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Influence of solid concentration on the flow characteristics and settling rate of coal-water slurries

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Abstract: Coal–water slurries were prepared with a sub-bituminous coal at varying coal and water ratios using an anionic liquid soap as a surfactant. The slurry properties, viscosity and stability were determined. The rheological properties of the slurries were investigated to ascertain the characteristics of the slurries. The results showed that increasing coal (solid) concentration increased the density of the slurries. Higher density gave rise to more viscous slurries. The behaviour of the slurries changed from Newtonian to non-Newtonian at higher solid concentrations. The slurries with lower solid concentration settled faster than the higher solid concentration slurries.

Keywords: Coal, Concentration, Flow, Viscosity, Slurries, Settling Rate

1. Introduction

Coal is a heterogeneous material, consisting of two–phase systems, the organic and the inorganic constituents [1]. It is a primary fuel, which over the years, was in use in its solid form to generate electricity and heat, both domestically and industrially. It has also been applied in metal and chemical industries. The usage of coal in its solid form limited its applications and availability in comparison to liquid fuels. Production of liquid fuels from coal has been successful through direct liquefaction via hydrogenation and by coal gasification as applied in the Fischer-Tropsch process [2]. Simpler and cheaper methods of coal liquefaction in solvents including oil, organic solvents and water have been developed and applied in countries including USA, Russia and China [3, 4].

Coal-water slurry is the fuel formed from the mixture of coal and water. Additives are usually included to improve stability, homogeneity and dispersability of the mixture [5]. The primary purpose of coal-liquid mixtures is to make solid coal behave as an essentially liquid fuel that can be transported, stored, and burned in a manner similar to heavy fuel oil [6]. Coal-water slurry has been successfully tested and operated in various boilers for power generation and in chemical and metallurgical industries [7].

Important slurry characteristics are stability, pumping, atomizability and combustion characteristics [8]. Numerous studies have been made on the rheological properties of coal-water slurries in an effort to obtain acceptable fluidity while maintaining sufficient stability against sedimentation of the coal particles [9]. Studies on the effects of particle size distribution and packing characteristics [10] as well as effects of the use of additives on the preparation of coal-water slurries have been undertaken [5]. The use of coal in water as a fuel is possible because coal contains carbon with high energy content depending on the type of coal. Coals of different classifications have been used to prepare slurry fuels [11]. The viscosity of a fluid is an important rheological property that affects the pumpability of a fuel and also the atomization of the fuel in the combustion chamber [12, 13].

The main objective of this investigation is to research on the slurrying, rheology(flow characteristics), and stability properties of a Nigerian coal. The rheology was investigated from the study of the viscosity of the slurries under different conditions. The stability was determined from the settling rate experiment.

2. Experimental

The coal used in this investigation was a sub-bituminous coal from Okobo Enjema in Kogi State, Nigeria and was provided by Zuma-828 Coal Limited, a coal mining company developing the Zuma coal mine. The coal was used as received, without any modification. The coal pieces were crushed, followed by grinding and screening through 250 micron sieve. The undersize coal was collected and packaged with plastic bags to prevent oxidation.

Proximate analyses were done to characterize the coal sample according to ASTM standards [14].

2.1. Physical and Chemical Properties Determination

The density of the slurry was determined with a density bottle. The flash point was measured with a Pemsky Martin semi-automatic multi flash closed cup flash point tester (Made in Japan). The viscosity was measured using a NDJ–5s Digital Viscometer (SearchTech Instruments, England).

2.2. Coal Slurries Preparation

The coal particles that passed through the mesh size sieve 60 (250 microns) were used to prepare the coal slurries with deionized water and an anionic liquid soap (surfactant). The coal was dried in the oven at 105ºC for 2 hours and then cooled in a dessicator. The necessary amount of deionized water and liquid soap were added into a 250mL volume beaker. The water and liquid soap mixture were put in a 500 mL plastic jar of the mixer and agitated for 2 minutes, followed by the addition of the pulverized coal. The coal/water/liquid soap mixture was agitated for 10 minutes in the mixer at 1200 rpm to ensure the homogenization of the slurries. Coal slurries with solid concentrations of 30%, 40%, 50%, and 55% (v/v) were prepared. The total volume of the coal-water slurry in the jar was kept constant at 250mL in all the experiments to standardize the mixing. The amount and type of liquid soap was kept constant at 1% on the basis of the weight of dry coal. At the end of the mixing, the measurements were taken.

2.3. Property Measurements

Rheological behaviour was investigated with a rotational viscometer. The viscosities of the different solid content slurries were measured at rotational speed of 6 rpm, 12 rpm, 30 rpm and 60 rpm at room temperature (27ºC) to understand whether the mixtures were Newtonian or Non-Newtonian; shear-thinning or shear-thickening. These were done with appropriate spindles. Also, at constant shear rate of 30 rpm, the viscosities of the different solid content slurries were measured and results were taken at 30 seconds intervals. These data showed the character of fluid. Another experiment was conducted measuring the viscosities of the 40% coal concentration slurry as the temperature was varied and the Viscometer was in a circulating water bath using Spindle No. 3 at 30 rpm.

The stability characteristic of coal slurries was determined by a settling test in a 50-mL graduated cylinder in which slurry of particular concentration is poured into the cylinder and allowed to settle under gravity after agitation. The height of the supernatant liquid was determined over a period of 6 days.

This study was conducted at the laboratory of the National Center for Energy Research and development, University of Nigeria, Nsukka between October, 2012 and April, 2013.

3. Results and Discussion

The values presented are averages of several readings per sample and of triplicate samples.

Table 1 show the results of the proximate analyses for the coal which was from a single source. It was a sub-sub-bituminous coal as the fixed carbon content was 46.55%.

Table 2 gives the result of some properties of the slurries. The density increased as the concentration of coal in the slurries increased. Similarly, the viscosities increased with increase in density for room temperature measurements conducted at 30 rpm.

Table 1. *Proximate Analyses of Okobo, Nigeria coal sample.*

Proximate Analysis (As Received)	
Moisture (wt %)	8.17
Ash (wt %)	9.35
Volatile Matter (wt %)	35.93
Fixed Carbon (wt %)	46.55
Total	100.00

Table 2. *Summary of some Coal Water Fuel (CWF) Properties*

CWF	**Density**	**Flash Point Viscosity**	**(%Coal)**
30%wt	0.4766	No Flash	29.84
40%wt	0.5344	No Flash	200.7
50%wt	0.6985	No Flash	724.6
55%wt	0.6213	No Flash	914.8

3.1. Rheological Properties of the Slurries

Viscosity is the most important rheological characteristics of Coal-water slurries [15]. The viscosity was evaluated as a function of shear rate, time and temperature, respectively. The rheological characteristics of the slurries were determined from the view of whether they were Newtonian or non-Newtonian fluid. Figure 1, which was a plot viscosity vs. shear rate, confirmed the character of fluid at coal concentrations over 30% as non-Newtonian. The viscosity of the fluids changed as the shear rate was varied. This behaviour may be attributed to the higher particle interactions at low shear rates. It is possible that higher shear rates will break the interactions and closeness thereby reducing the viscosity [16]. At 30% coal concentration and using 30 rpm and 60 rpm, the fluid was Newtonian.

Figure 2 showed that shear stress decreased with shear rate at above 40%wt coal. This is called pseudoplastic or shear-thinning behaviour. The behaviour of the slurry at 30% coal concentration and below could be like a Bingham fluid. The slurry characteristics changed as the coal concentration was over 40% wt.

From Figure 3, which was a plot of viscosity with time at constant shear rate of 30 rpm, the slurries exhibited a thixotropic behaviour with 40%wt and 50%wt at 30 rpm. The fluid at 55%wt exhibited rheopectic behaviour after 200s. At 30% coal concentration, the viscosity of the fluid remained unchanged over time.

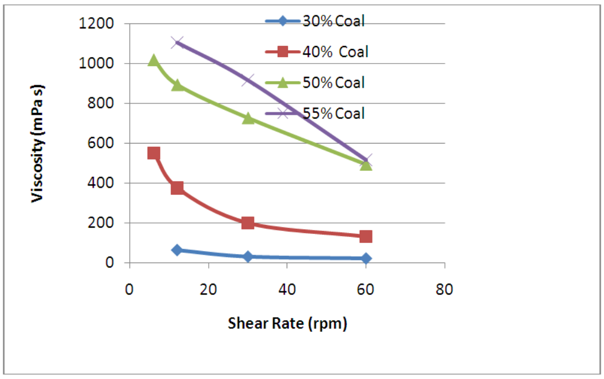

Figure 1. *Viscosity as a function of shear rate for coal slurries at room temperature (27 ℃).*

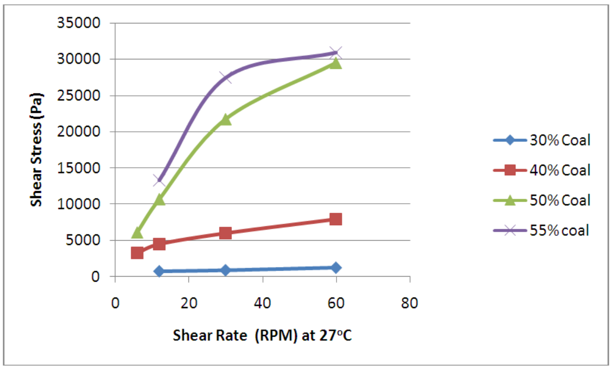

Figure 2. *Shear Stress Vs Shear Rate*

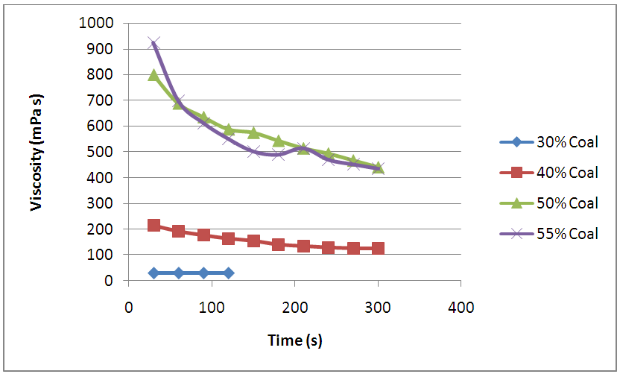

Figure 3. *Plot of Viscosity vs Time at 30 RPM*

Figure 4 is the viscosity-temperature relationship for 40% w/w coal-water slurry. In this figure, the viscosity of the fluid decreased as temperature increased. When the temperature is less than 333 K, the viscosity slowly decreased with increase in temperature. Above 333 K, there is a sharp decrease in viscosity, indicating flocculation.

The plot of the Interface Height Vs Time is given in Figure 5. As the storage time increased, the coal particles began to settle. The 30% coal concentration settled fastest, followed by the 40% coal concentration and finally the 50% coal concentration was the last to settle. The 55% coal concentration was a thick gel and the experiment could not be conducted with it at room temperature. This behaviour may be accounted for by the inter-particle distance which is supposedly further with the lower concentration slurry, thereby allowing a faster motion of each particle since they move unhindered. The implication is that the 30% coal concentration slurry is easier to pour followed by the 40% coal concentration slurry and then the 50% coal slurry.

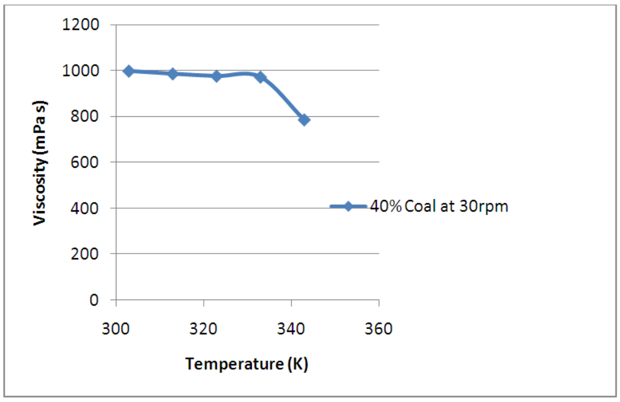

Figure 4. *Viscosity temperature relationship for coal-water slurry (40% w/w)*

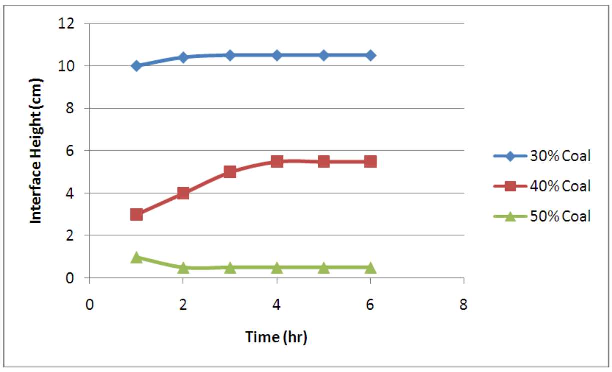

Figure 5. *Interface Height Vs Time*

These findings on the flow characteristics and settling rate of the coal-water slurries prepared from the studied coal sample provided vital information that would be useful for designing of transport system (pumping and pipeline), storage and the utilization of coal-water slurries as an energy source [15]. The stability of coal-water slurry is important in the pumping and storage of the fuel [17].

Slurries with less than 40% coal concentration were less viscous and more stable. These slurries may be more suitable for transportation via pipelines. The viscosity level of slurry affects the application for the slurry. Other factors like particle size distribution and additives are important to obtain slurries to meet specific requirements [18, 19].

4. Conclusion

Coal slurries were found to exhibit different flow characteristics, from Newtonian at low solid coal concentrations to shear-thinning at higher solid concentrations. The behaviour of the coal slurries at 40%, 50%

and 55% coal concentrations showed that the viscosities changed with time while it did not change at 30% coal concentration. The viscosities decreased with increase in temperature. The slurry with 30% coal concentration settled faster than the slurries with higher coal concentration. This result is important in the designing of pumps for transportation of coal slurries and also for the use of coal slurries in combustion systems. The result will be useful in making decisions on the storage of coal slurries.

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