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Utilization of Steel-Making Dust in Drilling Fluids Formulations

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Abstract: Steelmaking is an energy-intensive process that generates considerable amounts of by-products and wastes, which often pose major environmental and economic challenges to the steel-making industry. One of these by-products is steel dust that is produced during the separation of impurities in the smelting and refining of metals in steel-making furnaces. In this study, electric arc furnace (EAF) dust has been evaluated as a potential, low-cost additive to increase the viscosity and weight of drilling muds. Currently, the cost of drilling operations typically accounts for 50 to 80% of the exploration costs and about 30 to 80% of the subsequent field development costs. Utilization of steelmaking waste in drilling fluids formulations is aimed to produce new and optimized water-based drilling formulations, which is expected to reduce the amount of bentonite and other viscosifier additives used in the drilling formulations. The results showed that in a typical water-based drilling fluid of 8.6 ppg (1030.51 kg/m^3), the amount of standard drilling grade bentonite could be reduced by 30 wt.% with the addition of the proposed new additive to complete the required mud weight. The mixture proved to be stable with no phase separation.

Keywords: steelmaking; recycling; bentonite; solid waste management; sustainable materials

1. Introduction

The steel-making process produces large amounts of steel dust, which are reported to be as high as 2–4 tons for each ton of steel produced [1]. Consequently, waste management and processing of these by-products is becoming a major environmental issue [2]. The steel dust solid material is formed as a result of interactions between impurities such as silica and lime at various stages of steel production [3], and during the separation of flux and impurities in the smelting and refining of metals processes in steel-making furnaces [4]. Most of the produced steel dust is used for land filling [5,6] and many civil engineering applications including cement production [7–11]. It is also used as an asphalt mixture additive in the surface layer of roads or airport pavements [12–15]. Bentonite clays and steel dust share similar chemical composition. Both contain aluminum silicates and various combinations of oxides, in addition to sodium, calcium and magnesium ions [16,17]. As shown in the general formula below [18], bentonite clays consist of aluminum silicates with the presence of other ions, such as Na^+, Ca^{+2}, and Mg^{+2}, alongside other elements like iron oxide (FeO), manganese oxide (MnO), and magnesium oxide (MgO) [19]. Some compounds such as CaO, Fe_2O_3, SiO_2, Al_2O_3, TiO_2 and MgO also exist in the steel-making by-products with little variations in mass ratios [20,21].

Therefore, many studies propose using steel dust in applications where clays are similarly used. They are used as adsorbents to remove toxic and heavy metals from water [22–28], as catalyst [29–31], and for CO_2 sequestration [32,33]. In addition, steel dust was also reported to have been used for drill cuttings disposal [34,35]. The drilled cuttings were disposed through solidification by combining the drill cuttings with water and blast furnace slag to form highly concentrated drilled cutting wastes. The blast furnace slag was compatible with both oil and water-based drilling muds. The drill cutting wastes solidified by blast furnace slag were hard and unreachable [35].

Bentonite clays are also widely used in many industries, such as cosmetics and medical products, paints, water treatment [36–39], pharmaceuticals [40], dyes [41,42], and papermaking [43–45]. In drilling fluids formulation, bentonite mostly makes 80 wt.% of the drilling fluids. Circulation of viscous heavy fluids, such drilling fluids (drilling mud) is essential for successful drilling operation [46,47]. The favorable chemical composition and physical properties of bentonite increases mud viscosity and reduces filtration loss that occur due to differences in pressure between the column of drilling fluids and the formation pore pressure [48]. The fluid is injected through a hollow drill-string, and then flushed out of the well lifting the drilled cutting through annulus space between the drilling string and the wall of the well [49]. The mud circulation serves as hole cleaner by lifting rock cuttings, providing a reasonable hydrostatic pressure to suppress the overburden pressure of the formation and preventing formation fluids from flowing into the well while drilling [46,50]. This mud shares about 50% of the drilling cost, in addition to the overall field development cost due to mud related problems [51]. The proposed formula with the utilization of steel-making waste in drilling fluids is expected to reduce the amount of bentonite and other costly additives used in the drilling formulations.

Worldwide, the total production of steel increased recently to hundreds of million metric tons according to world steel association reports [52]. A typical integrated steel plant produces about 90 to 100 kg of steel slag per ton of steel during the refining of hot metal from the blast furnace. This generates alkaline solid residues about 10 wt.% to 15 wt.% of the produced steel, depending on the characteristics of the manufacturing process. The dust is extensively available and can be supplied as raw material from many steel industries [53]. Composition of the dust varies depending on the type of steel being manufactured, raw materials, cooling and crash methods. Various slag types are produced as by-products in metallurgical processes or as residues in incineration processes in large amounts, which can be classified into three categories according to its origins and the characteristics: ferrous slag, non-ferrous slag, and incineration slag [54]. The main types of steel dust produced at steelmaking process are Ladle Furnace (LF) slag, Bag house dust (BHD) and Cyclone silo dust. The bag house dust (BHD) is the type evaluated in this study and proposed as a drilling fluids additive [51].

Waste management focuses on managing and monitoring of waste and by-product materials, mainly collection, transportation, processing or disposal [55,56]. Steelmaking by-products, such as steel dust is being processed and utilized in many applications. However, to the best knowledge of the author, steel dust has never been evaluated as drilling fluid additives or used in drilling fluids formulations. In this study, the steelmaking by-products have been evaluated to make up to 30 wt.% of the drilling fluid base formulation.

2. Materials

Two types of steel by-products: Ladle Furnace (LF) slag and Bag house dust (BHD) were selected for the study. The samples were collected from the open-to-the atmosphere yard at a local steel factory. The samples were sieved through 200 mesh sieves (75 μm) to remove any coarse parts. Commercial bentonite was purchased from Sigma-Aldrich Company Ltd., Germany. The chemical compositions for the two types of steel dust and the commercial bentonite are shown in Figure 1, highlighting the major elements content in mass percentage.

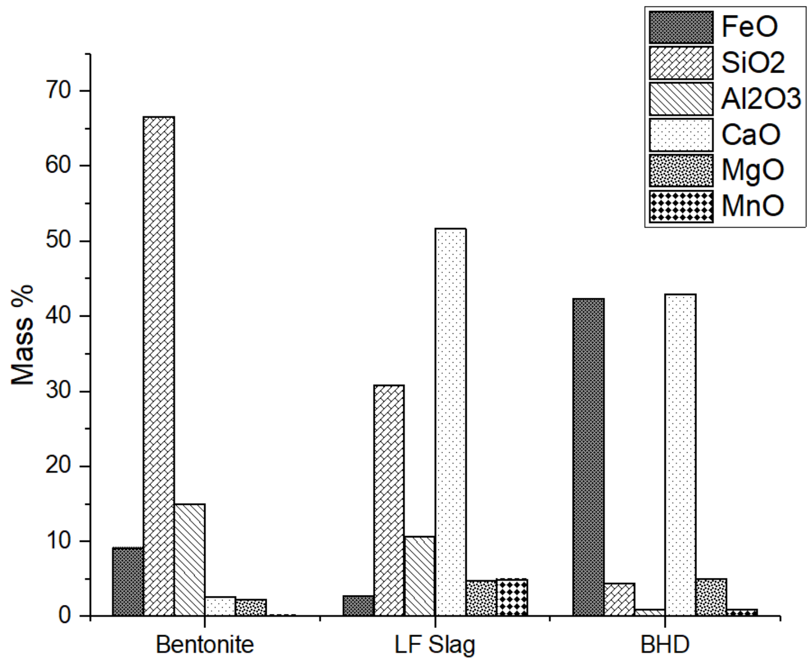

Figure 1. Chemical composition of bentonite and Ladle Furnace (LF) slag, Bag house dust (BHD) and Cyclone.

3. Methodology

The physical and chemical properties of the steel dust were investigated according to API recommendation, considering the chemical composition, dispersion stability, rheological properties and the standard drilling fluid testing.

3.1. Screening and Characterization

Dispersion stability was evaluated for screening and selecting the best steel dust type by measuring the turbidity of 150 mg/L suspension in Nephelometric Turbidity Units (NTU) at various pH values, using a Hach 2100N turbidity meter. Moreover, the stability of the suspension was assessed by measuring the electrokinetic potential (commonly known as Zeta Potential (ζ), that quantifies the magnitude of surface electric charges of the suspended particles) using Zetasizer ZEN3600 (Malvern Instruments Ltd., Worcestershire, UK). Analysis of particle size distribution was conducted using a laser diffraction particle size analyzer (Mastersizer 3000, Malvern Instruments Ltd., UK).

3.2. Sample Preparation and Drilling Fluid Testing

For viscosity and yield point measurements, a speed dial viscometer (Fann Model 35 Viscometer) was employed. The samples were prepared at room temperature by adding bentonite and steel dust in different ratios into 350 mL of distilled water while stirring in a mud mixer for 2 min to form dispersions, then the samples were stirred for another 20 min. Any powder at the wall of the container is scraped using spatula every 5 min to make sure that all powder is suspended in the mixture. Bentonite and steel dust mixture was then aged for 16 h at room temperature. Subsequently, the samples were stirred for 5 min to condition before testing. Dial readings at 600, 300, 200, 100, 6, 3 rpm were recorded when the reading was stabilized at each rotational speed. The low pressure/low temperature API filtration was used to evaluate water control efficiency of the drilling fluid under 100 psi differential pressure. The conductivity of the mud cake and filtrates were recorded, and a mud balance (Fann Model 140) was used to check the drilling fluid density. The commercial standard drilling grade bentonite was used as a reference for comparison.

3.3. Rheological Measurement

A flow sweep test at 25 °C was carried out using a controlled stress and strain instrument (Anton Paar rheometer, MCR302).Co-centric cylinder geometry was used with a cup radius of 15 mm, configured with DIN rotor of a 14 mm radius and a height of 42 mm. The shear viscosity for drilling fluids samples of 6 wt.% solid in water, at different steel dust to bentonite ratios, was determined from the readings of shear stress over a wide range of shear rates (1 e s^{-1} to 1000 s^{-1}). In addition, dynamic sweep test was conducted for the formulated samples of drilling fluid to obtain information about the structure and elastic properties of the mixture. The test was carried out at room temperature over a range of oscillation frequencies (0.1 to 100 rad/s) at constant oscillation amplitude. An equilibrium time of 5 min was given for the sample before applying any stress. For each experiment, three repeated runs were carried out and the results were reproducible with an average experimental error of less than 5%.

4. Results & Discussion

4.1. Dispersion Stability and Suspension Properties

Stability of the drilling fluids formula is an essential parameter to maintain the original properties of the injected drilling fluid and provide the main functions of the mud circulation throughout the drilling of oil and gas wells. Conducting zeta potential analyses provides evidence on the quality of suspension properties. In drilling fluids, high negative ZP values (more than −20 mV) represent high suspension stability [18,57]. Turbidity measurements also reflect the quantity of suspended particles at a given pH and concentration. Based on this, the results illustrated in Figures 2 and 3 show that bag house dust (BHD) seems to be a good candidate for consideration as drilling fluid additive. Although Ladle Furnace (LF) slag type seems to have a high silica and low iron content (see Figure 1), its suspension in water exhibited poor stability evident from turbidity and zeta potential measurements. The LF slag produced low zeta potential (≈ −15 mV) and low turbidity values over all pH ranges (Figure 2). On the other hand, the bag house dust (BHD) dispersions exhibited high negative zeta potential (≈ −35 mV) and high turbidity values, especially at higher pH values (the typical drilling fluid condition), displaying high dispersion stability (Figure 3).

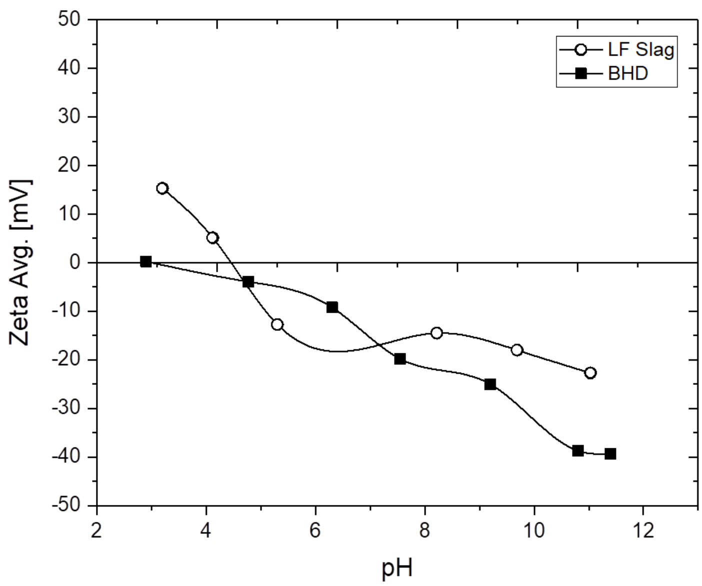

Figure 2. Zeta potential of steel dust LF and BHD in distilled water.

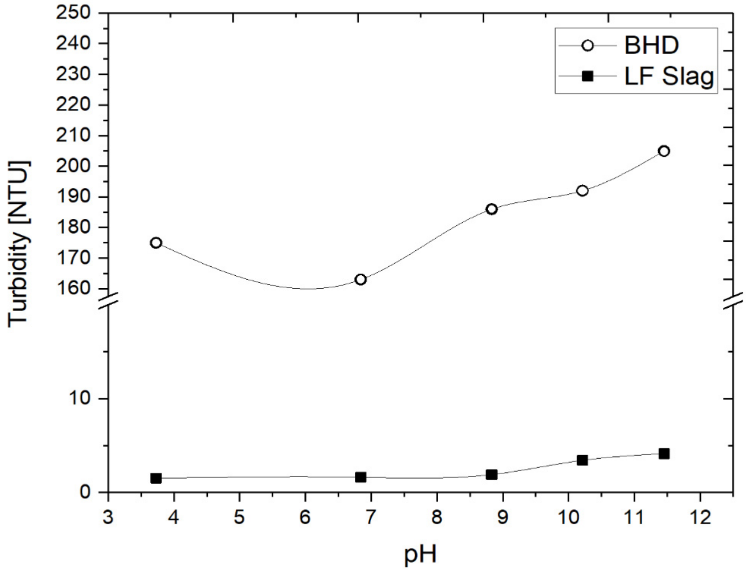

Figure 3. Turbidity of steel dust LF and BHD in distilled water.

Particle size and distribution (PSD) greatly influences dispersion stability and water filtration control. Drilling grade bentonite should have a narrow range of PSD with 96% of particles less than 75 µm [58]. In order to have a uniform PSD for the steel dust and bentonite mixture, the steel dust samples were sieved through 200 mesh (75 µm) to remove course particles. This makes all particles less than 75 µm, with 90% of particles (d.90) less than 59.8 µm and gives an average particle size (d.50) of 19.6 µm for steel dust compared to 7.9 µm of bentonite. The particle dispersity index of 1.7 for steel dust and 1.5 for bentonite was obtained. The full profiles of particle size distribution (PSD) are shown in Figures 4 and 5.

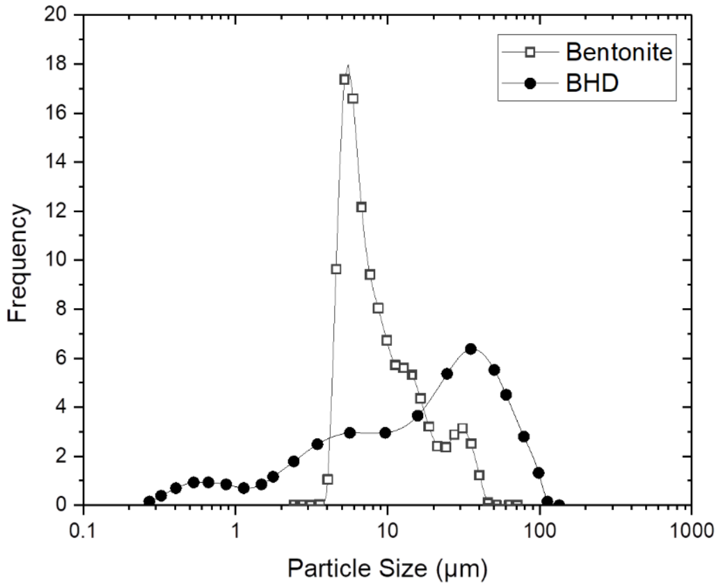

Figure 4. Particle size distribution of steel dust (BHD) compared to bentonite.

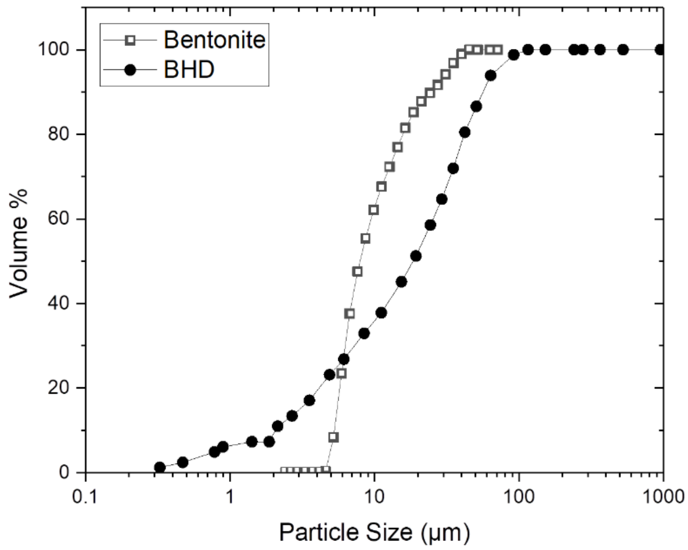

Figure 5. Mass percent of size distribution for steel dust (BHD) compared to bentonite.

4.2. Rheological Measurement

Rheological characteristics of drilling fluids are of high importance during drilling operations as the column of the drilling fluids inside the well may be subjected to different forces and stress [59,60]. High-speed mixers are used at well sites to prepare drilling fluids, where high shear rates are applied to formulate the mud prior to being pumped into the well. Inside the well, drilling fluids are also subjected to high shear resulting from rotation of the drilling string, in addition to the shear applied by circulation speeds and pressures. Viscosity of the fluids depends on the rate of shear that it endures. Results of viscosity at shear rates ranging from 1 s^{-1} to 1000 s^{-1} are shown in Figure 6. While keeping the total solid content in the drilling fluid fixed at 6 wt.%, the addition of steel dust (BHD) increased the viscosity of the drilling fluid up to 30 wt.% of BHD in bentonite, following which the viscosity began to decrease. This indicates that a maximum of 30 wt.% steel dust can be used in a mixture with bentonite. Figure 7 shows the changes in shear viscosity with the addition of steel dust. The effect is more obvious under high shear, where the viscosity increases from 43.6 mPa.s to 87.3 mPa.s and almost steadies up to 30 wt.% of BHD in bentonite.

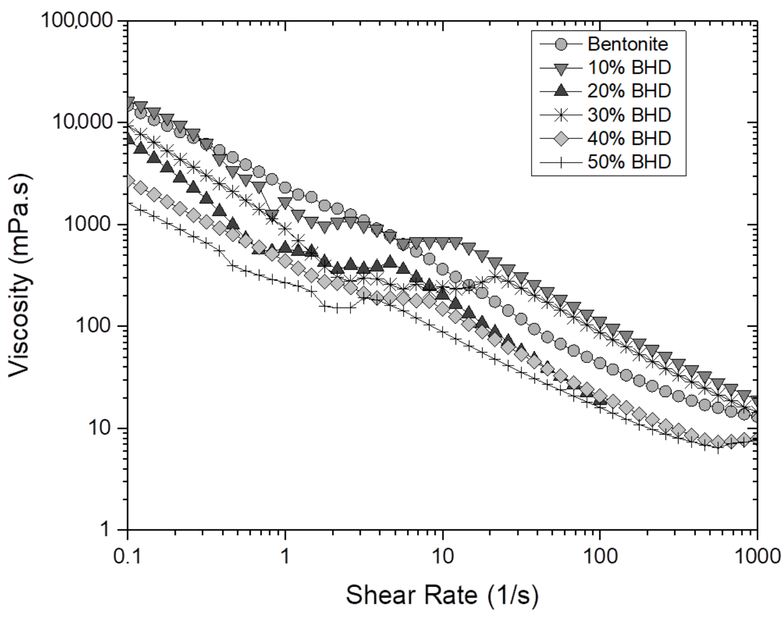

Figure 6. Flow sweep test, viscosity for different steel dust (BHD) ratios.

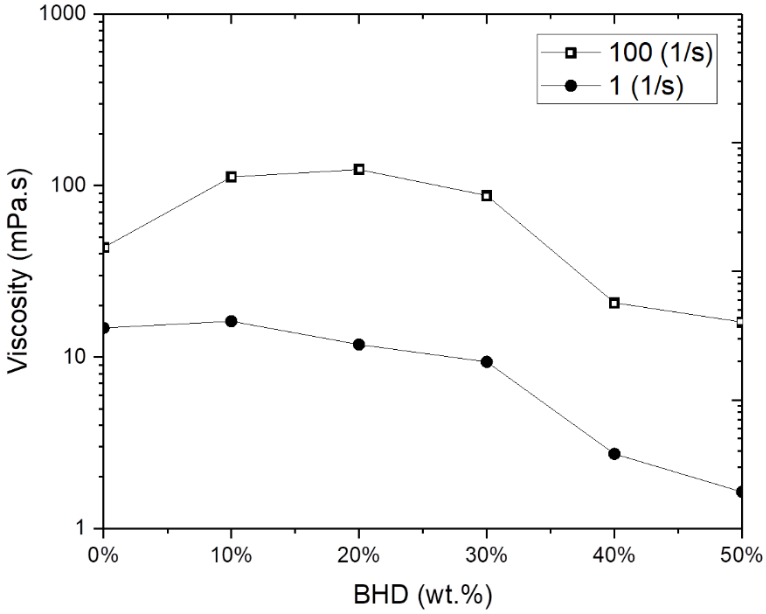

Figure 7. Effect of steel dust addition on viscosity at 1 s^{-1} & 100 s^{-1}.

Structure, elasticity and gel strength have great influence on the calculation of circulation hydraulics and hole cleaning efficiency. Efficient rheological properties maintain whole cleaning by insuring cutting removal and prevent cutting from settling or packing the well during downtime, tripping or pulling out of the hole (POOH). The results of dynamic flow test showed that the storage and loss modulus of bentonite suspensions increased in orders of magnitude with replacement of steel dust (BHD) in ratio of 30 wt.% to bentonite. Figure 8 shows that both elastic and viscous moduli increased. Large storage modulus reflects that the addition of steel dust to drilling fluids renders the dispersion to exhibit more solid-like behavior with increased elasticity, resulting in an enhanced cutting suspension property of the mud and improved hole cleaning.

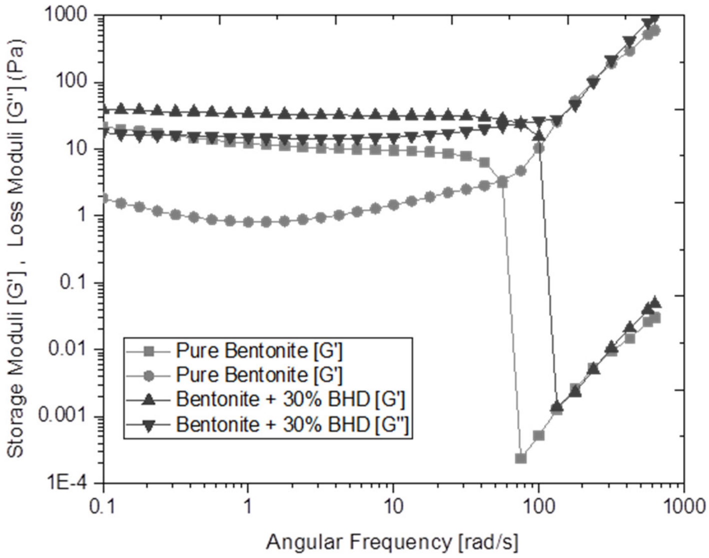

Figure 8. Dynamic flow test.

4.3. Drilling Fluid Testing

Measuring flow parameters of the drilling mud, such as apparent viscosity, plastic viscosity, and yield point is important for controlling frictional pressure drop and solids-bearing capacity. The results of 20 wt.% and 30 wt.% compared to 100% bentonite are shown in Figures 9 and 10. The viscometer readings increased with steel dust addition at 20 wt.% and then decreased at 30wt%. Subsequently, the apparent viscosity increased from 24.5 cP to 44 cP and then decreased to 38 cP at 30 wt.%. The structure of the mixture seems to be enforced by the presence of steel dust (BHD). The apparent viscosity was successfully maintained at 38 cP despite using less bentonite (70% of the initial mass), indicated by higher apparent viscosity and higher yield point. The plastic viscosity was maintained between 16 to 21 cP.

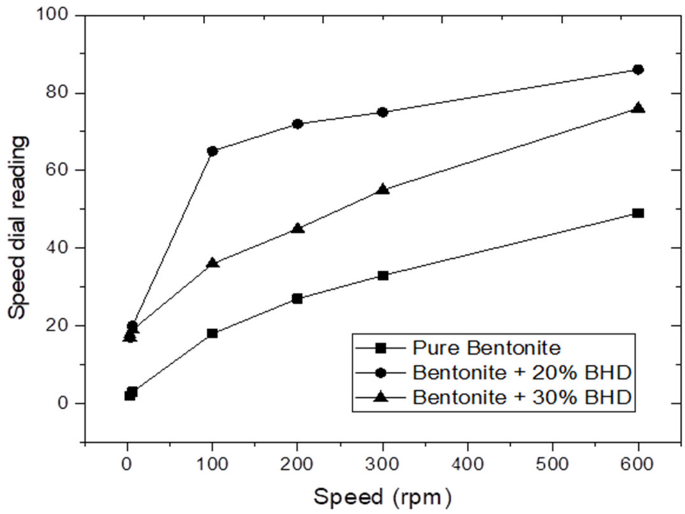

Figure 9. Viscometer readings.

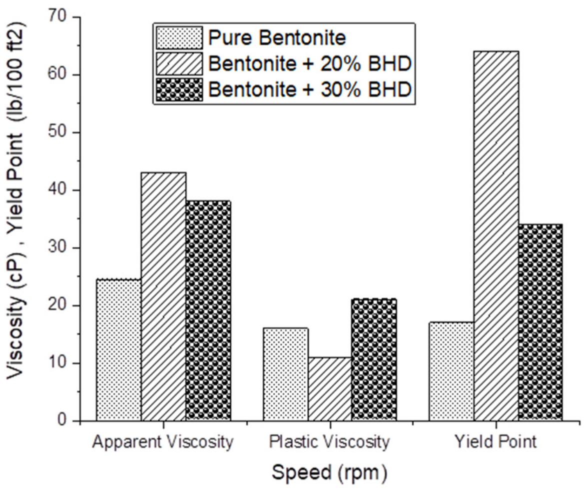

Figure 10. Apparent and plastic viscosities and yield point of bentonite and steel dust mixture (BHD).

Low pressure/low temperature API filtration test is also used to evaluate the drilling fluid quality. Filtrates volume and mud cake thickness are shown in Figure 11. The mixture of bentonite and steel dust exhibited higher filtration rates. However, the mud cake formed on the filter paper thickness did not increase and remained around 3 mm, suitable for preventing drill pipe stuck due to tight spots inside the borehole. If a high swelling formation is being drilled, the high filtrations rates may cause damage to the formation as well as pipe blockage. This may limit the amounts of steel dust to 20 wt.% to be used as drilling fluid additive to formulate the water-based drilling fluid and reduces the amount of bentonite needed to 80%. Since the filtration control is affected by the viscosity as well as the particle size, it is highly recommended to use additional additives to maintain the viscosity of the mud such as Xanthan gum, before increasing the amount of bag house dust in the formula. In addition, the steel dust can be used in some non-conventional drilling practices, where control of water filtration to formation is not required, such as underbalanced drilling (UBD). In this type of drilling, "the hydrostatic head of a drilling fluid is intentionally designed to be lower than the pressure of the formation being drilled", and the formation fluids are allowed to flow into the wellbore up to the surface [61].

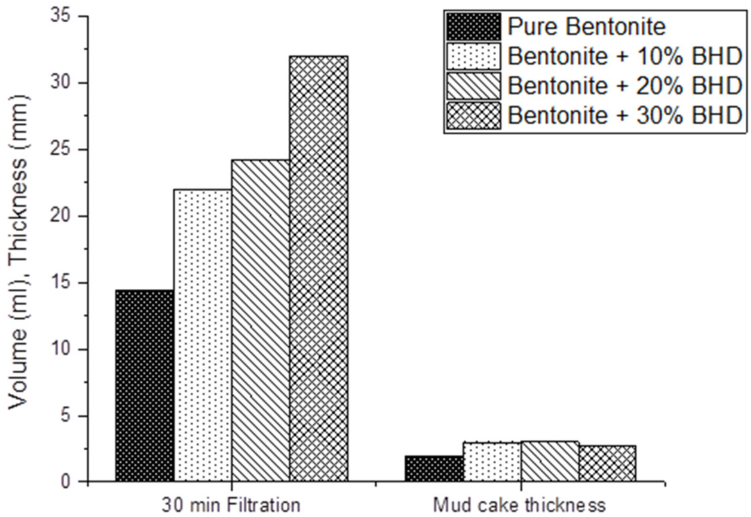

Figure 11. API filtration test for different ratios of steel dust (BHD) and bentonite.

The steel dust could also be used to formulate killing fluids in case of influx from formation fluids (Oil/Gas) into the wellbore, to prevent a blowout. Kill procedures typically involve pumping of higher density mud into the wellbore. In the case of an induced kick, steel dust of high specific gravity can provide mud density that is sufficient to kill the well [61]. Another possible utilization of steel dust is in the case of loss circulation (partial or total loss). In such cases, a very large amount of expensive fluids are lost into the formation due to highly permeable or fractured zones [62]. Steel dust is a low-cost material abundantly available that can be potentially used with lost circulation materials (LCM) to regain control of the well.

5. Conclusions

Steel dust powders were evaluated in this study and found to have a high potential for utilization as drilling fluid additives. Characterization and analysis of the steel dust showed that processing and pretreatment of the dust by cleaning, grinding, and sieving is recommended. The pretreatment is needed to homogenize the particle size distribution and enhance water filtration control in addition to improving dispersion stability. Evaluation of the proposed formula helped to conclude that the amount of standard drilling grade bentonite can be reduced by 30 wt.% to produce stable drilling fluids with sufficient density and rheological properties that compete well with standard formulations. The apparent viscosity and plastic viscosity increased from 24.5 cP to 38 cP and from 16 cP to 21 cP respectively. Moreover, the elastic properties were significantly improved as the storage modulus G' increased from 8.93 Pa to 132 Pa, which is expected to improve cutting lifting and hole cleaning efficiency. The mud cake resulted from API filtration test was 2 to 3 mm, which is less than the maximum allowable thickness of 4 mm. This guarantees the absence of tight spots through the drilled sections and prevents drill pipes from getting mechanically stuck. However, the water filtration was higher (22 to 32 mL). Therefore, to avoid formation damage, the new additive is recommended to be used for drilling the main hole (usually more than 90% of the total depth of the well) from the surface to the depth before the hydrocarbon zone. Special cases such as underbalanced drilling can also be a good application for steel dust drilling fluids. They can also be used in case of partial or total loss circulation in fractured zones, where a massive amount of expensive drilling fluids is lost.

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M.I.M.; Writing—review and editing, M.I.M., M.H.I., M.S.N. and M.H.E.-N.; supervision, M.S.N. and M.H.E.-N. All authors have read and agreed to the published version of the manuscript.

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