

RHEOLOGICAL BEHAVIOUR OF CONCENTRATED COAL-WATER SLURRIES PREPARED FROM INDIAN COAL

^[1]Jatinder Pal Singh, ^[2]Satish Kumar, ^[3]S.K. Mohapatra
^[1] ^[2] ^[3], Thapar University, Patiala, Punjab - 147004
^[1]jatinderpal.singh@thapar.edu, ^[2]Satish.kumar@thapar.edu

Abstract— The rheological behaviour of concentrated coal-water mixtures were investigated using standard Rheometer. Coal used in five different Indian thermal power plants was collected. Physical properties of coal-water mixture were varied to establish the rheological behaviour of coal-water mixture. The physical properties of mixture includes solid concentration, ash content of coal, particle size distribution, fraction of coal fines and dispersants. Rheological results show that coal-water mixture exhibits pseudoplastic behaviour at concentrations above 30% by weight. The apparent viscosity varies with the amount of coal in the slurry, fraction of fines, amount of dispersant and particle size distribution. However, it was reduced by addition of 0.5% natural additive and suitable blending of coarser coal particles in a finer fraction i.e. optimum coarse-to-fine ratio. Also for the lower values of distribution modulus, coal samples exhibits lower values of apparent viscosities at same shear rates.

Index Terms— coal-water slurry, slurry rheology, natural additive.

I. INTRODUCTION

The major challenge in the world today is to efficiently utilize fuel for generate power at most economic level. For this purpose various types of techniques of utilizing fuel in solid (e.g. pulverized coal), liquid (e.g. petroleum), and gaseous form (e.g. Compressed Natural Gas) have been adopted from the very beginning. A new technique for utilizing solid fuel is to suspend fuel in a carrier liquid to form slurry and use this fuel slurry in atomized form for direct combustion in furnaces. However, when the solid fuel is in powdered form mixed with carrier liquid, the obtained slurry flow behavior generally gets altered depending upon the solid concentration and interfacial properties in carrier liquid. One such slurry that is widely recognized as a possible alternative to conventional furnace fuel is coal water slurry (CWS), which is a mixture of pulverized coal and water [1]. The efficient utilization of coal water slurry is possible only when the slurry is prepared such that it permits maximum coal loading with appreciable viscosity and maintains a uniform concentration during its storage and transport.

The rheological behavior of coal water slurry have been

studied by [2]-[4] to determine the effect of particle size distribution on slurry rheology and they have proposed that a broader PSD of the sample results in much lower viscosities. [4]-[6] have reported that with an increase in solid content there is increase in apparent viscosity of coal water slurry. The investigations on the effect of addition of finer coal particles in a relatively coarser range to reduce apparent viscosity of coal slurry conducted by [8, 9] they revealed reduction in apparent viscosity by the addition of finer coal particles until an optimum ratio of coarse/fine was reached. The present work was undertaken for the estimation of rheological parameters of coal water slurries prepared from five different coal samples of Indian origin collected from different thermal power plants and coal traders of India. A natural additive, Shikakai Powder available commercially in India as a hair conditioner was tested as a dispersant for preparing highly concentrated coal water slurry.

II. EXPERIMENTAL

A. Coal Samples

The coal water slurry was prepared from five samples of Indian coals procured from thermal power plants and coal traders. These samples were Bathinda coal (S-I), Assam Non-steam coal (S-II), Panipat coal (S-III), Dhanbad coal (S-IV) and Assam Steam coal (S-V).

Table (i): Proximate analysis of Coal Samples

Parameters (%)	S-I	S-II	S-III	S-IV	S-V
Ash	28.75	14.99	38.97	34.63	8.60
Total Moisture	5.43	2.53	2.2	1.32	0.36
Volatile Matter	25.89	35.53	21.83	25.88	41.44
Fixed Carbon	39.93	46.95	37.0	38.17	49.60

The proximate analysis of the five samples was conducted as per the prescribed testing method of IS: 1350 to

determine the ash content and the results of the proximate analysis are listed in Table (i). The Proximate analysis revealed that coal samples S-II and S-V have less ash content in comparison to the other three coal samples viz. S-I, S-III and S-IV. To obtain the particle size distribution, a known weight of coal samples were taken and passed over B.S. 200 mesh. The coal particles were sieved through a set of British Standard sieves. The sample retained on each sieve was collected and the percentage retained on each sieve was calculated using the standard procedure to obtain the PSD curve. Fig. 1 shows the PSD curve of five coal samples.

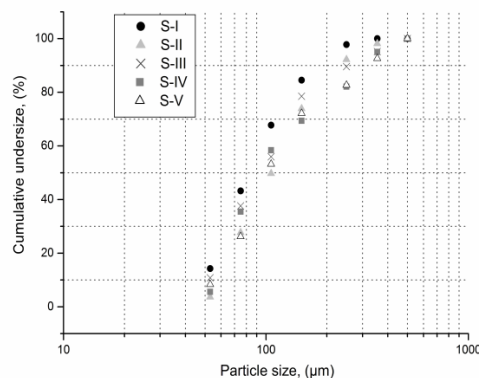


Figure 1: PSD curve for five coal samples

The PSD curve obtained indicated a continuous distribution with spread varying for each coal sample. The mass median diameters (d_{50}) of the five coal samples were found to be 80 μm , 100 μm , 105 μm , 110 μm and 112 μm for coal samples S-I, S-II, S-III, S-IV and S-V respectively. The Particle size distribution of five coal samples were fitted into the Rosin-Rammler mathematical model. The Rosin-Rammler model parameters i.e. n (distribution modulus) and K (size modulus) were calculated using least squares linear regression analysis. It was found that coal sample S-I was the narrowest of the five coal samples and S-V as the broadest coal sample with the width increasing from S-I to S-V.

Table (ii): RR model parameters of coal samples with respective R^2 values.

Coal sample	n	K	R^2
S-I	0.36	110	0.97
S-II	0.32	130	0.96
S-III	0.25	110	0.99
S-IV	0.23	105	0.96
S-V	0.22	125	0.98

The resulting distribution functions obtained by the

application of RR model are shown in Table (iii). By using these equations, the cumulative percent retained on a known size of mesh screen can be determined.

Table (iii): Distribution functions obtained by application of RR model.

Coal Sample	Distribution functions
S-I	$\left(\frac{R}{100}\right) = \exp\left[-\left(\frac{\varphi}{110}\right)^{0.36}\right]$
S-II	$\left(\frac{R}{100}\right) = \exp\left[-\left(\frac{\varphi}{130}\right)^{0.32}\right]$
S-III	$\left(\frac{R}{100}\right) = \exp\left[-\left(\frac{\varphi}{110}\right)^{0.25}\right]$
S-IV	$\left(\frac{R}{100}\right) = \exp\left[-\left(\frac{\varphi}{105}\right)^{0.23}\right]$
S-V	$\left(\frac{R}{100}\right) = \exp\left[-\left(\frac{\varphi}{125}\right)^{0.22}\right]$

B. Measurement of slurry pH

The pH of the coal water slurries at different solid loadings were measured using a digital pH meter. Before the measurement, the pH meter was calibrated by dipping the electrode in the buffer solutions and was cleaned with distilled water. The pH values obtained are shown in Table (iv). There was a variation in pH values at different solids concentrations and pH values decreased as the concentration of coal increased.

Table (iv): pH values of coal samples

Concentration (% by wt.)	CS-I	CS-II	CS-III	CS-IV	CS-V
30	6.12	6.18	6.21	6.23	6.29
40	6.08	6.13	6.13	6.19	6.27
50	6.05	6.07	6.08	6.15	6.23
60	5.97	5.99	6.01	6.10	6.18

C. Static stability measurements

The storage of coal water slurries in storage tanks requires the slurry to be stable, resisting sedimentation of coal particles with storage time. The static stability test of five coal samples was carried out using rod penetration method as prescribed by [7]. The sedimentation was detected by penetrating a steel rod of fixed weight and diameter into the coal water slurry. The appearance of soft sedimentation during the storage of coal water slurry for 48 hours was used as an indicator to measure static stability. Fig. 2 and 3 shows the static stability curve for five coal samples at solid concentration of 40 % and 50 %. (By weight).

It was observed from the static stability test that coal sample S-I ($d_{50} = 80 \mu\text{m}$) was having the maximum stability at both solids concentration of 40 % and 50 % (by weight) with penetrations of 75% after 48 hours of storage. The

least stable was S-IV ($d_{50} = 110 \mu\text{m}$) at 40 % solid concentration and S-III ($d_{50} = 105 \mu\text{m}$) at 50 % solid concentration. The investigation was done without using stabilizers and it was observed that the hard sediment layer depth reached 10 mm after 30 hours in case of 40 % solid concentration and after 24 hours in case of 50 % solid concentration.

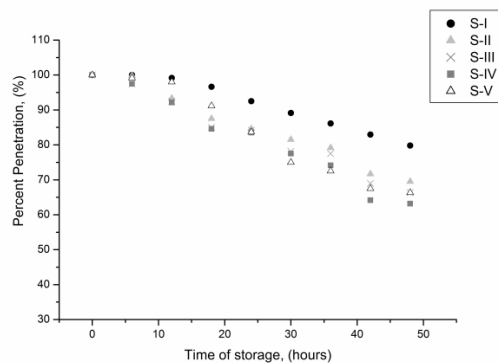


Figure 2: Static stability of coal samples at $C_w = 40\%$

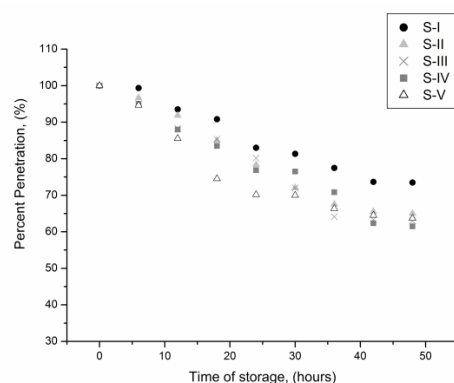


Figure 3: Static stability of coal samples at $C_w = 50\%$

D. Rheological Measurements

The coal water slurries at different coal concentrations i.e. 30-60% by weight were prepared by mixing the required amount of coal in distilled water. Rheological behaviour of coal water slurries were determined using Anton Paar rheometer (make: Germany) under controlled shear rate conditions. The rheological measurements were taken by varying the shear rate from 0 to 512 s^{-1} for each concentration. The temperature was kept constant within the range of $30 \pm 0.5^\circ\text{C}$.

III. RESULTS AND DISCUSSION

A. Effect of solids concentration on slurry rheology

The flow curves obtained from rheological experimentation revealed that rheological behavior of coal water slurry was immensely affected by variation in concentration of solid. With increase in solid concentration increase in apparent viscosity was noticed. Further it was found that at 30 % solid concentration, the coal water

slurry behavior was Newtonian for each of the five coal samples as shown in Fig. 4.

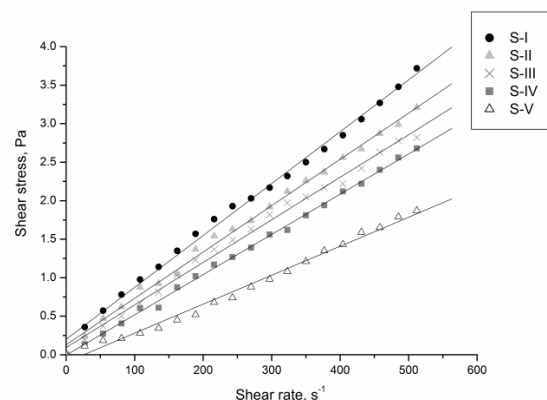


Figure 4: Rheogram with Power-Law model fit for coal samples at $C_w = 30\%$ (by wt.)

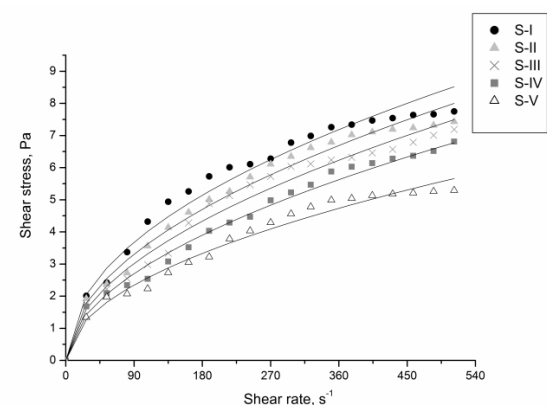


Figure 5: Rheogram with Power-Law model fit for coal samples at $C_w = 40\%$ (by wt.)

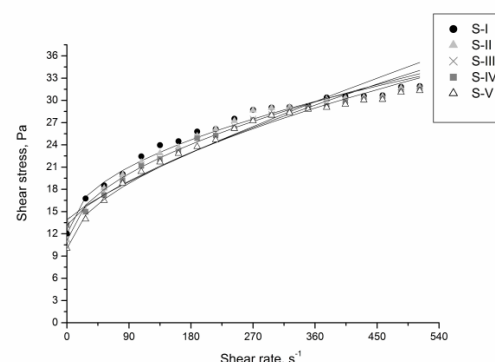


Figure 6: Rheogram with Herschel-Bulkley model fit for coal samples at $C_w = 50\%$ (by wt.)

At 30% solid concentration coal water slurry exhibits pseudo plastic behaviour with decreasing trend of apparent viscosity at higher shear rate. It was observed that at 40%

solid concentration coal water slurry behaviour was power-law fluid whereas at 50 % and 60 % solid concentration, Herschel-Bulkley fluid behaviour was exhibited by slurry. The Power-Law fit and Herschel-Bulkley fit were obtained after fitting the shear stress-shear rate data into the Power-Law and Herschel-Bulkley model by regression analysis. The model fits are shown in Fig. 5-7.

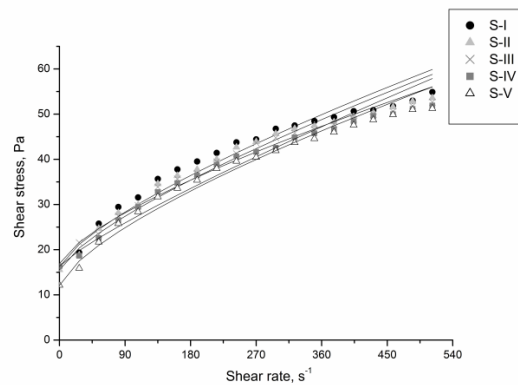


Figure 7: Rheogram with Herschel-Bulkley model fit for coal samples at $C_w = 60\%$ (by wt.).

It is concluded from the rheograms of all coal samples that coal water slurry exhibits Newtonian behavior at 30 % solid concentration and above which the slurry behaves as a pseudo plastic. Also, a yield is present at solid concentration of 50 and 60 % which indicates that this yield must be overcome before the flow can take place.

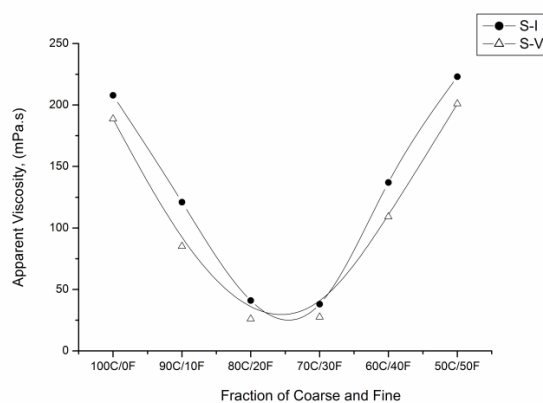


Figure 8: Effect of fraction of fines on the apparent viscosity

B. Effect of Ash Content

It was observed that yield obtained at 50 % and 60 % solid concentration of five coal samples were dependent on ash content of coal samples. As five coal samples had different ash contents, the yield increased as the ash content in coal increased. The same behavior was observed by [9]. The yield of coal samples was found to be greatest for coal sample S-III i.e. 13.88 (Pa) and 16.92 (Pa) at 50 % and 60 % solid concentration respectively with an order of $S\text{-III} > S\text{-IV} > S\text{-I} > S\text{-II} > S\text{-V}$.

C. Effect of fraction of fines on slurry rheology

It is reported by many authors that viscosity of coal water slurries could be reduced by blending the coal samples with a fraction of fines and hence making a bimodal particle size distribution. The two coal samples i.e. S-I and S-V were blended with fines in different ratios of coarse and fine fraction. The resulting values of apparent viscosities at a shear rate of 100 s^{-1} for different coarse to fine ratios are shown in Fig. 8.

By blending the coal samples with different ratios of coarse and fine fractions, it was found that as the fines were added the apparent viscosities decreased for both coal samples and as the blending ratio reached 70C/30F, the viscosities were minimum. By adding further fines the coal water slurry viscosity increased [10, 11]. Hence, the optimum coarse to fine ratio for two coal samples i.e. S-I and S-V were found to be 70C/30F.

D. Effect of dispersing agent on slurry rheology

The dispersant chosen was Shikakai Powder, a natural product that is prepared from the saponin of Acacia concinna plant. The additive was used in dosages of 0.5, 0.8 and 1 % (by weight).

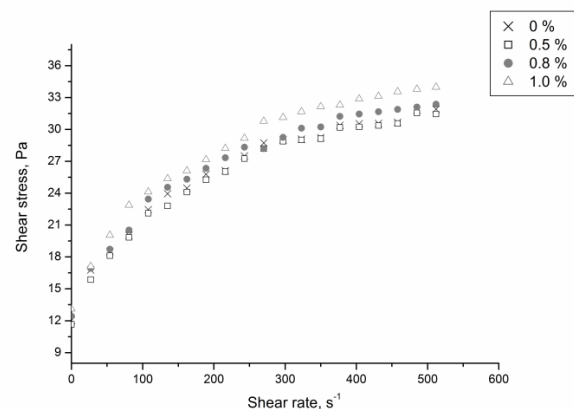


Figure 9: Rheogram of S-I at additive concentrations of 0.5, 0.8 and 1 % by wt.

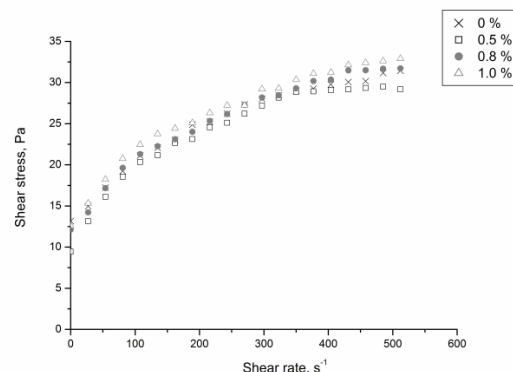


Figure 10: Rheogram of S-IV at additive concentrations of 0.5, 0.8 and 1 % by wt.

The two coal samples i.e. S-I and S-IV with solid concentration of 50 % were taken for analysis. The rheograms of coal water slurry prepared with additive at

different dosages at fixed solid concentration of 50 % are shown in Fig. 9 and 10. It was found that with additive dosage of 0.5 % (by weight), the apparent viscosity values were lowest for 50 % solid concentration. However, as the dosage was increased to 0.8 and 1 %, the apparent viscosity values were higher than those obtained without additive. Hence the optimum dosage of additive for 50 % by wt. concentration was 0.5 % for both coal samples. Similar percentage was found optimum by researchers [12, 13]

E. Effect of dispersing agent on slurry rheology

The particle size distributions of five coal samples were having different median diameters and different values of Rosin-Rammler distribution modulus. The variation of apparent viscosities at a shear rate of 100 s^{-1} at different values of RR model distribution modulus for five coal samples are shown in Fig. 11.

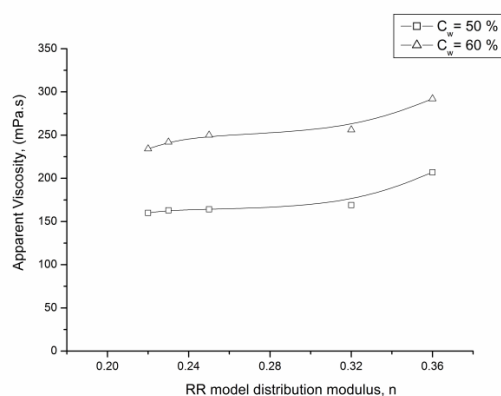


Figure 11: Apparent viscosity for different values of distribution modulus at 50 and 60 % solids loading by weight.

It was observed that as the Rosin-Rammler distribution modulus of five coal samples under consideration decreased, the apparent viscosity values also decreased. This can be attributed to the broader particle size distribution for lower values of 'n'. The small coal particles fill the voids in between relatively coarser coal particles and hence, the effective surface area for shear decreases and hence the apparent viscosity decreases. Similar type of phenomenon was observed by researchers [14, 15].

IV. CONCLUSIONS

The rheological behavior of Indian coal water slurries prepared from five different coal samples having different ash contents and mass median diameters revealed the following information:

1. The coal water slurries having solids loading greater than 30% (by weight) were pseudo plastic and a yield was observed for solids loading of 50 and 60 % by wt.
2. The yield increased as the ash content of the coal increased.

3. The apparent viscosity values were reduced by suitable blending of coarser coal particles with a finer fraction at an optimum coarse to fine ratio.

4. The natural additive was efficient in reducing the apparent viscosity of coal water slurry at a dosage of 0.5 % (by weight).

5. The lower values of distribution modulus of coal samples exhibits lower values of apparent viscosities at same shear rates.

REFERENCES

- [1] A. Gurses, M. Acikildiz, C. Dogar, S. Karaca and R. Bayrak, "An investigation on effects of various parameters on viscosities of coal-water mixture prepared with Erzurum-Aşkale lignite coal," *Fuel Process. Technol.*, vol. 87, pp. 821-827, 2006.
- [2] E. Harmadi, Suwarmin, S. Machmudah and S. Winardi, "Effect of particle size distribution on rheology and stability of high concentration coal-water mixture (cwm) with Indonesian low rank coal," *Jurnal Teknik Mesin.*, vol.2, pp. 93-98, 2002.
- [3] L.D. Lorenzi and P. Bevilacqua, "The influence of particle size distribution and nonionic surfactant on the rheology of coal water fuels produced using Iranian and Venezuelan coals," *Coal Prep.*, vol. 22, pp. 249-268, 2002.
- [4] S.K. Mishra, P.K. Senapati and D. Panda, "Rheological behavior of coal-water slurry," *Energ. Source Part A.*, vol. 24, pp.159-167, 2002.
- [5] M. Zhou, B. Pan, D. Yang, H. Lou and X. Qiu, "Rheological behavior investigation of concentrated coal-water suspension," *J Dispers. Sci. Technol.*, vol. 31, pp. 838-843, 2010.
- [6] N. Ongsiramongkol and M.H. Narasingha, "Effects of stabilizing agents on stability and rheological characteristics of the highly-loaded coal-water slurry," *Int. J. Chem. Engg. App.*, vol. 3, pp. 49-52, 2012.
- [7] H. Usui, T. Saeki, K. Hayashi and T. Tamura, "Sedimentation stability and rheology of coal water slurries," *Coal Prep.*, vol. 18, pp. 201-214, 1997.
- [8] G.V. Reddy, S.K. Mohapatra, and R.K. Sinha, "Influence of particle size distribution on rheological properties of coal-oil mixtures," *J. Institut. Engg.*, vol. 75, pp. 25-28, 1994.
- [9] S. Panda, and R.K. Swain, "Some Aspects of the Rheological Behaviour of Coal Water Slurries," *Int. J. of Therm. Env. Engg.*, vol. 8(2), pp.103-107, 2014.
- [10] P. Swain and D. Panda, "Rheology of coal-water mixtures," *Fuel Sci. Technol.*, vol.14, pp. 1237-1251, 1996.
- [11] M. K. Singh, D. Ratha, S. Kumar, D. Kumar, "Influence of Particle-Size Distribution and Temperature on Rheological Behavior of Coal Slurry," *Int. J. Coal Prep. Util.*, vol. 36, pp. 44-54, 2016.
- [12] B. K. Sah "Optimization of amount of additives to minimize relative viscosity of coal-water slurry," *IOSR J. Appl. Chem.*, ISSN: 2278-5736, pp. 58-62, 2014.
- [13] G. K. Pani, P. Rath, R. Barik & P. K. Senapati, "The Effect of Selective Additives on the Rheological Behaviour of Power Plant Ash Slurry," *Particul. Sci. Technol.*, 2014. DOI:10.1080/02726351.2014.990657.
- [14] R.S. Blissett, and N.A. Rowson, "An empirical model for the prediction of the viscosity of slurries of coal fly ash with varying concentration and shear rate at room temperature," *Fuel*, vol. 111, pp. 555-563, 2013.
- [15] J. Zhu G. Zhang, J. Li, F. Zhao, "Synthesis, adsorption and dispersion of a dispersant based on starch for coal-water slurry," *Colloids Surf. A*, vol. 422, pp. 165-171, 2013.

