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Research paper



Effect of Particle Size and its Distribution on Rheological Behaviour of Coal-Water Slurry

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Abstract

An experimental investigation has been conducted to study the rheological behaviour of coal-water slurry (CWS) of low rank coal. Different samples have been prepared by pulverizing it to powder form. Bi-modal and mono-modal samples have been prepared separately. Thereafter slurry was prepared by adding distilled water to the sample. CWS of different coal concentration have been prepared with particle size from 37 µm to 250 µm. The rheological behaviour of both mono-modal and bi-modal slurry have been investigated with help of HAAKE RHEO STRESS 1, a thermo scientific rheometer. Comparing the rheological behaviour of CWS prepared from bi-modal sample and mono-modal sample, it is observed that CWS from bimodal exhibit lower viscosity and shear stress compare to mono-modal sample. The stability of slurry prepared from bi-modal samples are found to be poor than mono-modal samples. The stability of coal sample below 75µm at different concentration has also been investigated. Also the characterization of coal sample has been done. It is observed that as the ratio of coarse particle decreases the shear stress and viscosity also decreases.

Keywords: *Coal-Water slurry, Particle size distribution, Rheology, Stability*

1. Introduction

Coal-water mixture is a viscous fluid having viscosity similar to crude oil which can replace the fuel oil used in oil fired boiler [1]. Earlier coal-oil mixture was used as fuel in oil fired boiler. Gradually large emphasis is given on coal-water fuels due to its good liquidity, stability, non-flammable and non-polluting properties [2]. The coal water slurry (CWS) is generally utilized in gasification of coal [3] and used as the fuel source in boiler combustion [4]. Generally coal-water slurry is the mixture of 60-75% solid particles, 35-40% water and about 1% additives (optional) [5, 6]. While preparing coal-water slurry, coal concentration is kept high, keeping the viscosity lower to get higher heating value, easy handling during preparation and transportation [7] and economical pumping power [8]. Less viscous slurry affects the rheological behaviour and wall-slip behaviour over wide range of wall shear stress [9]. This paper explains the findings of the experimental investigation of the rheological behaviour of CWS of mono-modal and bi-modal coal sample. Also it explains the investigation results of the static stability of the slurry.

2. Experimental

2.1. Materials

The coal samples were collected from the Mahanadi coal field limited (MCL), Odisha, India. They were crushed and sieved into different smaller particle sizes. The different sizes considered for experimentation are as follows: -250 µm, -210 µm, -150 µm, -105 µm, -75 µm and -37 µm. The proximate and ultimate analyses of coal sample are shown in Table 1.

CWS consisting of different composition of mono-modal and bi-modal samples considered for study of the rheological behaviour are as follows: -37 µm, -75 µm, (-105 µm +75 µm), (-210 µm + 105 µm) and (-250 µm + 150 µ). The bi-modal sample were prepared by mixing coarse particles with fine particle with different proportions like coarse to fine ratio is 0.8:0.2, 0.7:0.3 and 0.6:0.4. The coarse particles size distribution were considered as (-105 µm +75 µm), (-210 µm + 105 µm) and (-250 µm + 150 µm) and the fine particles were taken as -37 µm. The characterization of coal sample was carried out.

2.2. Ph Value Measurement of the Sample

Coal particles release either H^+ or OH^- ions when mixed in water, depending upon the pH medium. They undergo hydration, hydroxylation, and finally acquire this surface charge. Hence a fresh slurry sample was prepared by mixing 50% distil water and 50% coal particle (by vol.) and placed in a 150 ml beaker. A thermo scientific ORION STAR A211 pH meter was used to measure the pH of slurry. The test was conducted at room temperature. The electrode of the pH meter was doped in the slurry for 5 hours and steered continuously. The pH value of the slurry was recorded in every half an hour. After 5 hours the pH of the slurry was found to be stable and considered as the final pH of the coal water slurry.

2.3. Density Test

BOROSILICATE density glass pot of 50ml size was chosen for the density test. The tests were carried in three density glass pot for better and accurate result and finally its average value was calculated. Initially the weight of the empty bottle (A) was record-

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ed. Then weight of the bottle with sample (40% by volume of the pot) (B) and weight of the bottle with sample filled with enough water (C) were noted down. The weight of the bottle filled with distil water (D) was also noted down. Then the particle density was calculated as follows.

$$Particle\ density = \frac{(B-A)}{(D-A)-(C-B)}\ gm/cc$$

2.4. Determination of Maximum Static Settled Concentration (C_w Max %)

C_w max percentage of slurry gives the result of maximum solid concentration that can be absorbed by the slurry, where slurry exhibits its Newtonian behaviour. To conduct the test the coal particles with different concentration i.e. 45%, 50%, 55%, 60% and 65% by weight were taken in different jars. Remaining percentage of distil water is added to the solid concentration by volume. For better and accurate result two samples were prepared for each concentration. At initial stage due to the non-Newtonian behaviour 65% concentration was not considered for the test. The sample initial reading were noted down and left for settle down for 48 hrs.

2.5. Particle Size Analysis

Particle size analysis was done to find out percentage of particles with the different particle size present in a sample. This gives the result of particle size distribution by volume. PARTICA LA-960 a particle size analyser of HORIBA SCIENTIFIC was used as shown in Fig. 2.1. The total system is a complete arrangement of particle size analyser, compressor, an arrangement of sample suction, and a computer. The test was conducted by both dry and wet method. 20 gm coal sample of -75 µm was taken and dried for half an hour to remove the moisture. 10 to15 gm of dry sample was poured in the cup of particle size analyser and passed through the laser scattering. The results were generated based on incident ray and reflected ray and displayed in the computer screen. After the test the wastage portion of the samples were sucked by the vacuum sucker and drained.

2.6. Rheology Test

HAAKE RHEO STRESS 1, a thermo scientific rheometer was used to study the rheological behaviour of coal-water slurry. The total arrangement consisted of rheometer, chiller, compressor, computer and a printer as shown in Fig. 2.2. The chiller is used to maintain the temperature of sample cup used in rheometer. One rotor was attached to the spindle which mainly calculated the shear stress, shear rate and viscosity. Different rotors are used for coarse and fine particle i.e. for fine Z41 and for coarse particle Z38 rotor were used. The rotor and the cup distance were set to zero. 30 ml of slurry sample was poured in the preheated cup and placed in the rheometer. The rotor was fitted to the spindle and test was conducted.

Sample rheology data were collected and noted down. The rotor was detached from the spindle and rotor cup was taken away for cleaning. For each sample the experiment was repeated twice and average values of output data were considered for further analysis. The results were fitted with non-Newtonian fluid flow model, i.e.

Power Law or Ostwald de Waele model, $\tau = k\gamma^n$
And Bingham plastic model, $\tau = \tau_0 + \eta_p\gamma$
Where τ = Shear stress γ = Shear rate
τ_0 = Yield stress k = Flow consistency index



Fig. 2.1: Particle size analysis with PARTICA LA-960



Fig. 2.2: Rheology test of CWS with HAAKE RHEO STRESS 1

2.7. Static Stability Test

The samples of coal-water slurry were prepared with different concentrations i.e. C_W = 60%, 57.5%, 55% and 52.5% as presented in Table 2. Sample coal-water slurry is shown in Fig.2.3. The slurry was placed in four 100 ml beaker covered with aluminium foil and left for settling down. Stability test was conducted by rod penetration method. A glass rod of 19 g with 5 mm diameter was used for the test. In every 24 hours interval the rod was penetrated inside the slurry and the effective travel distance was noted down. The penetration ratio was calculated as follows.

$$\text{Penetration ratio (\%)} = \frac{\boldsymbol{d}}{\boldsymbol{d_t}} \times 100$$

Where d = Effective travel distance (in cm) by glass rod
d_t= Maximum travel distance (in cm) by glass rod

3. Results and Discussion

3.1. Measurement of pH

The pH values of CWS were noted down in every half an hour interval. After 5 hours pH value is found to be stable and considered as the final reading. Finally the pH value was found to be 7.040. It was found to be within range of 6 to 8 which was a good result to proceed further.

3.2. Density Test

For the accurate result three sets of test were conducted. Final reading is calculated by taking the average. The density is found to be 1.689 gm/cc.

Table 1

Proximate analysis of coal sample dry basis:

Inherent Moisture (%)	Ash (%)	Volatile matter (%)	Fixed Carbon (%)
5.76	37.89	24.22	32.13

Ultimate analysis of coal sample dry basis:

C (%)	H (%)	N (%)	O (%)	S (%)
84.26	4.72	1.75	8.66	0.5

Table 2

Particle size	weigh of coal in (g)	Water in ml
-75µm	60	40
-75µm	57.5	42.5
-75µm	55	45
-75µm	52.5	47.5



Fig. 2.3:. Stability test with rod penetration



Fig. 2.4: Particles below 37 µm

3.3. Maximum Static Settled Concentration (C_w Max %)

The C_w maximum percentage was found to be 61%. At 65% concentration, the slurry became thicker and the test could not be carried out.

3.4. Particle Size Distribution Analysis

The particle size distribution test was conducted with -75 µm size MCL coal. By considering the major percentage of particle size, a graph was plotted between on a semi log sheet between particle diameter (µm) and undersize (%) as shown in Fig. 3.1.

The mean particle size was found to be 26 µm with 69.6% undersize and 2.9 volume percentage. The median size (d_{50}) was observed to be 14 µm with having 7.4 volume percentage and 47.9% undersize.

3.5. Stability Test

The stability test was carried to determine the settling rate of the slurry. The stability test of bi-modal slurry was done. But due to poor stability the data were not recorded. Again the stability test of

particle size -75 µm was done and the data were recorded. From the Fig 3.2 it was found that the stability of CWS with C_w= 60% was much better than the other concentration. The penetration ratio of slurry with C_w= 60% was found to be 93.61% and lasts up to 11 days. Whereas at C_w= 52.5% the penetration ratio was found to be 85% and lasts up to 11 days.

3.6. Study of rheological behaviour

3.6.1. Slurry of Mono-Modal Sample

Initially the rheology of the mono-modal coal sample was carried out. The particle size below 75µm was selected with four different concentration i.e. C_w= 60%, 57.5%, 55% and 52.5%. C_w= 60%, that means 60 g coal and 40 ml water. Likewise other proportions were taken. In rheology basically viscosity and shear stress were measured with respect to shear rate. After generating the data graphs were plotted as follows.

From the Fig. 3.3 it is observed that as the coal-water slurry concentration increases, the shear stress of the slurry also increases. At C_w=52.5 the shear stress is observed to be minimum 2.77 Pa at 10.81 s^{-1} shear rate and it gradually increases as the concentration increases. At highest concentration of C_w=60, the shear stress was observed to be 13.35 Pa. At the same time in Fig 3.4 viscosity was also observed to be increasing as the concentration of slurry increased. At C_w=52.5 viscosity was observed to be minimum of 0.256 Pa.s at 10.81 s^{-1} shear rate. The maximum shear stress was observed to be 1.379 Pa.s at shear rate of 9.687 s^{-1} during the initial point of C_w=60.

3.6.2. Slurry of Bi-Modal Sample

For the first sample coarse particle was taken as (-210+105) µm and fine particle was taken -37 µm (as shown in Fig. 2.4). The slurry was prepared with different proportion like 0.8:0.2, 0.7:0.3 and 0.6:0.4. From the Fig. 3.5 it is observed that as the coarser content increases in sample the slurry shear stress also increases. The shear stress is found minimum of 1.147 Pa at shear rate 10.84 s^{-1} with the proportion of 6:4. At proportion of 8:2 the shear stress was found to be 2.816 Pa at shear rate of 11.0 s^{-1} during the initial stage. Likewise in Fig. 3.6 viscosity was observed to be increasing as the finer content reduced. Viscosity was found minimum 0.106 Pa.s with proportion of 6:4 at 10.84 shear rate s^{-1}. At 8:2 proportion it was observed to be 0.256 Pa.s at 11.0 s^{-1} shear rate. From Fig 3.7 it was found that as shear stress coarse particle content increases, shear rate also increase.

Similarly in next set of sample the coarse particle size was selected as (-250+150) µm and for fine size particles -37 µm was selected. Again the slurry was prepared with three different proportion i.e. 8:2, 7:3 and 6:4 and the rheology behaviour was studied at C_w= 57.5%. From the above Fig 3.5 it can observe that increased in coarser particles in the sample, shear stress of the slurry increases. The shear stress was found to be minimum of 0.618 Pa at shear rate of 10.83 s^{-1} for sample type 6:4. Again at proportion 8:2 the shear stress was observed to be 2.33 Pa at shear rate 10.49 s^{-1} during the initial stage. Similarly the apparent viscosity is observed to be decreasing as the ratio of fine particles increases. From the Fig 3.8 the apparent viscosity is found to be minimum 0.057 Pa.s with the proportion of coarser to fine 6:4 at shear rate 10.83 s^{-1}. At proportion 8:2 the apparent viscosity is observed to be 0.222 Pa.s at shear rate 10.49 s^{-1}. From all the graphs it is observed that apparent viscosity decreases with increase in shear rate. It allows the slurry to behave as flow able liquid. Also from the above set of experiments it is observed that as finer content increases apparent viscosity and shear stress of the slurry decreases. From the above interpretation it can be predicted that the extreme fine particles in a bi-modal suspension behave as fluid towards the coarse particles.

3.6.3. Comparison between Slurry of Mono-Modal and Bi-Modal Sample

After a few sets of experiment, few comparisons were found between bi-modal and mono-modal slurry by taking its rheological behaviour. From the Fig 3.9 and Fig 3.10, it can be observed that slurry prepared from bi-modal sample have comparatively less shear stress and viscosity in comparison to slurry prepared from mono-modal sample. It was also found that slurry prepared from particle size (-75+105) µm + (-37µm) exhibit comparatively higher apparent viscosity among the other bi-modal slurry. (-250+150) µm + (-37µm) exhibit lowest shear stress and apparent viscosity compare to (-75+105) µm + (-37µm) slurry prepared from bi-modal sample. With the particle size (-250+150) µm + (-37µm), initially the shear stress and apparent viscosity was found to be 0.618 Pa and 0.057 Pa.s respectively at a shear rate of 10.83 s^{-1}. Where as in case of slurry prepared from particle size -75 µm showed shear stress and viscosity 10.7 Pa and 0.969 Pa.s respectively at a constant shear rate of 10.7s^{-1}. From the study of rheological behaviour, it was found to satisfy both Binghum model and Ostwald De Waele model.

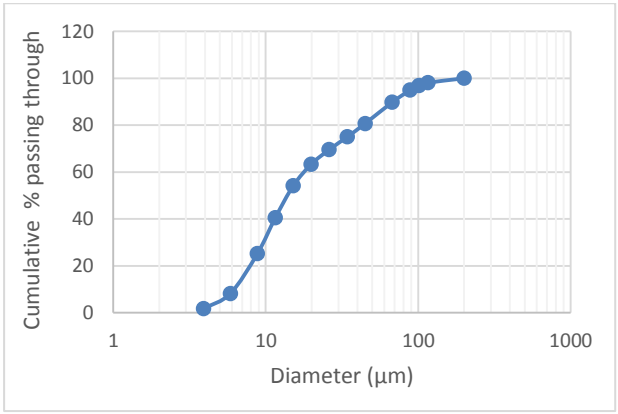


Fig. 3.1: Result of particle size distribution.

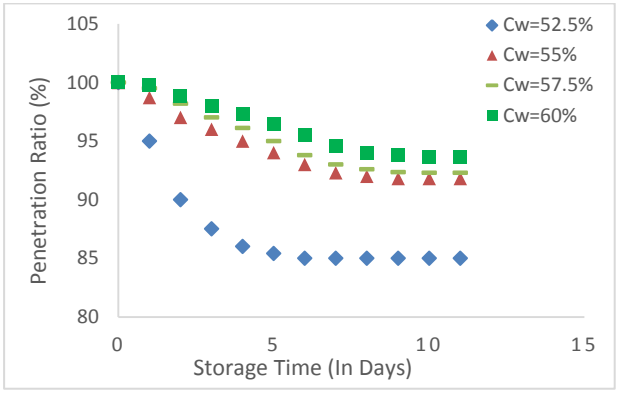


Fig. 3.2: Stability test of -75 µm coal water slurry at different concentration.

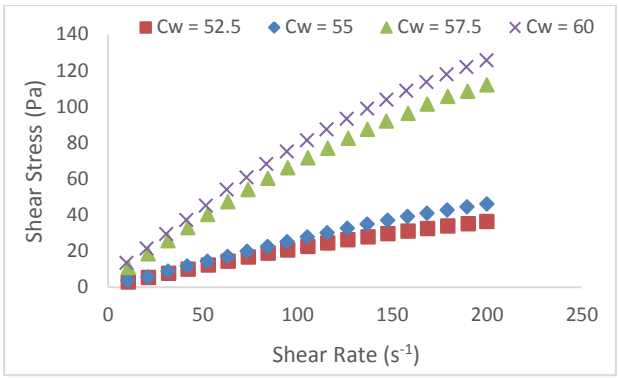


Fig. 3.3: Slurry prepared from mono-modal sample at different concentration

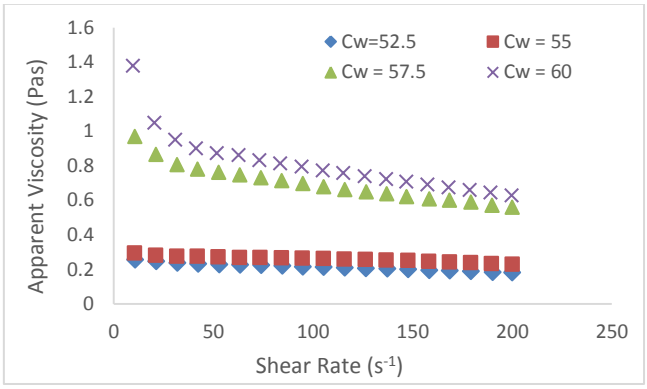


Fig. 3.4: Slurry prepared from mono-modal sample at different concentration

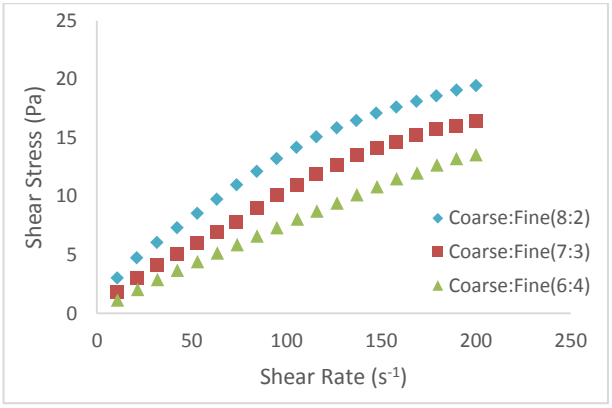


Fig. 3.5: Slurry at C_w= 57.5 %, the particle size (-210+105) µm + (-37 µm)

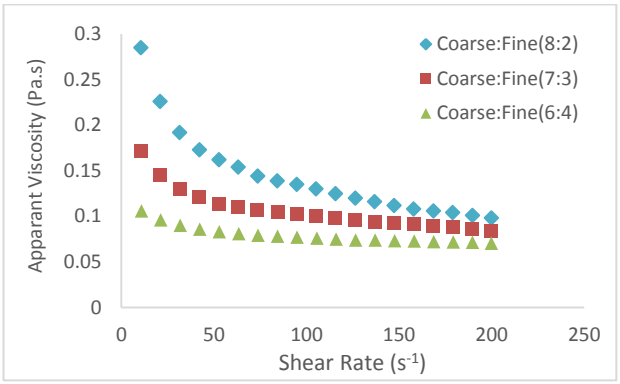


Fig. 3.6:. Slurry at C_w= 57.5, the particle size (-210+105) µm + (-37 µm)

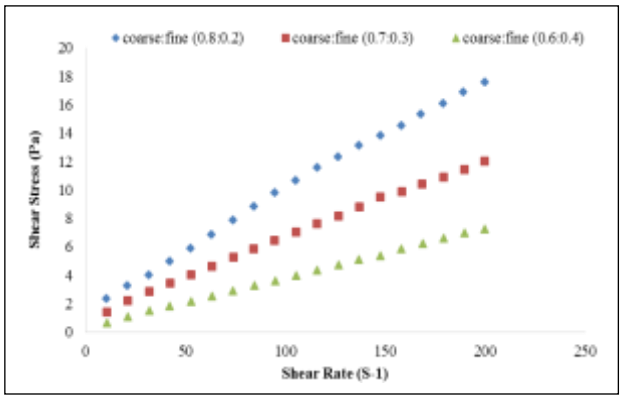


Fig. 3.7: Slurry at C_w= 57.5, the particle size (-210+105) µm + (-37 µm)

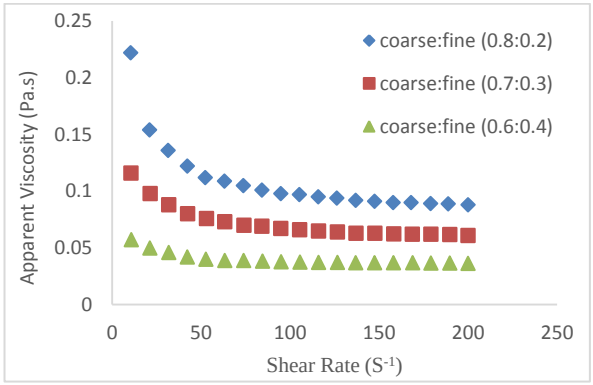


Fig. 3.8:. Slurry at C_w= 57.5%, the particle size (-250+150) µm + (-37 µm)

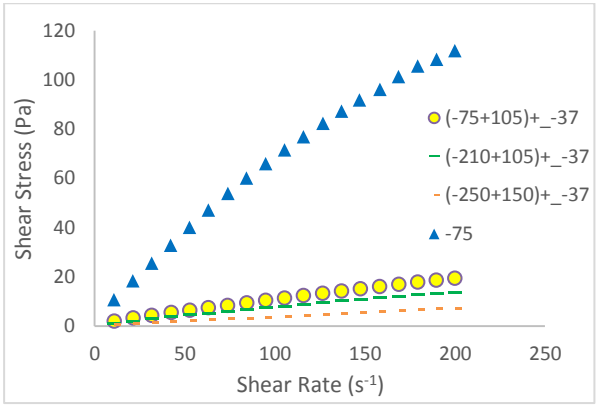


Fig. 3.9: Comparison of shear stress between bi-modal and mono-modal slurry at C_w = 57.5%.

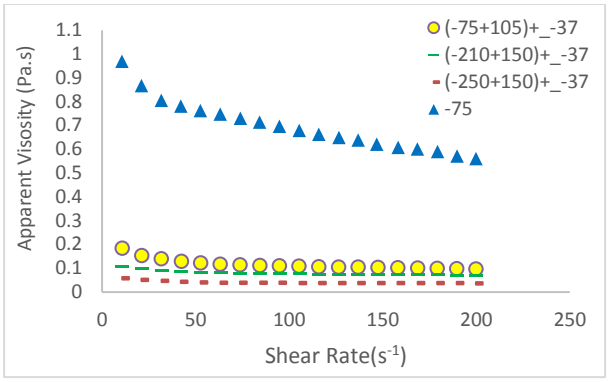


Fig.3.10:. Comparison of apparent viscosity between bi-modal and mono-modal slurry at C_w = 57.5%.

4. Conclusions

From the present experimental study it was observed that shear stress increases with increase in shear rate. The viscosity of CWS was observed to be decreasing with increase in shear rate. The slurry prepared from bi-modal sample showed lower viscosity and shear stress with respect to shear rate comparing with CWS prepared from mono-modal sample. From different categories of bi-modal sample like (-105+75) µm + (-37 µm), (-210+105) µm + (-37 µm) and (-250+150) µm + (-37 µm), CWS prepared from (-105+75) µm + (-37 µm) showed lowest shear stress and viscosity compared to others.

Along with this the stability of CWS was studied from mono-modal and bi-modal sample. It was observed that the slurry prepared from bi-modal sample with different proportion exhibit poor stability. The slurry prepared from mono-modal sample exhibit a better stability with higher concentration of coal at C_w = 60%. Lower the concentration was observed comparatively poor stability.

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