2. XRD pattern of fly ash (a) and rice husk ash (b).

FTIR measurements of fly ash and rice husk ash related to the silica is shown in Fig. 3. The peaks of fly ash are the most intense peak at about 1031 cm-1, which is corresponding to the asymmetric stretching vibrations Si–O; peak at about 423 cm-1 related to the bending vibrations O–Si–O and 777,65 cm-1 correspond to the symmetric stretching vibrations of Si–O–Si bridges. Presence of aluminum atoms in this coal ash corresponds to the shifts of the peaks. The lower wavenumber is about the 1031 cm-1 means that the increasing Al/Si ratio (Mozgawa et al., 2014).

When investigated the FTIR spectra of the rice husk ash the peak at 1064 cm-1 which related to the Si–O–Si asymmetric vibration and because of the ionic character of the Si–O group [utilization of agro residual waste]. The peaks at 789 and 455 cm-1 Si–O bending and band vibrations and the peak at 620 cm-1 is correspond to the cristobalite phase of silica (Parande et al., 2011).

As seen from Fig. 4, SEM analysis reveals that the fly ash particles are generally in spherical shape and composed of solid spheres, cenospheres and unburnt carbon. Also observed irregular shaped particles are composed of the minerals in the fly ash not melting but only soften (Yao et al., 2015). Spherical particles are relatively smooth and composed of quartz. The clump of iron oxide particles may also be observed in the figure.

The SEM analysis of rice husk ash is presented in Fig. 5. From the figure, it can be seen that the honeycombed hole structure Fig. 5(a and b) and between the outer and interior surfaces composed of crosswise mesh of chips Fig. 5(c and d). These chips have a large number of holes. The porous structure of rice husk ash could be burning up the organic components. Also pore size of rice husk ash varies from 1.0 µm to 30 µm Fig. 5(c–e) (Xu et al., 2012). SEM images of RHA shows that RHA has pores of varying sizes. These pores increase the SSA values of RHA.

The particle size distribution and specific surface area (SSA) values is important to consider in preparing the drilling fluid sample as the materials have quite different particle size distribution depending on the region obtained (Brown et al., 2011; Verma et al., 2006). These values affect the rate of formation of filter cake. In this case fly ash and rice husk ash supports the rapid formation of filter cake. Thereby, minimizing the fluid loss depending on the concentration of the fly ash and rice husk ash. Particle size distribution of raw and ground forms of fly ash and rice husk ash was presented in Fig. 6. As seen in the figure, the cumulative curves of fly ash and rice husk ash form an S-shape when plotted in semi-logarithmic coordinates, which is consistent with the particle size distribution pattern of conventional bridging material (Dick et al., 2000). While x axis denotes particle size, y axis shows cumulative undersize particles (%). It is clear that highly finer particle and higher SSA of fly ash was obtained with grinding process. In addition, mean particle diameter (D_{50}) and SSA of untreated fly ash are greater than those rice husk ashes.

3.2. Analyzing of different concentrations of fly ash on rheology and filtration

To develop mud system firstly an attempt has been made for determination of optimum concentration of fly ash. To address this, different concentration of fly ash (1, 3, 5, 7, and 9 wt%, i.e. 1 wt% means 1 g of fly ash is employed into 100 g of inhibitive mud at 1g/100 g) was introduced into KCl/gypsum/polymer mud. After addition, rheological and filtration tests were performed.

Fig. 7(a) demonstrates shear stress against shear rate for the samples containing 1, 3, 5, 7, and 9 (wt%) fly ash fractions employed. It can be seen that addition of fly ash into the mud affects the rheology profile.

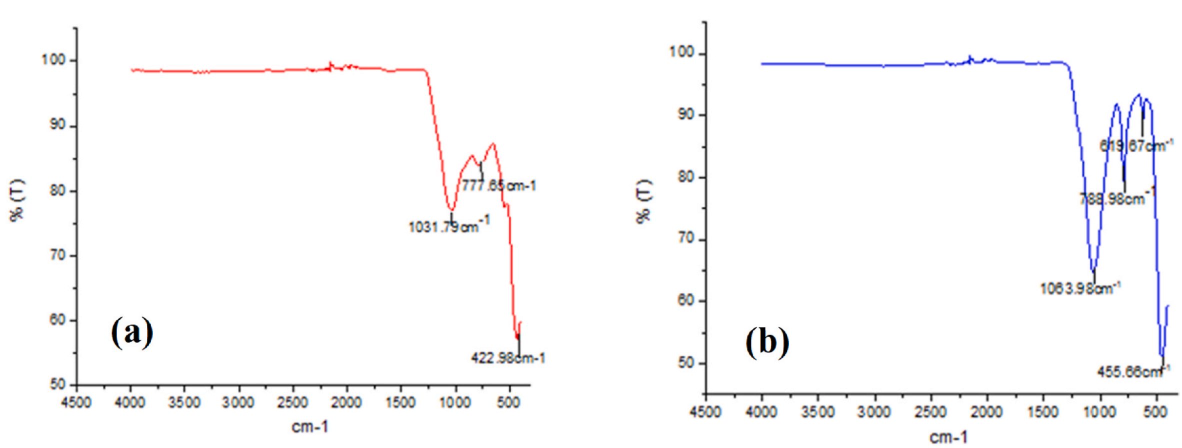

Fig. 3. FTIR spectrum of fly ash (a) and rice husk ash (b).

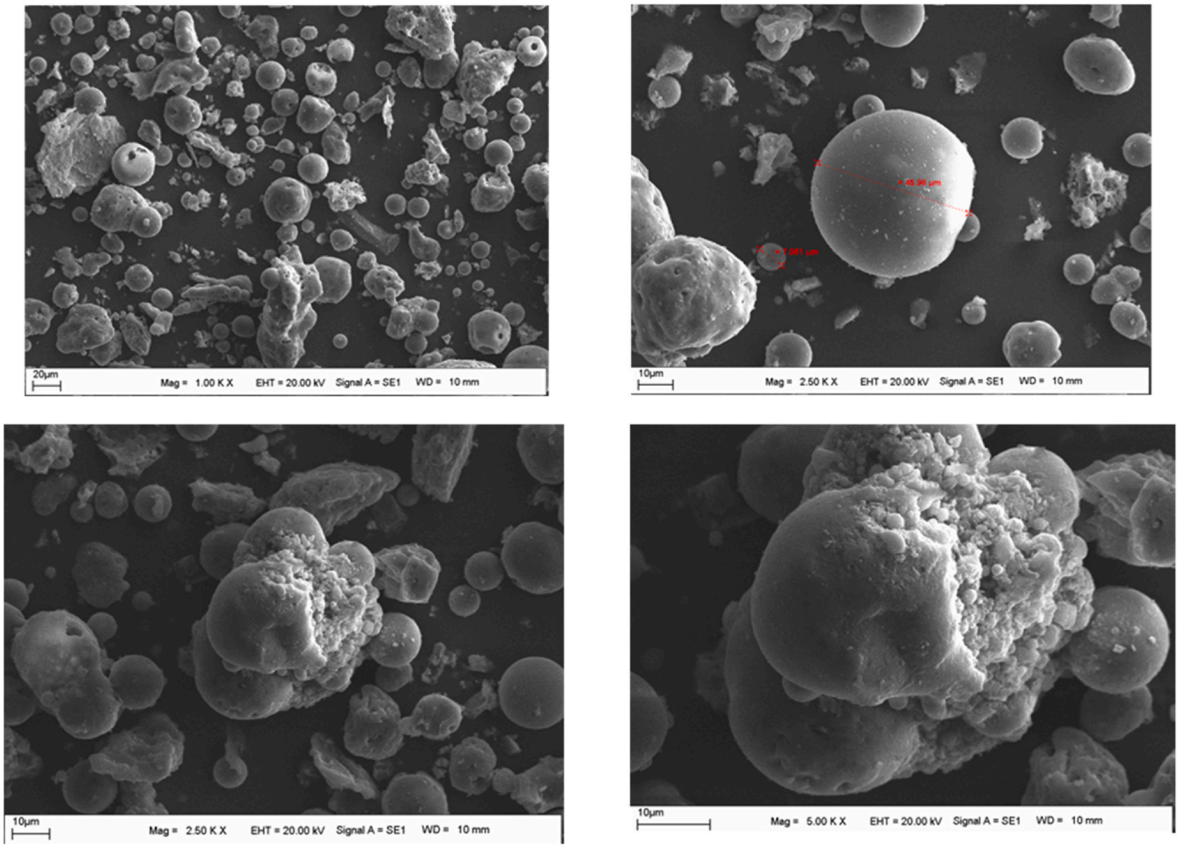

Fig. 4. SEM images of fly ash.

Shear stress magnitudes increases steadily with the increasing concentration of fly ash. It is worth noting that fly ash more than 5 wt% concentration shows a significant increment in the shear stress values. For example, while the shear stress of the base mud was 77.96 lb/100 ft^2 at a shear rate of 1022 s^{-1}, 80.10, 82.23, 84.37, 89.71 and 97.18 lb/100 ft^2 were recorded for muds containing 1, 3, 5, 7 and 9 wt% fly ash, respectively. This means that adding 9 wt% fly ash to the mud increases the shear stress of the base mud by 24.65%. The increasing shear stress with the addition of fly ash to the mud indicates that the viscosity of the mud increases. This means that the inhibitive mud incorporation with 9 wt% fly ash has a better cutting carrying capacity and thus the well cleaning ability of the mud is superior (Ghaderi et al., 2020). It was also observed that the difference between the shear stresses magnitudes under high shear rates is greater than at low shear rates for all concentrations studied. Moreover, apparent viscosity, plastic viscosity, and yield point results is shown in Fig. 7(b) based on 1, 3, 5, 7, and 9 (wt%) concentrations of fly ash. The figure shows that apparent viscosity, plastic viscosity, and yield point go up as fly ash concentration increases. However, when taking a closer look at the figure, it is seen that the increment in yield point and apparent viscosity is greater than the increment of plastic viscosity. For instance, yield point and apparent viscosity increased by 27% and 25%, respectively while plastic viscosity increased by 21% for 9 wt% fly ash concentration. These results are better than the results obtained from the study by Abo Taleb et al. (2019) investigating the use of environmentally friendly mandarin peel powder in drilling mud. In the study, with the use of 2% mandarin peel powder, plastic viscosity and yield point increased by 71% and 21%, respectively. In addition, in the study performed by Ekeinde et al. (2019), where green additives were used in drilling mud, in contrast to the increase in yield point, it decreased by 54%, 22% and 9%, respectively in the presence of Brachystegia nigerica (Achi), Detarium microcarpum (OFFOR) and Averrhoa carambola L. (Kian). These results indicate that inhibitive mud incorporation with 9 wt% fly ash has better rheological behavior.

Fig. 7(c) demonstrates variation of gel strengths of drilling fluid with the employment of fly ash. The gel strengths of mud slightly increased with the different concentrations of fly ash and while the initial gel strength of drilling muds formulated with fly ash varied in the range of 7–8 lb/100 ft^2, the 10-min gel strength was found in the range of 11–13 lb/100 ft^2. This indicates that drilling fluids formulated with fly ash possess a good gel strength, which means that the drilling fluids have a better ability to suspend cuttings in the wellbore when circulation is stopped. In addition, the muds also do not require high pumping pressure when drilling is restarted after a well shut-down period (Hossain and Wajheeuddin, 2016; Jain and Mahto, 2015).

Fig. 7(d) shows that fluid loss of the muds recorded at the end of 30 min. The fluids loss of the mud exhibits a fluctuation with the employment of different concentrations of fly ash and showed an increase up to 5 wt%. Beyond this, the fluid loss exhibits a declining trend and decreased by 13% for 9 wt% fly ash concentration. Filtrate volume of the formulated fluid (2.6 ml) is an accepted value (Kosynkin et al., 2012; Khodja et al., 2010a). In addition, lower fluid loss was obtained compared to the study by Jain and Mahto (2015). This result shows the binding effect of fly ash, by decreasing the fluid loss. In contrast to fluid loss results, similar mud cake thickness was observed. Fig. 7(e) shows that mud cake thickness decreases constantly as fly ash concentration increases. The cake thickness decreased by %65 with 9 wt% fly ash concentration, which it is the thinnest cake thickness among the other concentrations. With the reduction of the filter cake, not only the effect on the formation or the pay zone is reduced, but it also provides the advantage of being easily removed when the well is put into production. These results may be due to the bridging effect of the fly ash and can be attributed to the fact that fly ash molecules bridge the pores of the filter paper quickly (Mahto et al., 2013).

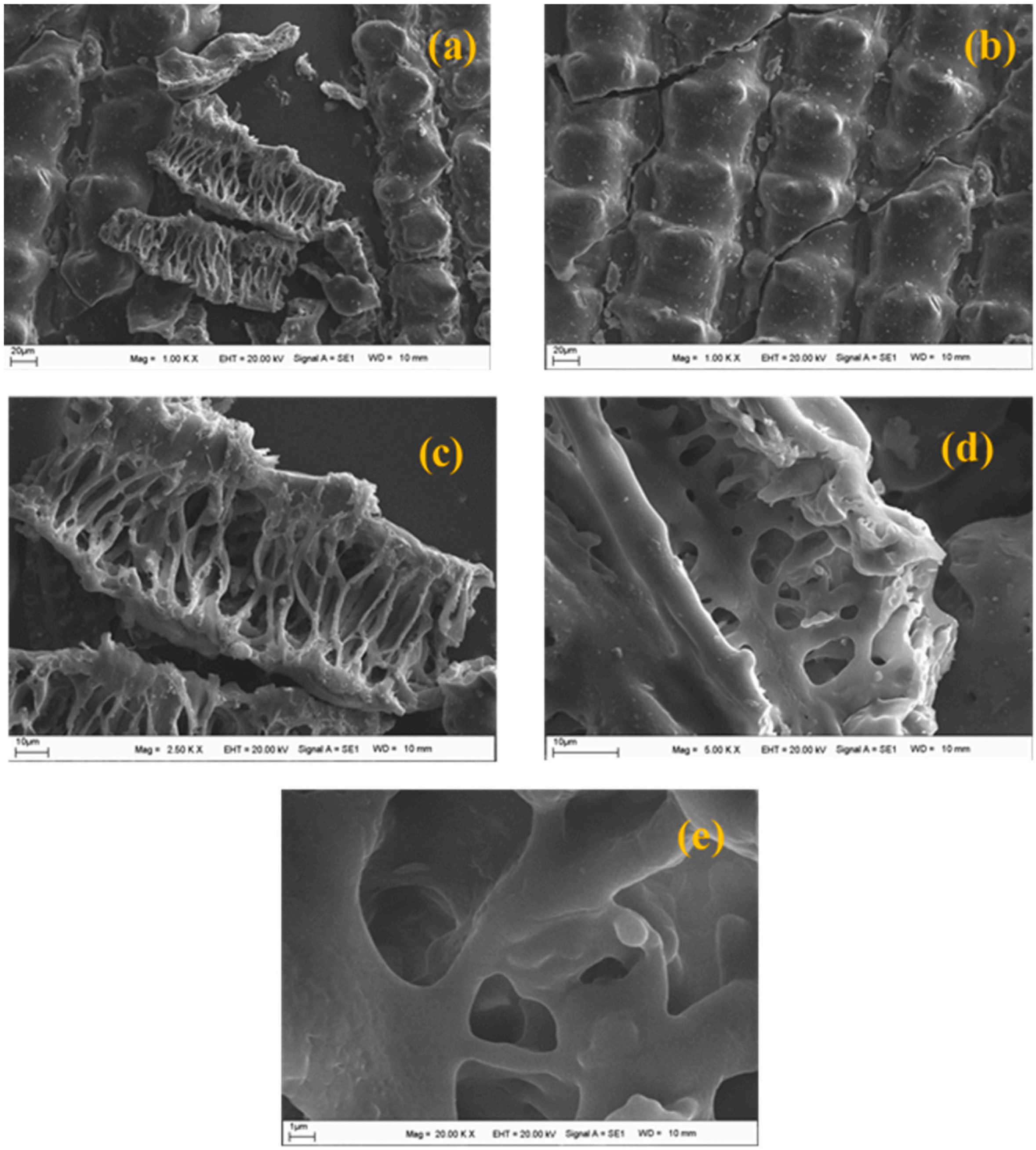

Fig. 5. SEM images of rice husk ash.

Overall analysis results in this section shows that 9 wt% fly ash was determined as optimum concentration exhibiting higher rheology, lower filtration and thinner filter cake.

3.3. Analyzing of different particle size of fly ash on rheology and filtration

The particle size has an important role in characteristics of drilling mud. In the oil and gas industry, one of the purpose of particle size distribution analysis is as a basis for determining the filtration loss characteristic of drilling mud (Hossain and Wajheeuddin, 2016). The optimum concentration that is 9 wt% of fly ash determined in section 3.2 in KCl/Gypsum/Polymer mud was introduced into the KCl/K_2CO_3/Shalehib Ultra mud to analyze role of fineness of fly ash on its flow characteristics.

Analysis of shear stress against shear rate test results of the samples with different particle size were presented in Fig. 8(a). It can be clearly seen that addition of ground fly ash has negligible effect on rheology profile. Almost same shear stress magnitude was obtained with 30, 60 and 120 min grinding time under all given shear rates at constant 9 wt% fly ash concentration. It should be noted that raising rheogram compared to the base mud due to amount of fly ash used. On the other hand, it was analyzed that addition of sieved fly ash at same concentration (9 wt%) increases the rheology profile compared to both base mud and ground fly ashes mud. The sieved fly ash showed the highest shear stresses under all given shear rates among all ground samples.

Fig. 8(b) shows AV, PV, YP and gel strength of KCl/K_2CO_3/Shalehib Ultra mud with different grinding time (30, 60, and 120 min) of fly ash and non-grinding (sieved) fly ash for 9 wt% concentration. Grinding time has negligible effect on AV, PV and YP of the mud, as can be seen from the figure. Non-ground fly ash shows higher rheology than those of 30 min, 60 min and 120 min ground fly ashes. This indicate that the

Samples	D10, µm	D50, µm	D90, µm	SSA, cm²/cm³
Rice husk ash	44.53	102.39	218.45	831.47
Sieved FA	21.25	67.89	117.90	1349
30 min. ground FA	7.26	18.25	48.74	4242.9
60 min. ground FA	5.61	13.75	28.90	5687.4
120 min. ground FA	3.46	9.38	17.61	9814.2

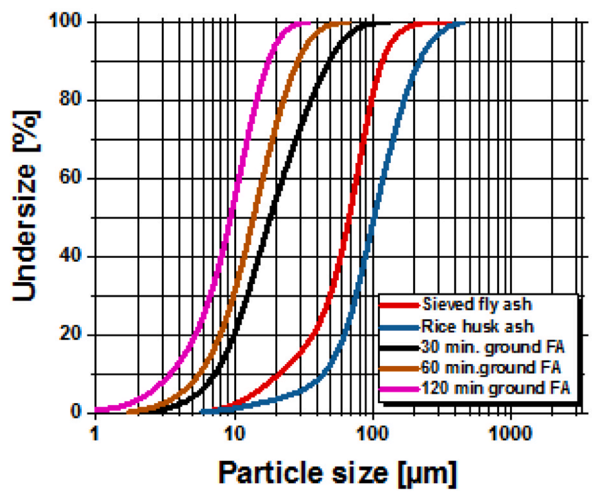

Fig. 6. Particle size distributions of fly ashes and rice husk ash.

drilling fluid incorporated with sieved fly ash has better superior hole cleaning than that of 30, 60, and 120 min grinding time of fly ashes. Same scenario was also observed in gel strength characteristics. Fig. 8(c) demonstrates that 10 s, 1 min and 10-min gel strengths remains constant with different grinding time of fly ashes. Similarly, highest gel strengths were obtained with non-grinding fly ash. It is worth noting that the increased rheology and gel strengths with addition of the different grinding time of fly ash is result from 9 wt% concentration of fly ash compared to the base mud not containing fly ash.

In contrast to rheology, particle size of fly ash plays a significant role in fluid loss, cake thickness and density of the mud. Fig. 8(d) shows that filtrate amount of the drilling fluid collected at the end of 30 min in case of usage of 9 wt% concentration of fly ash having different particle size. From the figure, it is seen that influx amount increases as grinding time of fly ash increases that means finer particle size. This can be attributed to the decrease in the permeability of the filter cake as colloidal particles are packed firmly compared to coarser size particles (Hossain and Wajheeuddin, 2016). On the other hand, the use of 9 wt% concentration and non-grinding of fly ash, reduces the risk of formation damage and associated difficulties due to reduced filtering. While filtrate increases with longer ground time of fly ashes, mud cake thickness decreases with the increased grinding time of fly ashes as can be seen in Fig. 3(e). However, it should be noted that similar to fluid loss the lowest mud cake thickness was achieved with non-grinding, sieved, fly ash. The sieved fly ash used at a concentration of 9 wt% reduced the mud cake thickness by 45%, while the ground fly ash for 120 min reduced by 35%.

Density of the drilling fluid increases with finer particle size of fly ashes. Since grinding time increases the particle density of fly ash increases, this can be attributed to higher particle density. KCl/K_2CO_3/ Shalehib Ultra mud containing 9 wt% 120 min grinding fly ash shows the highest density, as can be seen in Fig. 3(f).

From literature (Ma et al., 2020; Hoxha et al., 2016; Oort et al., 2016; Liangchun et al., 2015) it is seen that most solid particle sizes in conventional drilling fluids are in the range of 1 µm–100 µm, and in general the solid particle size ranges from 0.1 µm to 1000 µm. When evaluating the particle size analysis in general, as can be seen from Fig. 6, the particle size distribution of the fly ash and rice husk ash examined in the study is in accordance with the range specified in the literature.

3.4. Comparative performance of drilling fluid samples

To analyze effect of high concentration of fly ash also in KCl/K_2CO_3/ Shalehib Ultra mud system, 7, 9, 12.5 and 15 (wt%) of fly ashes were introduced into the mud. Hence, effect of fly ash in different inhibitive mud compositions was analyzed as well. The flow behavior of rice husk ash was also investigated in the mud at increasing concentrations (2, 4, 7, 9, 12.5 and 15 (wt%).

Fig. 9(a) presents shear stress against shear rate results of mud samples with high concentrations fly ash and increasing concentration of rice husk ash. It is clearly seen that addition of both fly ash and rice husk have a great variation of rheology profile. It was observed that the shear stress magnitudes also increase under high concentration of fly ash for given shear rates, as can be seen from the figure. Similar to lower concentration rheology profile analyzed in section 3.2, this increment particularly at high shear rates is more apparent. A similar pattern was observed for rice husk ash, which is given in Fig. 9(b). Increasing concentration of rice husk ash results in increment in shear stress values and has more effect on shear stress at high shear rates as well. The shear stress caused by the increase in the amount of fly ash and rice husk ash indicates that these waste materials have a significant physical interaction with the water-based drilling fluid (Ghaderi et al., 2020). When taking a closer look at the figure, it was analyzed that samples with rice husk ash have higher shear stresses than fly ash at constant shear rates and same concentrations. The difference of shear stress magnitude between mud with fly ash and rice husk ash become more apparent under high shear rates. Another noticeable observation is samples with high concentration fly ash have a steady increment in the shear stress at constant shear rate whereas rice husk ash particularly more than 9 wt% shows a significant increment in the shear stresses for the given shear rates.

Fig. 9(c) and (d) show AV, PV, YP and gel strength of the mud system in presence of fly ash and rice husk ash, respectively. AV reflects the

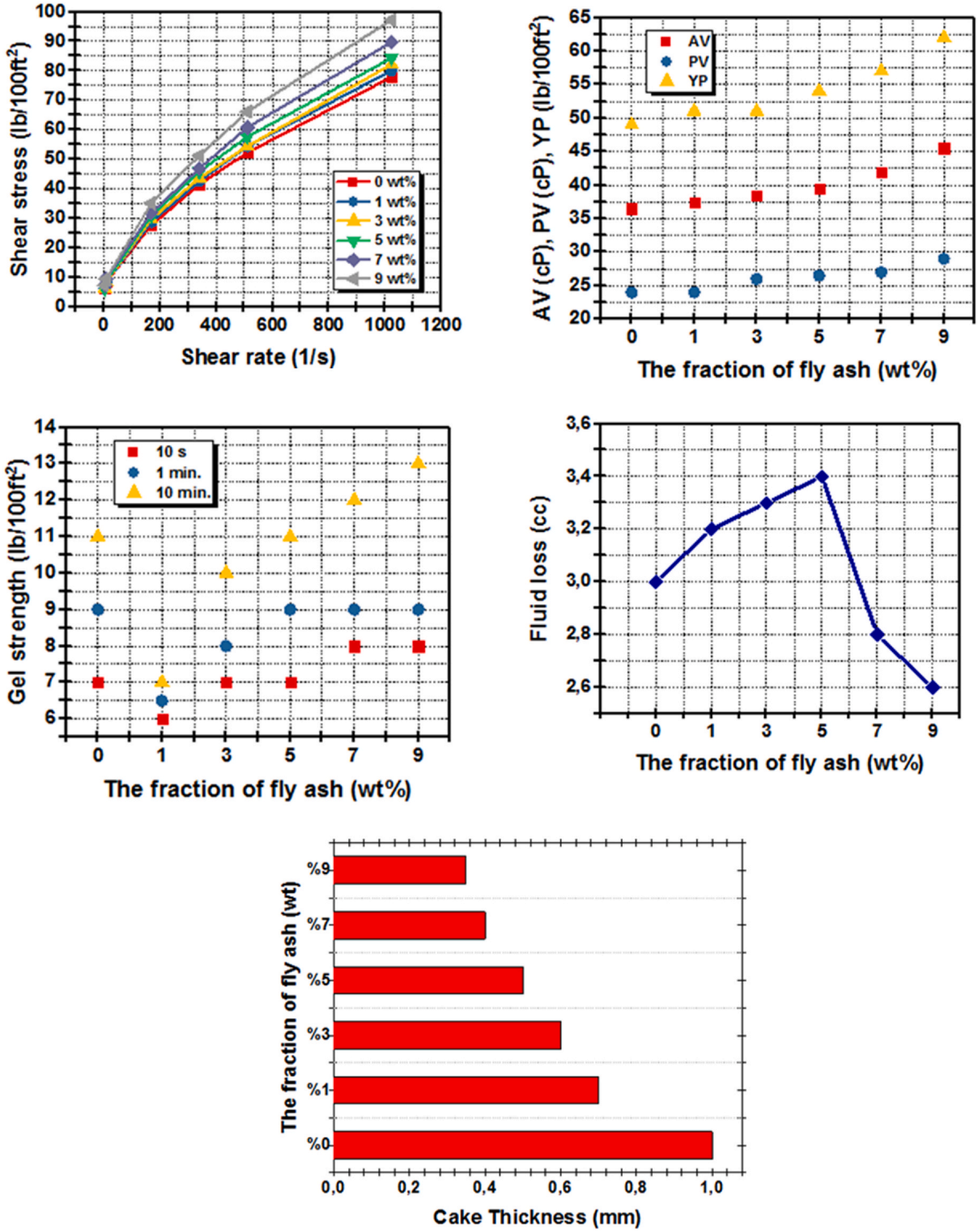

Fig. 7. Effect of fly ash concentration on the rheological and filtration properties of drilling fluid.

flowability of drilling fluids and is related to the rate of penetration, and PV is due to friction between suspended particles and is affected by the viscosity of the base fluid. In addition, high yield point of drilling fluid indicates better cutting carrying capacity (Falode et al., 2008; Meng et al., 2012; Hossain and Wajheeuddin, 2016). In order to effectively remove cuttings from the bottom of the well to the surface, low viscosity is required within the drill-string where shear rates are high, while relatively higher viscosity is essential in the annulus with where shear rates are low. In addition, moderate level apparent viscosity is required for the circulation of the drilled solids (Gao et al., 2021; Jain and Mahto, 2015; Ogugbue et al., 2010; Mahto and Sharma, 2004). On the other hand, increase in the ratio of yield point to plastic viscosity indicates that the drilling mud exhibits better shear thinning behavior (Jain and Mahto, 2015; Mahto and Sharma, 2005). From the figures, it is seen that AV, PV and YP increases with the increasing concentration of both fly ash and rice husk ash. It should be noted that higher AV, PV and YP was obtained with rice husk ash compared to fly ash at same concentrations. For instance, AV, YP and PV increased by 41%, 34%, 35%, respectively

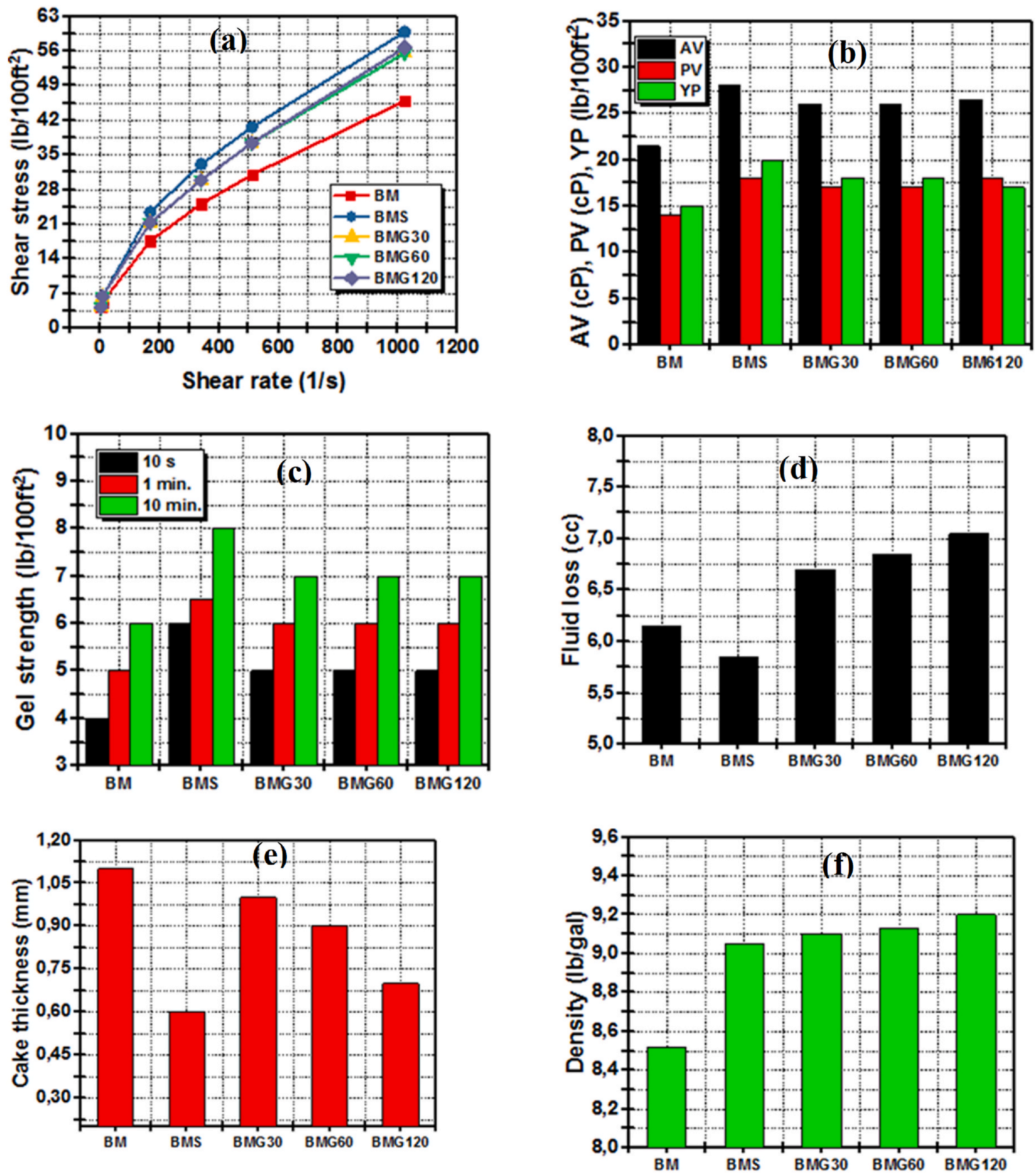

Fig. 8. Effect of particle size of fly ash on the on the rheological and filtration properties of drilling fluid.

with fly ash for the highest concentration that is 15 wt% while the rheological parameters increased by 100%, 113%, 92%, respectively with rice husk ash. On the other hand, AV, YP and PV increased by 35%, 32%, 28%, respectively with fly ash for the 12.5 wt% concentration while the parameters increased by 19%, 27%, 14%, respectively with the 4 wt% rice husk ash. These results were found to be better when compared to previous studies. For instance, in the study by Al-Hameedi et al. (2019a), the use of potato peel powder in drilling mud resulted in a decrease in the yield point. Moreover, in the study conducted by Iranwan et al. (2009) in which corncobs and sugar cane was used in drilling mud, the materials used caused a decrease in the yield point of the drilling mud. It should be noted that, although the results obtained in this study show that the plastic viscosity of drilling mud increased with fly ash and rice husk ash, the ratio of yield point to plastic viscosity increased as increment of yield point is higher than the increase in plastic viscosity. It worths to mentioned that, from the literature, it was seen that (Al-Saba et al., 2018) and (Al-Hameedi et al., 2019a) did not examine the apparent viscosity parameter, which is one of basic property of drilling fluid, in their studies investigating the efficiency of environmentally friendly materials in drilling mud.

Similar pattern was observed for gel strengths of the mud system. Drilling mud must have sufficient gel strength so that solid particles can be suspended and prevented from settling at the bottom of the well in static conditions (Salmachi et al., 2016). From Fig. 9(e) and (f), it is seen that 10 s, 1 min and 10 min gel strength increases with the increasing concentration of both fly ash and rice husk ash. These results are seen to be more favorable when compared to the studies in the literature. For instance, in the studies carried out by (Al-Hameedi et al., (2019a)) and Iranwan et al. ((2009)), decreasing gel strengths were obtained with the environmentally friendly material they examined. On the other hand,

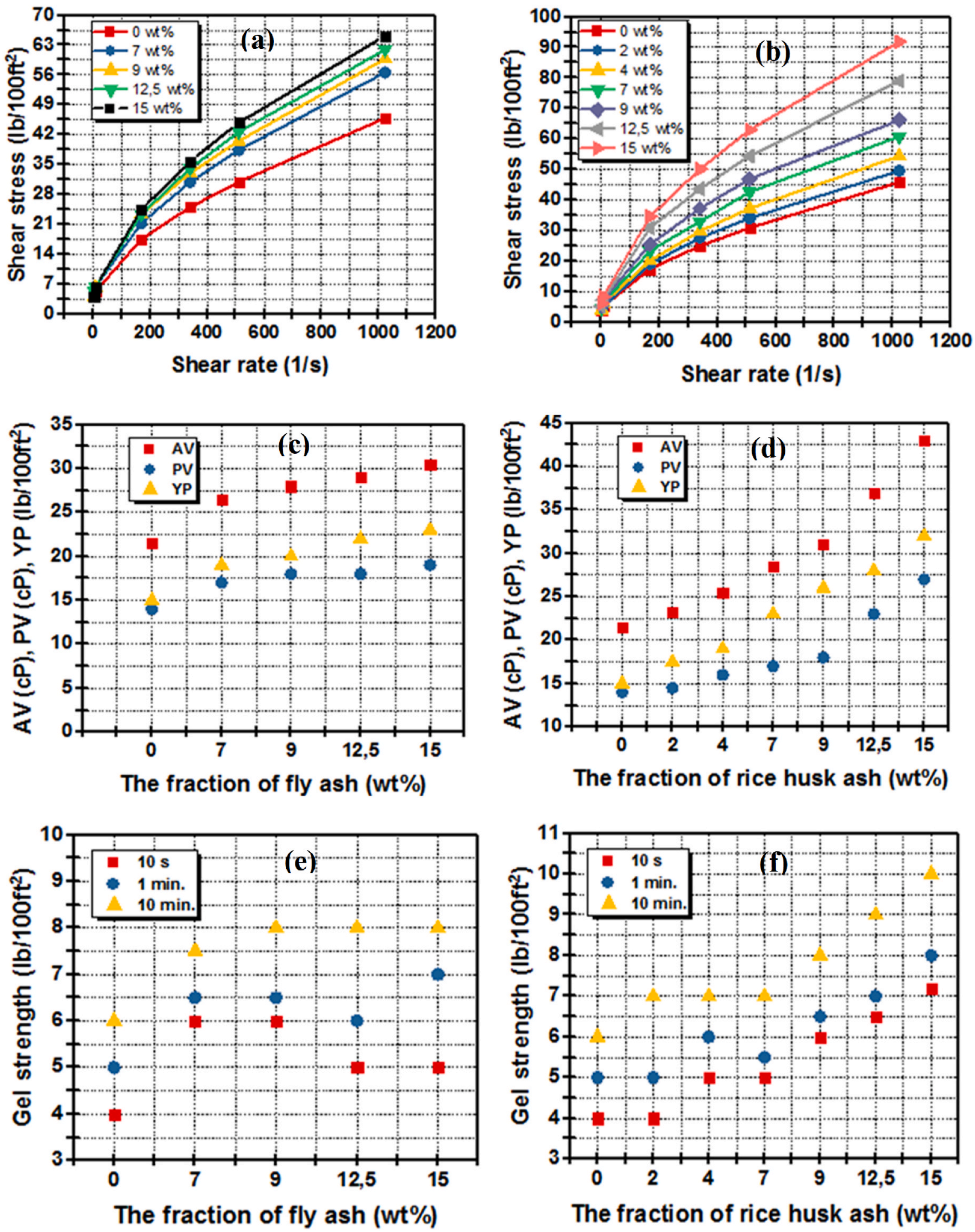

Fig. 9. Rheological properties of drilling fluid in presence of various concentration of fly ash and rice husk ash.

for a properly formulated drilling mud, the 10-s gel strength should be greater than at least 4 lb/100 ft^2, and the 10-min gel strength should be higher than a minimum of 6 lb/100 ft^2 (Gao et al., 2021; Ahmad et al., 2018). The 10 s and 10 min gel strength of water-based drilling mud formulated with 12.5 wt% of fly ash is 5 lb/100 ft^2 and 8 lb/100 ft^2, respectively, while that of 4 wt% rice husk ash drilling mud is 5 lb/100 ft^2 and 7 lb/100 ft^2, respectively. It should be emphasized that 10 s and 10 min gel strength of the reference mud is not higher than the minimum required value. This shows that gel strengths of both drilling fluid with 12.5 wt% of fly ash and 4 wt% of rice husk ash developed are greater than the minimum required values, and this indicates that developed muds possess enhanced cutting suspend ability. In the study (Al-Saba et al., 2018), an unacceptable value such as 89 lb/100 ft^2 of gel strength for 10 s was obtained when 5 ppb of soya bean peel powder was used in water-based mud.

As it is mentioned that the filtrate volume collected at the end of 30 min of drilling fluid systems was given in Fig. 10(a) and Fig. 10(b). The figures show that fluid loss measured with addition of fly ash and rice

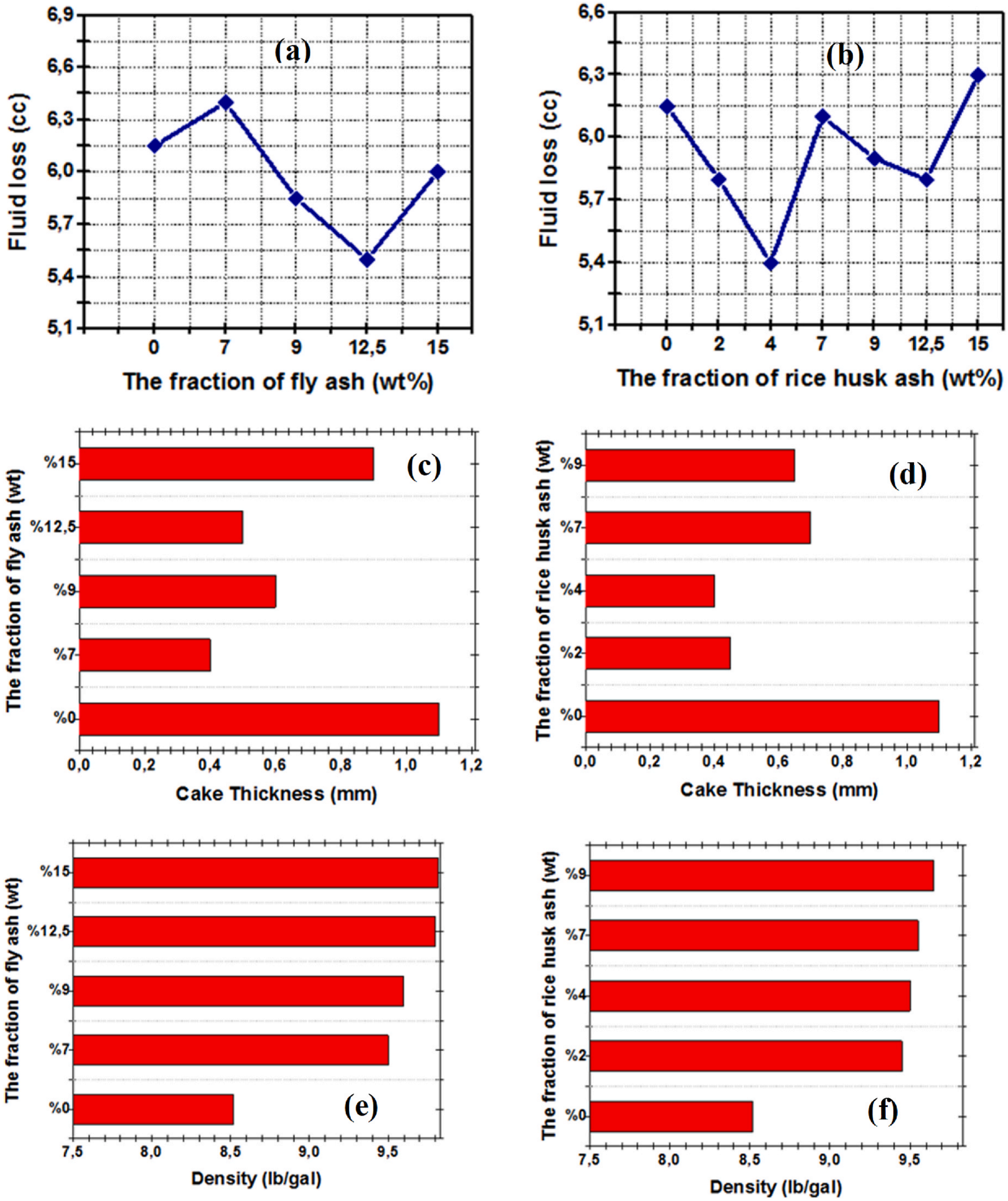

Fig. 10. Filtration properties and density of drilling fluid in presence of various concentration of fly ash and rice husk ash.

husk ash. A variation was observed for filtration and mud cake thickness of KCl/K_2CO_3/Shalehib Ultra mud system with increasing concentration of both fly ash and rice husk ash. Moreover, analyzing of the figures show that fluid loss reduced by 10% with the addition of 12.5 wt% concentration of fly ash while reduced by 12% with the usage of 4% rice husk ash, these are the lowest values obtained among the concentrations studied. It should be emphasized that when these results are compared with the study performed by (Saengdee and Terakulsatit, 2017), it was observed that both fly ash and rice husk ash are more effective in reducing filtration. The authors obtained an approximately 6% fluid loss reduction in the water based drilling mud when 1% sugar cane ash was incorporated with reference fluid. However, it should be noted that the mud incorporated with fly ash has lower filtrate volume than that of rice husk ash under high concentrations employed that are 12.5 wt% and 15 wt%, respectively. These results are mainly regarding with their pore stability.

In addition to fluid loss volume cake thickness could also affect the production in two ways. A thicker cake may reduce production restrictions, while a thinner cake may have the reverse effect. Since higher cake thickness need to be removed through the drilling operations and therefore some additional operations are needed, and this will cause higher cost and lost time (Azar and Samuel, 2007; Lake, 2006). Mud cake thickness results of the drilling fluid was presented in Fig. 10(c) and (d). From the figures, it is seen that similar results were not observed for mud cake thickness as well with the increasing concentration of both fly ash and rice husk ash. Mud cake thickness reduced by 54% at 12.5 wt% concentration for fly ash whereas reduced by 63% with the addition of 4 wt% concentration of rice husk ash. Similar to filtration, thinner mud cake thickness was obtained with fly ash than the mud with rice husk ash under high concentration (9, 12.5 and 15 (wt%)). When filtration property of the developed drilling mud is evaluated in terms of both fluid loss and mud cake thickness, it can be concluded that superior filtration results were obtained in this study due to the fact that improved results were obtained in both fluid loss and mud cake thickness when compared to some studies in the literature. For instance, in the study Okon et al. (2014), when 20 g of rice husk was used in water-based drilling mud, the mud cake thickness increased by 220%, although it significantly reduced the fluid loss. Similarly, Agwu et al. (2019) although using rice husk and saw dust in water-based drilling mud resulted in a significant decrease in filtration, the thickness of mud cake increased by 280% and 230%, respectively, with the use of 0.020 kg rice husk and saw dust compared to control drilling fluid. The results indicate that mud containing high concentration fly ash, 12.5 and 15 wt %, forms a relatively better-quality mud cake and decrease the possibility of serious problems such as formation damage, stuck pipe, wellbore stability problems compare to the mud containing rice husk at the same high concentrations. These challenges can cause loss of time and increase the cost of drilling operations, even the loss of the oil, gas and geothermal wells. To overcome for all mentioned problems, fly ash and rice husk ash could be used as binding agent.

The reason of results about the filtration is depends on the particle size of the fly ash and rice husk ash in fluid samples which quickly forms thin impermeable filter cake. Also, the filtration loss depends not only the binding effect of the fly ash and rice husk ash but also particle size and specific surface area (SSA) values (Wajheeuddin and Hossain, 2018; Hossain and Wajheeuddin, 2016).

Density of the second mud system increases with the increasing concentration of both fly ash and rice husk ash, which is given in Fig. 10 (e) and (f). However, when same concentration fly ash and rice husk ash was employed higher density values were obtained with rice husk ash. This can be attributed to higher particle density of rice husk ash than fly ash. Finally, from this analysis, optimum concentrations for fly ash and rice husk ash were determined as 12.5 wt% and 4 wt%, respectively considering both rheological and filtration results.

Fig. 11 shows that AV, PV and YP increment and filtrate volume and mud cake thickness reduction when 9 wt% concentration of fly ash was introduced into the two-mud system (KCl/gypsum/polymer mud (first) and KCl/K_2CO_3/Shaleib ultra mud (second)) having different compositions. It was analyzed that fly ash has more impact on the second mud system than that of first mud system. The addition of fly ash at a concentration of 9 wt% to the first mud increased the AV, PV and YP values by 25%, 21% and 27%, respectively, while the AV, PV and YP values of the second mud increased by 30%, 33% and 29%, respectively. It was also observed that contrary to rheology results, fly ash exhibits better filtration performance in the first mud system. The magnitude of both filtrate volume and mud cake thickness reduction in the first mud is higher than second mud. Addition 9 wt% of fly ash to the first mud system reduced the volume of filtrate collected at the end of 30 min by 13%, while reducing fluid loss by 5% in the second mud system. Furthermore, cake thickness decreased by %65 in first mud system at 9 wt% whereas decreasing the cake thickness by %45 in the second mud system for same concentration.

3.5. Analyzing of combination of fly ash and rice husk ash on rheology, filtration, and density

After the analyzing of different concentration of fly ash and rice husk ash on flow characteristics of the mud, 12.5 wt% fly ash and 4 wt% rice husk ash was found to be the optimum concentrations achieved from the analysis were employed simultaneously into the KCl/K_2CO_3/Shaleib ultra mud system to investigate the effects when fly ash and rice husk ash were combined.

It should be noted that drilling fluid system developed were coded as following: BM: Base mud, CM: Combined Mud-Base mud+12,5 wt% FA+4 wt% RHA, 12.5FAM: Base mud+12.5 wt% FA, 4RHAM: Base mud+4 wt% RHA.

The analysis results of shear stress versus shear rate were presented in Fig. 12(a). From the figure, combined mud has greater effect than optimum concentrations on rheology profile. The shear stress magnitudes for the combined mud higher than both optimum concentration of fly ash and rice husk ash for all given shear rates. As it can be seen from the figure, shear stress increases as shear rate increases for all mud samples. This indicate that both combined mud and mud with optimum concentrations of fly ash and rice husk ash shows shear thinning behavior. The behavior is a favorable feature for the performance of drilling mud. Due to this feature, the combined mud and mud with optimum concentrations of fly ash (12.5 wt%) and rice husk ash (4 wt%) separately yield a lower apparent viscosity in the drill string and bit nozzle flows where high shear rates are experienced, thereby reducing pressure losses. Thus, it helps transmit more hydraulic power to the bit. On the other hand, it helps to clean the well by increasing the carrying capacity of the mud that behaves more viscous in the annulus where the shear rate is low (Gao et al., 2021; Jain and Mahto, 2015; Ogugbue et al., 2010; Mahto and Sharma, 2004).

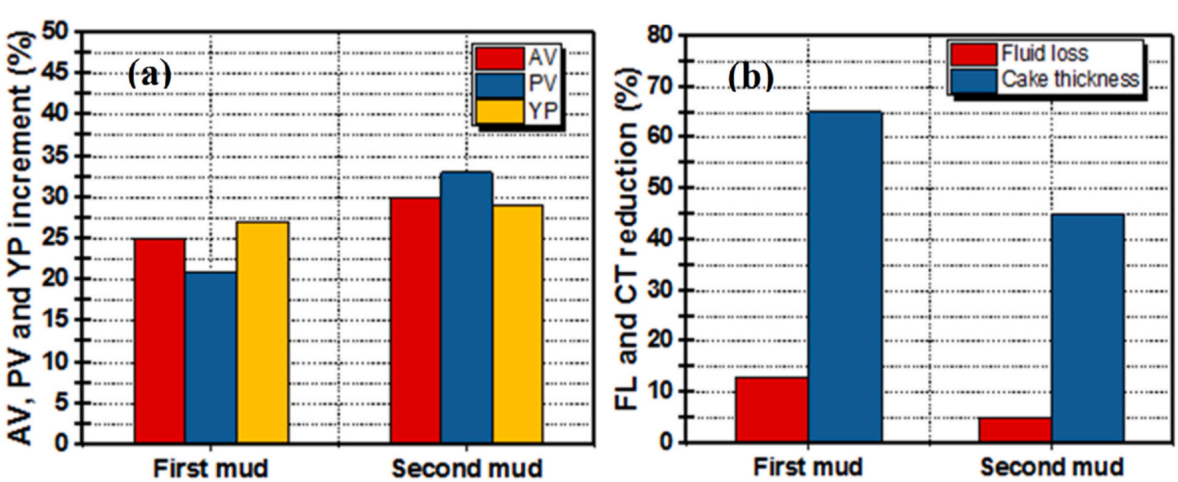

Fig. 11. Apparent viscosity, plastic viscosity and yield point increment (%) (a) Filtrate volume (FL) and cake thickness (CT) reduction (%)(b) in presence of 9 wt% concentration of fly ash.

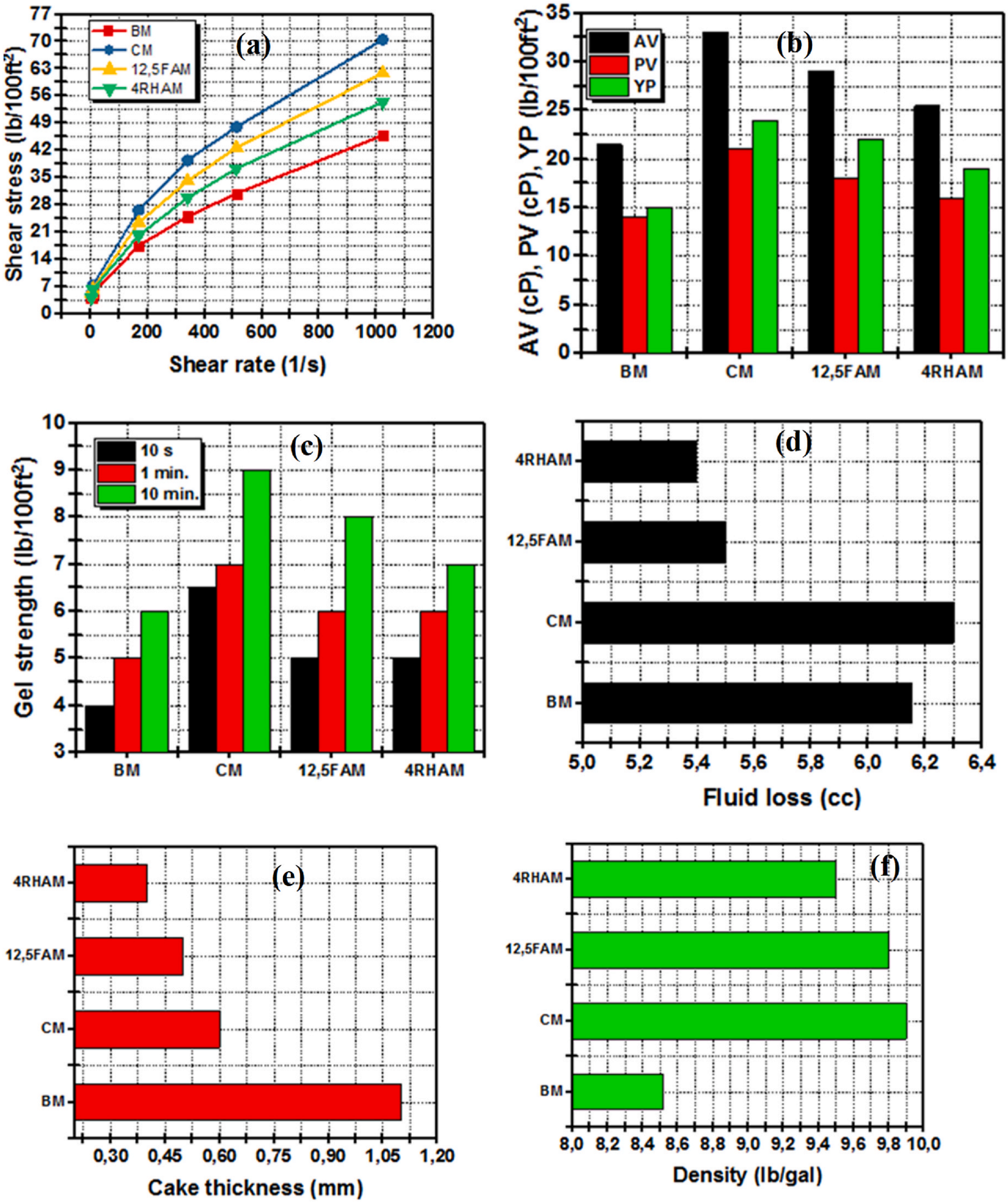

Fig. 12. Rheological, filtration properties and density of combined mud and samples with optimum concentrations.

Fig. 12(b) and (c) show AV, PV, YP and gel strengths of the mud system when those concentration of fly ash and rice husk ash were introduced into the mud. From Fig. 7(a), it can be noted that with this attempt AV, PV, YP increased by 53%, 50%, 60%, respectively compared to base mud without fly ash and rice husk. Moreover, it was observed that the rheological parameters AV, PV and YP of the mud incorporated both fly ash and rice husk ash have greater values compared to mud containing both only 12.5 wt% concentration of fly ash and 4 wt% concentration of rice husk ash. These results indicate that the combination of fly ash and rice husk ash in the mud has the better rheological behavior compared to the both base mud and mud containing 12.5 wt% concentration of fly ash and 4 wt% concentration of rice husk ash, separately. Similar trend was also observed for gel strength of the combined mud, which is given in Fig. 12(c). 10 s, 1 min and 10 min gel strengths of the mud slightly increased compared to mud which fly ash and rice husk ash were employed separately.

Another noticeable feature is the use of a combination of fly ash and rice husk enhances rheology of the mud system, filtration properties worsened compared to both base mud and mud containing 12.5 wt% concentration of fly ash and 4 wt% concentration of rice husk ash, separately. Fig. 12(d) shows that would in general skip optimum combination with optimum concentration of fly ash rice husk ash increased fluid loss of by about 2%. It was also analyzed that fluid loss with the combined FA/RHA mud about 13% and 14% higher than the mud including only fly ash 12.5 wt% and 4 wt% rice husk ash, respectively. Similarly, combination of optimum concentration of fly ash rice husk ash also negatively affects the mud cake thickness. It caused an increase in cake thickness of the muds including only both 12.5 wt% fly ash and 4 wt% rice husk ash, as can be seen in Fig. 12(e). Fig. 12(f) shows that the density of both base mud and mud containing 12.5 wt% fly ash and 4 wt % rice husk ash increases with the combine of optimum concentration of fly ash rice husk ash, as expected. This is a result of the increasing mass of solids in the mud.

When this study is evaluated in general, the scope of the study seems to be broader when compared to previous studies using environmentally friendly additives. For instance, Al-Hameedi et al. (2019b) investigated the effectiveness of grass powder in water-based drilling mud and results obtained from their studies showed grass powder showed an improvement in the filtration properties of the drilling mud. However, how the grass powder affects the rheological properties of the drilling mud was not studied by the authors. Likewise, in the study Okon et al. (2014) where rice husk was used in water-based mud, it was determined that there was a good reduction in fluid loss of control mud in the presence of rice husk ash, nevertheless no information was given about the rheological properties of the control mud when rice husk was introduced. In addition, in the study conducted by Iranwan et al. (2009) in which corn cobs and sugar cane was used in drilling mud, the effectiveness of these environmentally friendly materials in the drilling mud was evaluated only on the basis of rheological properties, without taking into account the filtration properties. It should also be emphasized that in these studies, neither evaluation of the environmentally friendly materials was made on more than one different type of drilling mud, nor the performance of the materials used in drilling mud as a result of mechanical grinding was examined. On the other hand, it should be emphasized that in this study, both rheological and filtration properties of the drilling muds developed were improved with both fly ash and rice husk ash. In the study conducted by (Meng et al., (2012)), the effectiveness of carbon ash in the water drilling mud was investigated and their results show that although carbon ash improved the rheological properties of water-based mud, it significantly increased fluid loss and filter cake. In addition, in the study (Al-Saba et al., 2018), although 5 ppb of banana peel powder showed improvement in filtration, it worsened the rheological properties of drilling mud. Similarly, in the study conducted by Al-Hameedi et al. (2019a), potato peels powder improved the filtration properties of the water based drilling mud, while it had a negative effect on its rheological properties.

In order to determine the applicability of the developed drilling mud systems, they were compared with the existing drilling mud systems. Table 5 contains the data of the water-based drilling fluids currently used in the drilling industry and the drilling fluids developed. Comparisons were made on the basis of density, PV, YP, gel strength and fluid loss parameters, which are the basic drilling fluid properties. As can be seen from the table, different drilling fluid systems have different properties. It is seen that the developed mud systems are quite comparable with the water-based drilling muds currently used in drilling.

The developed drilling fluids are expected to be less costly as it is predicted to reduce potential well instability problems to some extent due to their improved rheological and filtration properties as well as abundance of the source materials, their availability and easy accessibility (Al-Hameedi et al., 2019c; Wajheeuddin and Hossain, 2018; Hossain and Al-Majed, 2015).

4. Conclusions

In the study, fly ash and rice husk ash were used to develop inhibitive drilling fluid system with different concentrations based on KCl/gypsum/polymer and KCl/K_2CO_3/Shaleib ultra muds at room temperature. An extensive laboratory work was conducted by studying rheological and filtration properties of the systems and various particle sizes obtained as a result of mechanical grinding of fly ash were also taken into account in the development of the drilling mud. Experimental results show that employing fly ash (12.5 wt%) and rice husk ash (4 wt%) into the KCl/K_2CO_3/Shaleib ultra muds not only improved the drilling fluid rheology but also yielded superior filtration characteristics with respect to reduction in fluid loss and mud cake thickness. Moreover, the results reveal that particle size of fly ash plays an important role on flow behavior of the drilling mud which reveal that binding effect of the ash particles cause a reduction in cake thickness and fluid loss volume. The optimum particle size of fly ash was obtained with sieving process (<106 μm) compared to 30 min, 60 min and 120-min. ground forms. Based on the study, it can be concluded that achieving superior results with respect to mitigation of fluid loss volume and enhancement in rheology characteristics as well as reduction of mud cake thickness are advantages of the developed mud systems, thereby reducing the risk of issues such as formation damage, wellbore instability and associated challenges. Moreover, development of the drilling fluid systems with good characteristics from fly ash and rice husk ash, which are encountered as large amounts of wastes, has a distinct advantage in terms of the recycling of these wastes as well as being more cost-effective. Finally, since the developed mud systems were formulated based on drilling fluid systems used in oil and gas drilling well, novel findings obtained from the study can be regarded as a guide on applicability of fly ash and rice husk ash for future researches.

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Table 5
Comparison between proposed drilling fluids and existing water-based drilling fluid systems.

Type of drilling fluid	Density, ppg	Plastic viscosity, cP	Yield point, lb/100 ft^2	Gel strength, lb/100 ft^2		Filtrate, cm^3/30 min
				10 s.	10 min	
Lignite/lignosulfonate muds[a] (deflocculated)	9	8–12	6–10	2–4	4–10	8–12
Lime muds[a]	10	15–18	6–10	0–2	0–4	6–12
Lime muds[a]	9	9–12	2–20	0–5	1–20	8–12
Gypsum muds[a]	9	12–15	6–10	2–4	8–12	8–12
Brackish-water muds[a]	9	16	10–18	2–4	5–10	6–10
KCl-polymer muds[a]	9–10	12–25	10–20	6–8	8–20	10–12
KOH-lignite muds[a]	9	12–24	9–12	2–4	4–8	10–12
KOH-lime muds[a]	9	10–12	8–12	4–6	6–10	6–9
New fly ash mud	9.8	18	22	5	8	5.5
New rice husk ash mud	9.5	16	19	5	7	5.4

[a] Source-(Amoco Production Company, 2010, Hossain and Wajheeuddin, 2016).

Credit author statement

Emine Yalman: Conceptualization, Methodology, Investigation, Writing – original draft, Reviewing and Editing. Gabriella Federer Kovacsne: Supervision, Conceptualization, Validation, Visualization, Methodology. Tolga Depci: Supervision, Conceptualization, Validation, Visualization, Methodology. Hani Al Khalaf: Conceptualization, Methodology, Writing. Volkan Aylikci: Supervision, Conceptualization, Validation, Visualization, Methodology. Mustafa Goktan Aydin: Conceptualization, Visualization, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

API	American Petroleum Institute
AV	Apparent Viscosity
FA	Fly Ash
FTIR	Fourier-Transform Infrared Spectroscopy
lb/gal	Pound per gallon
min	Minute
mL	Milliliter
PSD	Particle Size Distribution
psi	Pound square inch
PV	Plastic Viscosity
RHA	Rice Husk Ash
rpm	Revolution Per Minute
s	second
s^{-1}	Per second
SEM	Scanning Electron Microscopy
SSA	Specific Surface Area
wt	Weight
XRD	X-ray Diffraction Analysis
YP	Yield Point
ppb	Pound per barrel

Appendix A

Table A.1
Major XRD reflections of fly ash and phases

Peak list of quartz						
No	h	k	l	d [Å]	2θ [°]	I [%]
1	0	1	0	425.738	20.848	29.3
2	−1	1	0	334.542	26.624	100.0
3	2	1	1	181.899	50.109	16.4
Peak list of mullite						
No	**h**	**k**	**l**	**d [Å]**	**2θ [°]**	**I [%]**
1	0	1	1	5.39259	16.425	61.2
2	0	1	2	3.42705	25.979	62.9
3	0	2	1	3.39432	26.234	100.0
4	1	0	0	2.88500	30.972	20.3
5	0	2	2	2.69629	33.200	44.6
6	1	1	1	2.54383	35.253	53.9
7	0	1	3	2.42722	37.007	15.6
8	1	2	0	2.29403	39.241	21.7
9	1	1	2	2.20707	40.854	63.4
10	0	2	3	2.12168	42.577	22.1
11	1	0	4	1.59954	57.577	17.8
12	1	3	3	1.52563	60.650	46.9
13	2	0	0	1.44250	64.553	22.1
Peak list of hematite						
No	**h**	**k**	**l**	**d [Å]**	**2θ [°]**	**I [%]**
1	−2	1	0	3.68313	24.144	53.9
2	4	1	0	2.70102	33.140	100.0
3	0	1	1	2.51740	35.635	64.3
4	6	0	0	2.29378	39.245	34.8
5	6	1	1	1.69551	54.042	21.4
6	4	2	1	1.48632	62.431	23.0

(*continued on next page*)

Table A.1 (*continued*)

Peak list of tridymite						
No	**h**	**k**	**l**	**d [Å]**	**2θ [°]**	**I [%]**
1	0	0	2	4.30428	20.619	56.3
2	1	2	0	4.30168	20.631	51.0
3	10	0	0	4.09319	21.694	100.0
4	5	0	2	3.80980	23.330	16.3
5	6	2	0	3.80793	23.342	15.5
Peak list of aragonite						
No	**h**	**k**	**l**	**d [Å]**	**2θ [°]**	**I [%]**
1	1	1	1	3.39654	26.216	100.0
2	2	1	0	3.27374	27.218	55.6
3	1	2	0	2.70147	33.135	50.8
4	0	2	1	2.48534	36.111	27.0
5	0	0	2	2.48100	36.176	17.5
6	1	2	1	2.37263	37.890	40.7
7	3	0	1	2.34187	38.407	27.7
8	2	2	0	2.32958	38.618	19.3
9	2	0	2	2.10609	42.907	20.9
10	2	1	2	1.97732	45.855	71.4
11	4	1	0	1.88221	48.316	29.4
12	0	2	2	1.87733	48.449	19.7
13	3	2	1	1.81484	50.231	29.9
14	1	3	1	1.74279	52.462	32.0
15	2	3	0	1.72552	53.028	15.4
Peak list of $Ca_4O_{16}C_8H_8$						
No	**h**	**k**	**l**	**d [Å]**	**2θ [°]**	**I [%]**
1	1	1	0	5.47311	16.182	88.1
2	0	2	0	3.40050	26.185	100.0
3	1	2	0	3.19042	27.943	33.0
4	3	1	0	2.80065	31.929	75.4
5	4	0	0	2.30500	39.046	19.0
6	1	3	0	2.20143	40.963	27.6
7	2	3	0	2.03433	44.500	24.6
8	2	3	1	1.94900	46.560	16.2
9	3	3	0	1.82437	49.951	17.3

Table A.2
Major XRD reflections of rice husk ash and phases

Peak list of cristobalite						
No	h	k	l	d [Å]	2θ [°]	I [%]
1	1	1	0	4.06097	21.869	100.0
2	0	2	0	2.49450	35.974	13.0
Peak list of tridymite						
No	h	k	l	d [Å]	2θ [°]	I [%]
1	0	1	1	4.32593	20.514	100.0
2	0	0	2	4.30000	20.639	45.1
3	2	0	0	4.10707	21.620	82.5
4	1	−1	1	3.86408	22.998	32.6
5	1	0	2	3.80958	23.331	30.2
6	1	1	1	3.79209	23.440	24.3
7	0	1	3	2.48757	36.077	20.0
Peak list of anorthite						
No	h	k	l	d [Å]	2θ [°]	I [%]
1	2	0	2	4.69636	18.881	18.0
2	0	2	0	4.04281	21.968	53.1
3	1	1	3	3.78226	23.502	27.3
4	3	1	−1	3.76156	23.633	16.7
5	1	1	−3	3.62257	24.554	41.7
6	3	−1	1	3.46390	25.698	15.0
7	3	−1	−1	3.36286	26.484	30.0
8	2	2	2	3.26375	27.303	60.1
9	0	0	4	3.20970	27.772	47.5
10	2	−2	0	3.19626	27.891	100.0
11	4	0	0	3.18373	28.003	81.5
12	2	2	−2	3.12689	28.523	46.8
13	3	1	3	3.04535	29.303	22.7
14	2	0	4	2.95465	30.224	33.3
15	4	0	2	2.93939	30.385	21.4

(*continued on next page*)

Table A.2 (*continued*)

16	3	1	−3	2.82957	31.594	27.5
17	3	−1	−3	2.65332	33.754	16.9
18	0	2	4	2.52349	35.547	20.6
19	0	2	−4	2.50418	35.830	33.5

References

Aboulrous, A.A., Mahmoud, T., Alsabagh, A.M., Abdou, M.I., 2016. Application of natural polymers in engineering. In: Natural Polymers, pp. 185–218.
Agwu, O.E., Akpabio, J.U., Archibong, G.W., 2019. Rice husk and saw dust as filter loss control agents for water-based muds. Heliyon 5, e02059.
Ahmad, H.M., Kamal, M.S., Al-Harthi, M.A., 2018. Rheological and filtration properties of clay-polymer systems: impact of polymer structure. Appl. Clay Sci. 160, 226–237.
Ahmaruzzaman, M., 2010. A review on the utilization of fly ash. Prog. Energy Combust. Sci. 36, 327–363.
Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Alashwak, N.A., Alshammari, A.F., Alkhamis, M.M., Alsaba, M.T., 2019a. Environmental friendly drilling fluid additives: can food waste products be used as thinners and fluid loss control agents for drilling fluid?. In: SPE Symposium: Asia Pacific Health, Safety, Security, Environment and Social Responsibility OnePetro.
Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Al-Alwani, M.A., Alshammari, A.F., Albazzaz, H.W., Al-Bazzaz, W.H., 2019b. Proposing a new eco-friendly drilling fluid additive to enhance the filtration properties of water-based drilling fluid systems. In: SPE Gas & Oil Technology Showcase and Conference. OnePetro.
Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Albazzaz, H.W., Alkhamis, M.M., 2019c. Insights into eco-friendly and conventional drilling additives: applications, cost analysis, health, safety, and environmental considerations. In: SPE Symposium: Asia Pacific Health, Safety, Security, Environment and Social Responsibility. OnePetro.
Al-Saba, M.T., Amadi, K.W., Al-Hadramy, K.O., Al Dushaishi, M.F., Al-Hameedi, A., Alkinani, H., 2018. Experimental investigation of bio-degradable environmental friendly drilling fluid additives generated from waste. In: SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility. Society of Petroleum Engineers.
Amoco Production Company, 2010. Drilling fluids manual. https://www.academia.edu/6348534/Drilling_Fluids_Manual. (Accessed 26 October 2021), 444.
ASTM C 618, 1997. Standard Specification for Coal Fly Ash and Raw or Calcined Pozzolan for Use as a Mineral Admixture in Concrete. ASTM International, West Conshohocken, PA.
ASTM C618, 2008. 08 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. ASTM International.
Avci, E., Szabo, T., Federer, G., 2019. Rheological performance of fly ash in inhibitive water-based drilling fluids. Petroleum & Coal 61, 1307–1313.
Azar, J.J., Samuel, G.R., 2007. Drilling Engineering. PennWell books.
Biltayib, B.M., Rashidi, M., Balhasan, S., Alothman, R., Kabuli, M.S., 2018. Experimental analysis on rheological and fluid loss control of water-based mud using new additives. J. Petrol. Gas Eng. 9, 23–31.
Brown, P., Jones, T., BéruBé, K., 2011. The internal microstructure and fibrous mineralogy of fly ash from coal-burning power stations. Environ. Pollut. 159, 3324–3333.
Chen, G., Chenevert, M.E., Sharma, M.M., Yu, M., 2003. A study of wellbore stability in shales including poroelastic, chemical, and thermal effects. J. Petrol. Sci. Eng. 38, 167–176.
Chepaitis, P.S., Millette, J.R., Vander Wood, T.B., 2011. A novel coal fly ash sphere reveals a complete understanding of plerosphere formation. Microscope-Chicago 59, 175.
Diaz-Perez, A., Cortes-Monroy, I., Roegiers, J.C., 2007. The role of water/clay interaction in the shale characterization. J. Petrol. Sci. Eng. 58, 83–98.
Dick, M.A., Heinz, T.J., Svoboda, C.F., Aston, M., 2000. Optimizing the selection of bridging particles for reservoir drilling fluids. In: SPE International Symposium on Formation Damage Control. OnePetro.
Ekeinde, E.B., Okoro, E.E., Dosunmu, A., Iyuke, S., 2019. Optimizing aqueous drilling mud system viscosity with green additives. Journal of Petroleum exploration and production technology 9, 315–318.
Falode, O.A., Ehinola, O.A., Nebeife, P.C., 2008. Evaluation of local bentonitic clay as oil well drilling fluids in Nigeria. Appl. Clay Sci. 39, 19–27.
Fliss, M.C., Szabo, T., Avci, E., 2019. Effect of micro-sized fly ash on the rheological and filtration properties of water-based muds. Petroleum & Coal 61, 1361–1364.
Fungaro, D.A., Silva, M.V.D., 2014. Utilization of water treatment plant sludge and coal fly ash in brick manufacturing. Am. J. Environ. Protect. 2, 83–88.
Gao, X., Zhong, H.Y., Zhang, X.B., Chen, A.L., Qiu, Z.S., Huang, W.A., 2021. Application of sustainable basil seed as an eco-friendly multifunctional additive for water-based drilling fluids. Petrol. Sci. 18, 1163–1181.
Ghaderi, S., Haddadi, S.A., Davoodi, S., Arjmand, M., 2020. Application of sustainable saffron purple petals as an eco-friendly green additive for drilling fluids: a rheological, filtration, morphological, and corrosion inhibition study. J. Mol. Liq. 315, 113707.
Guancheng, J., Yourong, Q., Yuxiu, A., Xianbin, H., Yanjun, R., 2016. Polyethyleneimine as shale inhibitor in drilling fluid. Appl. Clay Sci. 127, 70–77.
Hossain, M.E., Al-Majed, A.A., 2015. Fundamentals of Sustainable Drilling Engineering. Wiley, Scrivener Publishing, Hoboken, Salem, ISBN 978-0-470-87817-0, p. 786.
Hossain, M.E., Wajheeuddin, M., 2016. The use of grass as an environmentally friendly additive in water-based drilling fluids. Petrol. Sci. 13, 292–303.
Hoxha, B.B., Yang, L., Hale, A., van Oort, E., 2016. Automated Particle Size Analysis Using Advanced Analyzers. AADE Fluids Technical Conference and Exhibition, Houston, Texas, USA, pp. 12–13.
Iranwan, S., Azmi, A., Saaid, M., 2009. Corn cobs and sugar cane waste as viscosifier in drilling fluid. Pertanika Journalof Science & Technology 17, 173–181.
Jain, R., Mahto, V., 2015. Evaluation of polyacrylamide/clay composite as a potential drilling fluid additive in inhibitive water based drilling fluid system. J. Petrol. Sci. Eng. 133, 612–621.
Jongpradist, P., Homtragoon, W., Sukkarak, R., Kongkitkul, W., Jamsawang, P., 2018. Efficiency of rice husk ash as cementitious material in high-strength cement-admixed clay. Adv. Civ. Eng. 2018, 1–11. doi: 10.1155/2018/8346319.
Khodja, M., Canselier, J.P., Bergaya, F., Fourar, K., Khodja, M., Cohaut, N., Benmounah, A., 2010a. Shale problems and water-based drilling fluid optimisation in the Hassi Messaoud Algerian oil field. Appl. Clay Sci. 49, 383–393.
Khodja, M., Khodja-Saber, M., Canselier, J.P., Cohaut, N., Bergaya, F., 2010b. Drilling Fluid Technology: Performances and Environmental Considerations. Products and Services; from R&D to Final Solutions, pp. 227–256.
Kosynkin, D.V., Ceriotti, G., Wilson, K.C., Lomeda, J.R., Scorsone, J.T., Patel, A.D., Tour, J.M., 2012. Graphene oxide as a high-performance fluid-loss-control additive in water-based drilling fluids. ACS Appl. Mater. Interfaces 4, 222–227.
Labenski, F., Reid, P., Santos, H., 2003. Drilling fluids approaches for control of wellbore instability in fractured formations. In: SPE/IADC Middle East Drilling Technology Conference and Exhibition. OnePetro.
Lake, L.W., 2006. “Petroleum engineering handbook”, Volume II. Chapter 10-Drilling Problems and Solutions, Soxciety of Petroleum Enginners 433–455.
Liangchun, P.U., Mingyi, D.E.N.G., Hongming, L.I., Junlin, S.U., 2015. Effect of three new high temperature filtrate reducers on particle size distribution of drilling fluid. Drill. Fluid Complet. Fluid 32, 21–24.
Liu, D., Zhang, W., Lin, H., Li, Y., Lu, H., Wang, Y., 2016. A green technology for the preparation of high capacitance rice husk-based activated carbon. J. Clean. Prod. 112, 1190–1198.
Ma, T., Peng, N., Chen, P., 2020. Filter cake formation process by involving the influence of solid particle size distribution in drilling fluids. J. Nat. Gas Sci. Eng. 79, 103350.
Mahto, V., Jain, R., 2013. Effect of fly ash on the rheological and filtration properties of water based drilling fluids. Int. J. Renew. Energy Technol. 2, 50–156.
Mahto, V., Sharma, V.P., 2004. Rheological study of a water based oil well drilling fluid. J. Petrol. Sci. Eng. 45, 123–128.
Mahto, V., Sharma, V.P., 2005. Tragacanth gum: an effective oil well drilling fluid additive. Energy Sources 27, 299–308.
Mahto, V., Srikanth, P., Krishna, B.V., 2013. Development of non-damaging and inhibitive water based oil well drilling fluids. Petrol. Sci. Technol. 31, 721–726.
Melbouci, M., Sau, A.C., 2008. Washington, DC: U.S. Patent and trademark office. U.S. Patent No. 7, 384–892.
Meng, X., Zhang, Y., Zhou, F., Chu, P.K., 2012. Effects of carbon ash on rheological properties of water-based drilling fluids. J. Petrol. Sci. Eng. 100, 1–8.
Moghaddam, A.K., Saadatabadi, A.R., 2020. Rheological modeling of water based drilling fluids containing polymer/bentonite using generalized bracket formalism. J. Petrol. Sci. Eng. 189, 1–16.
Mozgawa, W., Król, M., Dyczek, J., Deja, J., 2014. Investigation of the coal fly ashes using IR spectroscopy. Spectrochim. Acta Mol. Biomol. Spectrosc. 132, 889–894.
Nmegbu, C.J., Ohazuruike, L., 2014. Wellbore instability in oil well drilling: a review. Int. J. Eng. Res. Dev. 10, 11–20.
Ogugbue, C.C., Rathan, M., Shah, S.N., 2010. Experimental investigation of biopolymer and surfactant based fluid blends as reservoir drill-in fluids. In: SPE Oil and Gas India Conference and Exhibition. OnePetro.
Okon, A.N., Udoh, F.D., Bassey, P.G., 2014. Evaluation of rice husk as fluid loss control additive in water-based drilling mud. In: SPE Nigeria Annual International Conference and Exhibition. Lagos, Nigeria.
Oort, E.V., Hoxha, B.B., Yang, L., Hale, A., 2016. Automated drilling fluid analysis using advanced particle size analyzers. In: IADC/SPE Drilling Conference and Exhibition. OnePetro.
Parande, A.K., Stalin, K., Thangarajan, R.K., Karthikeyan, M.S., 2011. Utilization of Agroresidual waste in effective blending in Portland cement. International Scholarly Research Notices 2011, 1–12. https://doi.org/10.5402/2011/701862.
Patel, A., Stamatakis, S., Young, S., Friedheim, J., 2007. Advances in inhibitive water-based drilling fluids—can they replace oil-based muds?. In: International Symposium on Oilfield Chemistry. OnePetro.
Prasara-A, J., Gheewala, S.H., 2017. Sustainable utilization of rice husk ash from power plants: a review. J. Clean. Prod. 167, 1020–1028.

Rahman, M.E., Muntohar, A.S., Pakrashi, V., Nagaratnam, B.H., Sujan, D., 2014. Self compacting concrete from uncontrolled burning of rice husk and blended fine aggregate. Mater. Des. 55, 410–415.
Rood, J.A., Noll, B.C., Henderson, K.W., 2006. Synthesis, structural characterization, gas sorption and guest-exchange studies of the lightweight, porous metal− organic framework α-[Mg3(O2CH) 6]. Inorg. Chem. 45, 5521–5528.
Salmachi, A., Talemi, P., Tooski, Z.Y., 2016. Psyllium husk in water-based drilling fluids: an environmentally friendly viscosity and filtration agent. In: Abu Dhabi International Petroleum Exhibition & Conference. OnePetro.
Skalle, P., 2011. Drilling Fluid Engineering. Bookboon.
Steiger, R.P., Leung, P.K., 1992. Quantitative determination of the mechanical properties of shales. SPE Drill. Eng. 7, 181–185.
Subashi De Silva, G.H.M.J., Priyamali, M.W.S., 2020. Potential use of waste rice husk ash for concrete paving blocks: strength, durability, and run-off properties. Int. J. Pavement Eng. 1–13.
Van Oort, E., 2003. On the physical and chemical stability of shales. J. Petrol. Sci. Eng. 38, 213–235.
Van Oort, E., Hale, A.H., Mody, F.K., Roy, S., 1994. Critical parameters in modelling the chemical aspects of borehole stability in shales and in designing improved water-based shale drilling fluids. In: Drilling and General Petroleum Engineering.
Vempati, R.K., Borade, R., Hegde, R.S., Komarneni, S., 2006. Template free ZSM-5 from siliceous rice hull ash with varying C contents. Microporous Mesoporous Mater. 93, 134–140.
Verma, A.K., Singh, S., Seshadri, V., 2006. Effect of particle size distribution on rheological properties of fly ash slurries at high concentrations. Int. J. Fluid Mech. Res. 33.
Wajheeuddin, M., Hossain, M.E., 2018. Development of an environmentally-friendly water-based mud system using natural materials. Arabian J. Sci. Eng. 43, 2501–2513.
Wang, Z., Liu, X., Luo, H., Peng, B., Sun, X., Liu, Y., Rui, Z., 2021a. Foaming properties and foam structure of produced liquid in alkali/surfactant/polymer flooding production. J. Energy Resour. Technol. 143, 103005.
Wang, Y., Li, X., Lu, J., 2021b. Experimental study of natural ions and rock interactions for seawater breakthrough percentage monitoring during offshore seawater flooding. SPE J. 1–21.
Xu, W., Lo, T.Y., Memon, S.A., 2012. Microstructure and reactivity of rich husk ash. Construct. Build. Mater. 29, 541–547.
Yang, E., Fang, Y., Liu, Y., Li, Z., Wu, J., 2020. Research and application of microfoam selective water plugging agent in shallow low-temperature reservoirs. J. Petrol. Sci. Eng. 193, 107354.
Yao, Z.T., Ji, X.S., Sarker, P.K., Tang, J.H., Ge, L.Q., Xia, M.S., Xi, Y.Q., 2015. A comprehensive review on the applications of coal fly ash. Earth Sci. Rev. 141, 105–121.
Yu, M., Chen, G., Chenevert, M.E., Sharma, M.M., 2001. Chemical and thermal effects on wellbore stability of shale formations. In: SPE Annual Technical Conference and Exhibition. OnePetro.
Yue, Y., Chen, S., Wang, Z., Yang, X., Peng, Y., Cai, J., Nasr-El-Din, H.A., 2018. Improving wellbore stability of shale by adjusting its wettability. J. Petrol. Sci. Eng. 161, 692–702.
Zeynali, M.E., 2012. Mechanical and physico-chemical aspects of wellbore stability during drilling operations. J. Petrol. Sci. Eng. 82, 120–124.