Effect of microwave pretreatment of coal for improvement of rheological characteristics of coal–water slurries

B.C. Meikap [a,*], N.K. Purohit [b], V. Mahadevan [b]

[a] Department of Chemical Engineering, National Institute of Technology (NIT), Deemed University, Rourkela 769 008, India
[b] Department of Chemical Engineering, Indian Institute of Technology (IIT) Kharagpur, Kharagpur 721 302, India

Abstract

Indian high-ash coal contains α-silica components of the mineral matter. When coal is transported in the form of a slurry, α-silica adds to the settling properties of coal and enhances erosion of pipelines. As such any technique that will contribute to changing the characteristics of mineral matter by selective demineralization is bound to supplement the knowledge of coal slurries in the science of rheology. One such method is the use of a novel microwave technology, which changes the α-silica to less harmful β-silica. Thus microwave-treated coal slurry facilitates enhanced flow characteristics and abates the erosion problem in pipeline transport as well as in coal-slurry injection furnaces. This paper reports on the rheological study of closely sized coal particles of medium-volatile, low-ash, low-moisture cleans and high-ash rejects with and without microwave treatment. Viscosity of suspensions of microwave-treated coal was found to be less than that of untreated coal, in the case of both cleans and rejects. Microwave pretreatment thus reduces the viscosity and the pumping cost and opens a new outlook for pipeline transport. An attempt has been made to quantify the improvement of rheological characteristics due to microwave pretreatment.

Keywords: Microwave treatment; Coal slurries; Viscosity; Rheological properties; Slurry transport

1. Introduction

Transportation of coal in the form of a slurry through a pipeline is gaining importance. The slurry is transported over long distances of a few hundred kilometers, which creates severe problems such as settling of solids, wear of the conduit by erosion, and huge power requirements for the whole transport process. The present mode of transportation of solids in bulk quantities over a long distance cannot cope up with the future requirements. Microwave pretreatment seems to be very promising in this direction due to the multiple beneficial advantages that could be derived from it economically. Hence in this new mode of transportation of coal–water slurries, power requirements for pumping the slurries are one of the important factors.

Therefore any attempt made in the direction of reduction of energy consumption in handling solid–liquid suspensions is of great importance. Microwave pretreatment of coal has been found to selectively heat the mineral matter based on differences in dielectric properties, thereby causing the pyrite to decompose magnetically susceptible pyrrhotite. Also, it resulted in weakening of the coal–mineral matrix, thereby altering the angularity and surface properties of the ground particles. The rheological behavior of solid–liquid suspensions has a great bearing on the power requirements for pumping of solid–liquid suspensions. This rheological properties of suspensions are very much influenced by the nature of the suspending medium, particle size, shape, surface characteristics, and size distribution. It is therefore quite logical to observe the effect of microwave treatment on the rheological properties of coal–water suspensions as they influence the particle shape and surface characteristics.

Ergun and Bean [1] have suggested the possibility of using microwave to heat selectively only the pyrites in the

* Corresponding author. Fax: +91-3222-282250.
E-mail address: bcmeikap@che.iitkgp.ernet.in (B.C. Meikap).

coal, leaving other components unaffected. Fanslow et al. [2] have reported that pyrite and ash would heat 1.3–3.3 times faster than coal matter. Meikap [3,4] reported that the selective heating of mineral matter of coals by microwave radiation resulted in enhanced grinding, partial desulfurization, and decomposition of mineral matter and enhanced magnetic susceptibility. Meikap [5] reported the surface characteristics of microwave-treated coals by microscopic photographic methods and SEM analysis. They reported that microwave treatment on few Indian high-ash coals resulted in smoothing of surface and conversion of α-silica to β-silica. Williams and Onischak [6] developed a general criterion for determining the selective heating of sulfur-bearing compounds in coal by microwave energy, which is more efficient than the conventional heating of a whole sample. Several works have showed that magnetic susceptibility of pyrites can be enhanced by heating. The advantage of this effect is the improved possibility of removing pyrite from coal by magnetic separation. However, to heat the pyrite some energy is also wasted by heating the coal. A possible solution is the preferential dielectric heating of the pyrite.

Beeson [7] has indicated the need for a systematic frequency search to determine the optimum frequency for selective heating. Dielectrically heated mixtures containing a coal and pyrite run of mine coal were separated by a gravitational technique into fractions designated as 1.3 float clean coal and 2.0 sink (pyrite and ash). Dielectric properties were measured and used to predict heating rates. Predicted values suggested that pyrite and ash would heat 1.3–3.3 times faster than clean coal. Weng and Wang [8,9] investigated the influence of microwave irradiation on coal desulfurization. Nelson and Fanslow [10] have reported that dielectric loss factors of pyrite-bearing fractions of lower sulfur content were high at frequencies below about 50 GHz and decreased with increasing frequency to low values at microwave frequencies. Wang et al. [11] reported the use of microwave energy for desulfurization of coal.

The rheological behavior of suspensions depends on a large number of parameters. Literature survey reveals that work has been carried out mostly for stable suspensions with respect to fluidity handling, atomizability, etc., and some rheological models have been expressed in terms of solid concentration, particle size distribution, and shape of the particle by Thomas [12], Toda [13], and Frankel [14]. The influence of particle size distribution and shape has also been reported by Williams [15] with a particle size of 12–400 μm; at higher concentration the larger-sized particles showed the higher viscosity.

Toda [13] and Munro et al. [16] have reported an increase in the viscosity of suspensions with decreased in particle size for same solid concentration. The effect of particle size distribution on the rheological properties of suspensions has been studied by Skolnik [17]. Thomas [12] studied both rheological and hindered-settling characteristics of small-particle-size suspensions of 10–50 μm with particles of thorium oxide in water, methanol in titian kaolin, and alumina and graphite in water.

Jeffery and Acrio [18] reported the Newtonian behavior of glass spheres of different-sized particle of 12, 8, and 4 μm in a glycerol and water medium. The effect of particle concentration on viscosity has been reported by many workers. Williams [15] obtained data up to a concentration of 50% by volume of glass spheres in glycerol–water solutions.

Botsaris [19] derives the following expression for spheres of solids in liquid:

$$\mu_{\mathrm{sl}} = (1 + 2.5X_{\mathrm{v}} + 7.17X_{\mathrm{v}}^2 + 16.2X_{\mathrm{v}}^3)\mu. \tag{1}$$

A detailed study of coal–water slurry rheology has been carried out by them using 20 coals of different origins having ash content 2.6–37.8% by weight. They have generalized the flow behavior into three categories based on carbon content of coal. Skolnik [17] has also observed the dilatant behavior of coal slurries, whereas Papachristodoulou [20,21], working on several coal–water suspensions of rigid spherical particles, from that the rheological behavior of small particle concentrations is that of a Newtonian fluid, while at large concentrations the behavior becomes that of a viscoelastic fluid.

Mishra and Seversan [22] studied irregular particles of rigid spheres in Newtonian fluids at low and moderate concentration of solids and experimental data correlated by

$$\frac{\mu}{\mu_{\mathrm{sl}}} = 1 - KX_{\mathrm{v}}, \tag{2}$$

where K is a constant, the value of which depends on the system.

Thomas [12] proposed the following expression for suspensions of high solid concentration:

$$\frac{\mu_{\mathrm{sl}}}{\mu_{\mathrm{l}}} = 1 + 2.5X_{\mathrm{v}} + 10.05X_{\mathrm{v}}^2 + 0.062\exp^{\left(\frac{1-0.875X_{\mathrm{v}}}{1-1.595X_{\mathrm{v}}}\right)}. \tag{3}$$

The effects of particle shape or irregularity on the rheological behavior of suspensions have been reported by a number of workers. In general it has been found that the viscosity of suspensions of irregular particles is higher than that of smooth spherical particle suspensions.

Literature review reveals that the viscosity of a suspension depends on the nature of the solid particles, shape, particle size distribution, nature of suspending medium, solid concentration, additives, pressure, and temperature. The rheology of coal slurries has been studied mostly with low-ash coals. Since Indian coals are high in ash content and moreover the nature of low-ash coal is completely different from at of those found elsewhere, it is very much essential to measure rheological characteristics. In addition, after microwave treatment, the rheological behavior of pretreated coal should show different behavior from that of untreated coal. As microwave treatment causes possible changes in the mineral matter, it might change the surface properties of both coal and mineral matter. In addition, it weakens the coal–mineral matrix due to differences in dielectric constants that might alter the angularity after comminution. The development of pores both in the mineral matter and in the coal will result in the change in specific gravity. The transformation of the α-silica component to a β-silica component during microwave treatment may change the rheological properties of the suspension. All these factors will contribute to the change in the rheological properties. However, detailed rheological characteristics of microwave-treated coal–water suspensions are very limited.

2. Mechanism of microwave selective heating

The potential application of microwaves to coal desulfurization was suggested by Wang and Yang [23]. It is known that microwave power dissipation by a medium is proportional to the imaginary part of the so-called complex dielectric constant, which is a measure of the dissipated power per unit electric field according to the equation

$$P = 55.63 \times 10^{-12} \times F \times E^2, \quad (4)$$

where P is the power absorbed per unit volume of mineral (w/m^3), F is the frequency of microwave radiation (Hz), and E is the imaginary part of the complex dielectric constant (dimensionless). If the imaginary dielectric constant E at a microwave radiation frequency for a material is negligible, the material is said to be transparent, nonabsorbing, or nonconducting. When an inhomogeneous mixture made up of transparent and absorbing components is subjected to microwave treatment, the electromagnetic radiation traversing it would be absorbed only by the conducting component, resulting in selective heating of the component (Wang and Takarada [24]).

Measurement of dielectric properties of coal and some of its significant sulfur compounds such as pyrite (FeS_2), thianthane ($C_{12}H_8S$), and diabenzothiohene ($C_{12}H_8S_2$), were made at different microwave frequencies. It has been reported that coal in pyrite was relatively transparent to microwaves at a frequency of 8.3 GHz, while pyrite would greatly change the level of absorption. After relatively low exposure of coal, it was found that treated samples could be further cleaned with ease by a low-intensity bar magnet due to the extensive conversion of pyrite (FeS_2) to the more magnetic iron sulfur complex FeS_x (where $x = 1.14$).

Therefore an attempt has been made in the direction of reduction of energy consumption in handling solid–liquid suspensions. A microwave pretreatment of coal has been found to selectively heat the mineral matter based on the difference in dielectric properties, thereby causing the pyrite to decompose into magnetically susceptible pyrrhotites. Also, it resulted in weakening of the coal–mineral matrix, thereby altering the angularities and surface properties of the ground particles.

This investigation has been undertaken for both untreated and microwave-pretreated Indian coals, namely clean coal (18% ash) and reject coal (50% ash) from the Jamadoba washery (TISCO) in four sizes, namely 253, 182, 138, and 60 μm, corresponding to (−52, +72), (−72, +100), (−100, +120), and (−200) mesh (IS) fractions in water from 30 to 50% in weight. Hence an attempt has been made in this paper to investigate the flow behavior of microwave-pretreated coal and untreated coal–water slurries of different ash content with and without microwave treatment to see the effect of microwave treatment on the rheology of coal–water slurries.

3. Experimental setup and technique

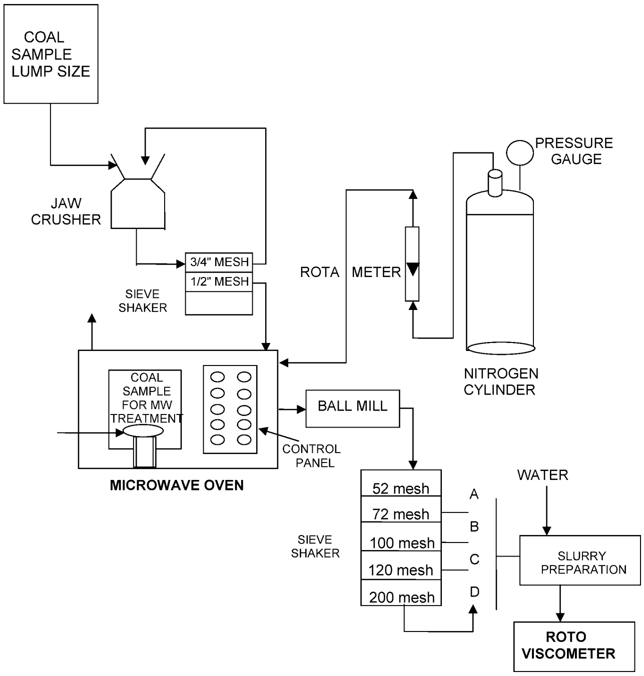
Fig. 1a shows the experimental setup for microwave treatment of coal. To get the desired sizes of different particles, original coal of lump size about 15 kg was crushed in a jaw crusher and sieved in a 52 mesh screen; materials passing through a 52 mesh screen was sieved to get the four cut fractions (−52, +72; −72, +100; −100, +120, and −120, +200). The +52 fraction materials were then ground in a ball mill for 20 min. The ground material from the ball mill was sieved to collect the desired four fractions. The same procedure was followed for microwave-treated clean coal, microwave-treated reject coal, and untreated clean and reject coals.

The particle size selection for investigation of rheological studies mainly depends upon the viscometer used for the best interpretation. For the present investigation a Haake rotoviscometer was used for rheological studies, which can be used for particles 360 μm on finer. The particle sizes selected were −52, +72; −72, +100; −100, +120, and −120, +200 mesh size.

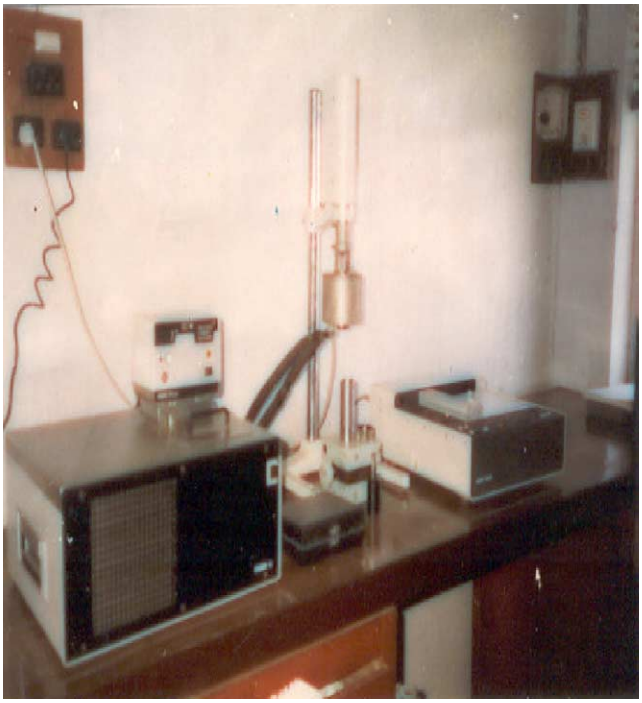
The microwave oven used for microwave pretreatment of coal was a Microwin MX. Model 1100. The oven consists of a door handle (incorporating an automatic door lath mechanism), oven cooker window (to visualize the sample during treatment, but microwave-radiation-proof), stirrer fan cover (plastic shield to cover the stirrer fan, which operates whenever the oven is used and provides uniform distribution of microwave energy throughout the cavity), revolving tray (rotates during operation and ensures uniform distribution of microwaves), control panel (consists of several soft-touch programmable panels, through which any desired values of power consumption duration of heating, and start and stop operation are chosen, and oven cavity light. Nitrogen gas at a controlled flow rate was maintained within the oven as an inert atmosphere.

During cooking in the microwave oven, hot air, steam, and vapors are generated within the oven cavity; to expelling these vapors and other gases during operation, and air vent was provided. The microwave oven used for coal pretreatment is a 380 × 550 × 370-mm-capacity oven with specifications frequency 50 Hz, power level 1150 W at high level, output frequency 2.45 GHz, usable volume 27 L.

The coal samples of $(-3/4'', +1/2'')$ fractions were taken in a glass container of around 500-g capacity. The



(a)



(b)

Fig. 1. (a) Experimental setup for microwave treatment of coal; (b) experimental setup for viscosity measurement (Haake rotoviscometer).

height of the coal bed is approximately equal to the diameter of the container. The container containing the coal samples was placed on the floor of the oven in the revolving tray. Then the oven box was purged with nitrogen gas for about 5 min, and then the door was closed carefully. The oven was switched on for a programmable time of 60 s and power level 6 (550 W). Then the oven samples were collected for different-sized fractions by ball mill. To measure the temperature in the actual experiment, after a fixed programmable time five thermocouples were inserted at different positions in the coal sample and average temperature was taken after calibration. For calibration the coal sample was taken out from the oven immediately after a fixed duration of treatment and it was then dumping to a closed container with 5 L of water. The rise in the temperature of the water was measured with the help of a thermocouple. Then the temperature of the coal was determined by heat balance calculation.

The viscometer (Haake Rotovisco) gives a direct plot of shear stress vs shear rate with a programmable panel. The viscometer consists of three main parts, namely, a programmable package with a printer, a viscometer body, bob, and cylinder, and a constant-temperature controlling device, which is shown in Fig. 1b. The viscometer works on the principle of two concentric cylindrical bobs containing slurries and developing shear stress. The viscometer consists of two cylinders, one cylinder (diameter 5.0 cm and height 10.0 cm) made of stainless steel, in which the suspension is taken around 70 ml. Another cylindrical bob (diameter 4.0 cm and height 6.0 cm) was placed inside the cylinder containing the test suspension. The volume of the suspension is taken in such a manner that after the bob with threaded socket is inmersed, the whole outer surface of the bob will be wetted by suspension. One motor at the top of the viscometer rotates the central bob during rheology measurement. The constant-temperature device is useful for measurement of rheology at different temperatures. The programmable panel is used to fix the percentage of shear rate parameter and percentage shear stress parameter. The viscosity of the suspensions is then calculated from the data generated by the viscometer.

4. Results and discussion

Proximate analysis of microwave-pretreated and untreated coals (both cleans and rejects) for four sizes is presented in Table 1. Results show that the ash content of microwave-treated coals is lower than that of original untreated samples. This lowering of ash content due to microwave treatment may be due to the partial removal of mineral matter finer than 60 µm by grinding and screening. Due to microwave treatment mineral matter is heated faster than coal; as a result the binding force in minerals is weakened and the form fines while being ground in a ball mill. However, the moisture content of microwave-treated coals was found to be lower than that of untreated coal. The same trend has been observed for coals of different particle sizes.

The volatile matter and fixed carbon of microwave-treated coals are found to be more than those of untreated coals for both clean and rejects, which is quite obvious, as discussed earlier, due to partial removal of mineral matter.

In order to see the effect of particle size distribution on viscosity, particle size distribution analysis has been done by a Malvern particle size analyzer using isobutyl alcohol as

Table 1
Proximate analysis of coal

Constituents	253 μm (%)	182 μm (%)	138 μm (%)	60 μm (%)	Untreated clean coal
	MW-treated clean coal				
Fixed carbon	59.66	58.50	60.24	58.91	57.00
Volatile matter	23.99	24.72	24.08	24.34	23.88
Moisture	01.45	01.38	01.12	00.83	01.00
Ash	14.85	15.40	14.56	15.92	18.65
	MW-treated reject coal				Untreated reject coal
Fixed carbon	31.89	31.22	34.09	33.15	31.00
Volatile matter	19.96	21.45	20.96	20.45	18.12
Moisture	01.68	01.56	01.06	01.10	00.82
Ash	46.47	45.77	43.89	45.30	49.99

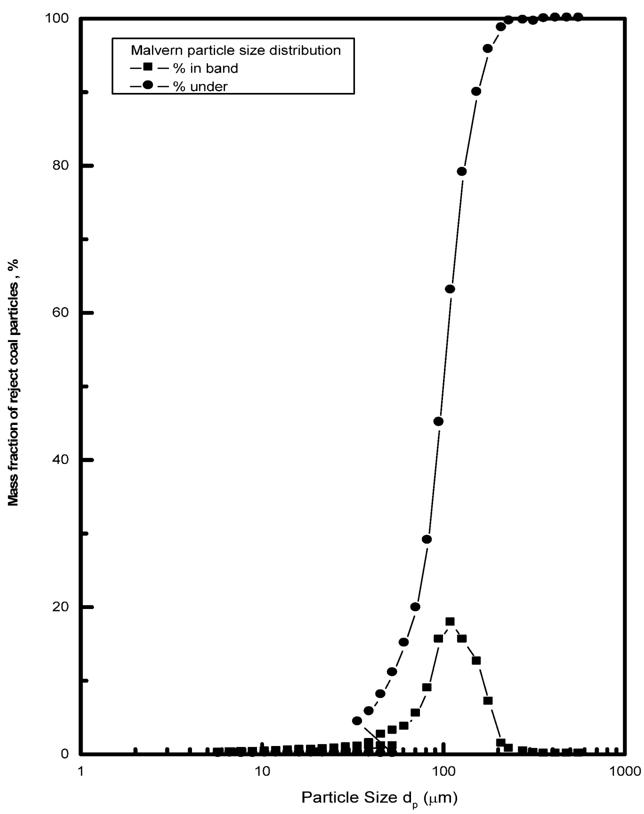


Fig. 2. Malvern particle size distribution of reject coal before MW treatment.

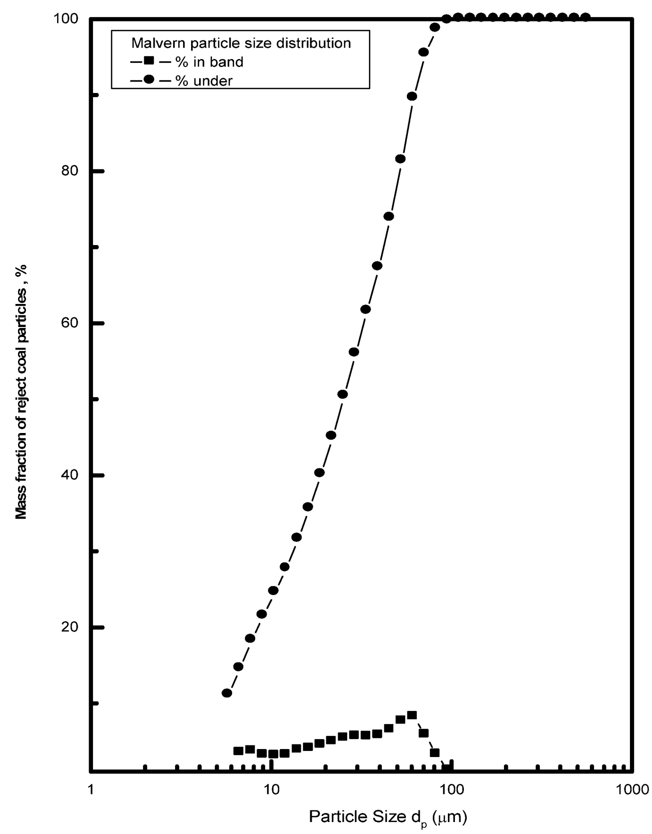


Fig. 3. Malvern particle size distribution of reject coal after MW treatment.

the dispersion medium. A typical particle size distribution of microwave-treated reject coal is shown in Fig. 2. From the figure it can be seen that more than 60% of the particles have a diameter of 138 μm. Almost the same trend of size distribution has been observed for other samples. However, four samples were found to have less than 50% particles with an average particle diameter corresponding to their mesh size.

A comparison of the particle size distribution for untreated and microwave-treated coal of the same size fraction of 253 μm particles is shown in Figs. 2 and 3, respectively. It shows that 80% of untreated cleans have an average particle diameter of 253 μm, whereas 75% of the particles have an average particle diameter of 253 μm for the microwave-treated cleans.

Densities of different coal particles for both microwave-treated and untreated coals are presented in Table 2. It has been found that the density of 60-μm particles of untreated clean is greater than that of 253-μm particles with a minimum for 138-μm particles. However, after microwave treatment, the density of 60-μm particles was found to be less than that of 253-μm particles. For reject untreated coals, density gradually increases with increased particle diameter.

Table 2
Density of microwave-treated and untreated coal

Particle size (μm)	Clean coal density (g/cm^3)	MW-treated clean coal density (g/cm^3)	Reject coal density (g/cm^3)	MW-treated reject coal density (g/cm^3)
253	1.420	1.420	1.900	1.950
182	1.370	1.340	1.872	1.916
138	1.350	1.330	1.830	1.894
60	1.460	1.390	1.750	1.876

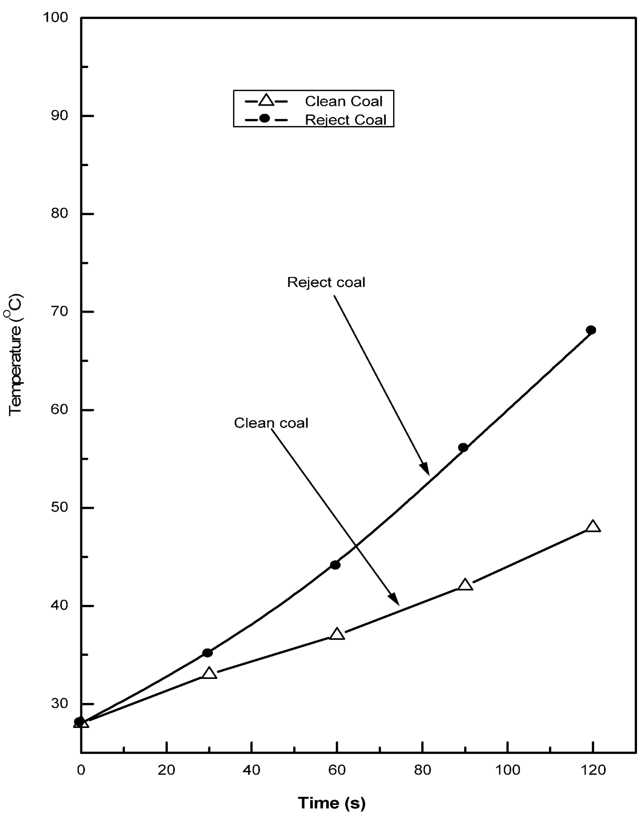


Fig. 4. Effect of duration of MW treatment on temperature of coal.

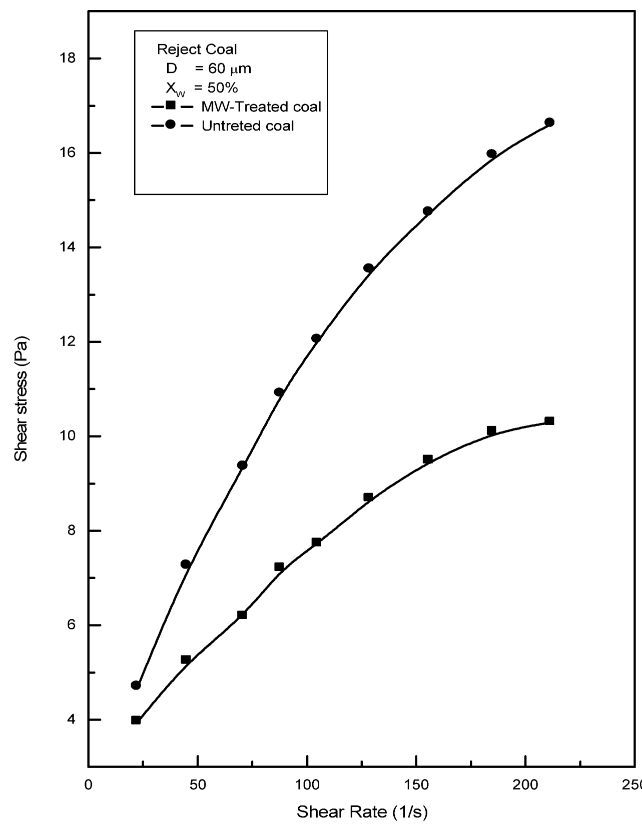


Fig. 5. Effect of shear rate on shear stress for MW-treated and untreated reject coal.

However, the reject microwave-treated coals have a higher density than the untreated rejects at the same particle diameter. In the case of clean coal, increase in particle size marginally increased the density of the solids. For the same size, the microwave treated coals have lower density compared to clean. This is perhaps due to the effect of microwave treatment of mineral matter resulting in the decomposition of pyrite and mullite and possibly the conversion of α-silica to β-silica, which may reduce the erosion considerably. For the same size and solids concentration, the viscosity of the suspension of microwave-treated particles was found to be less than that of the untreated ones, in the case of both cleans and rejects.

It has been observed that the coal temperature increases with the duration of microwave treatment. The rise in temperature of reject coal for the same treatment period is greater than that of clean coal shown in Fig. 4, which is obvious, as the percentage of mineral matter in reject coal is higher than in clean coal and microwave energy absorption of minerals is 2–3 times faster than that of carbonaceous matter. During microwave treatment smokes and some sparks were observed when the temperature rose to a higher value with longer duration (more than 5 min) of treatment.

4.1. Rheological characteristics of coal slurries

4.1.1. Effect of shear rate on shear stress for coal sample

Fig. 5 shows effect of the shear rate on shear stress for microwave-treated and untreated reject coal. A similar trend has been found for all other coal samples. All suspensions have been found to follow pseudo-plastic behavior, which is higher at higher concentrations. A comparison has been made of microwave-treated to untreated reject coal. It is clear from this figure that the shear stress for untreated reject coal is higher than that of microwave-treated coal. This can be explained on the basis of the changing surface characteristics of microwave-treated coal. It has also been found that untreated clean coal suspensions of 30 and 40% concentration show pseudo-plastic behavior. The same trend has been observed for microwave-treated coals (cleans and rejects) of different particle diameters. It is interesting to note that the pseudo-plastic behavior for 138- and 60-µm low-ash coals is more regular than that for the 253-µm particles. The aged microwave-treated cleans more or less follow the same trend of pseudo-plastic behavior.

4.1.2. Effect of MW treatment and slurry concentration on viscosity

Figs. 6 and 7 show the effect of slurry concentration on viscosity for microwave-treated and untreated reject and clean coal of 60- and 135-µm particles. From the figure it can be seen that the viscosity at infinite shear rate (viscosity calculated at constant and relatively high shear rate, i.e., 202.9 s^{-1}) increases with increased slurry concentration. Generally shear stress increases with increased shear rate up to a certain point, after which it becomes almost constant. The viscosity at this constant shear stress (infinite shear rate, 202.9 s^{-1}) is termed μ_∞.

It is interesting to note that the viscosity of microwave-treated coals was lower than that of the untreated coals. The decrease in viscosity of microwave-treated coals might be due to the decrease in irregularity of the particles after grinding, as reported by Meikap [5], and may be due to surface smoothing of treated samples. It has also been found that the power consumption to grind the microwave-pretreated coal materials is less than for untreated coal. For softer particles the irregularity decreases from coarser to finer sizes. This decrease in irregularity of microwave-pretreated coals might decrease the viscosity of suspensions. Decreased viscosity was observed with increased shear rate and increased viscosity with decreased particle sizes and increased particle concentration indicate that large surface area or higher particle concentration lead to corresponding decreases in fluidity of the system. Although viscosity of coal suspensions increases with decrease in particle size, above 26% the viscosity of

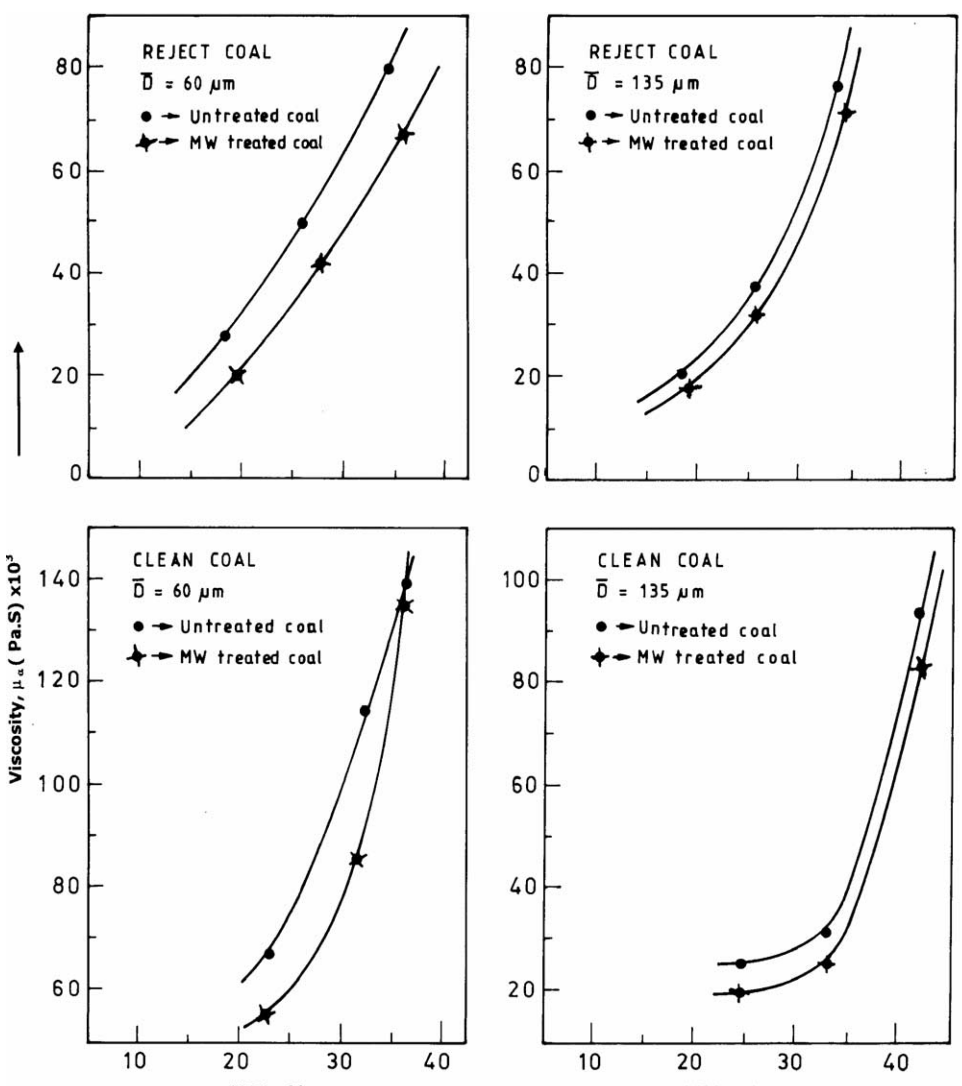


Fig. 6. Effect of slurry concentration on viscosity of MW-treated and untreated coal.

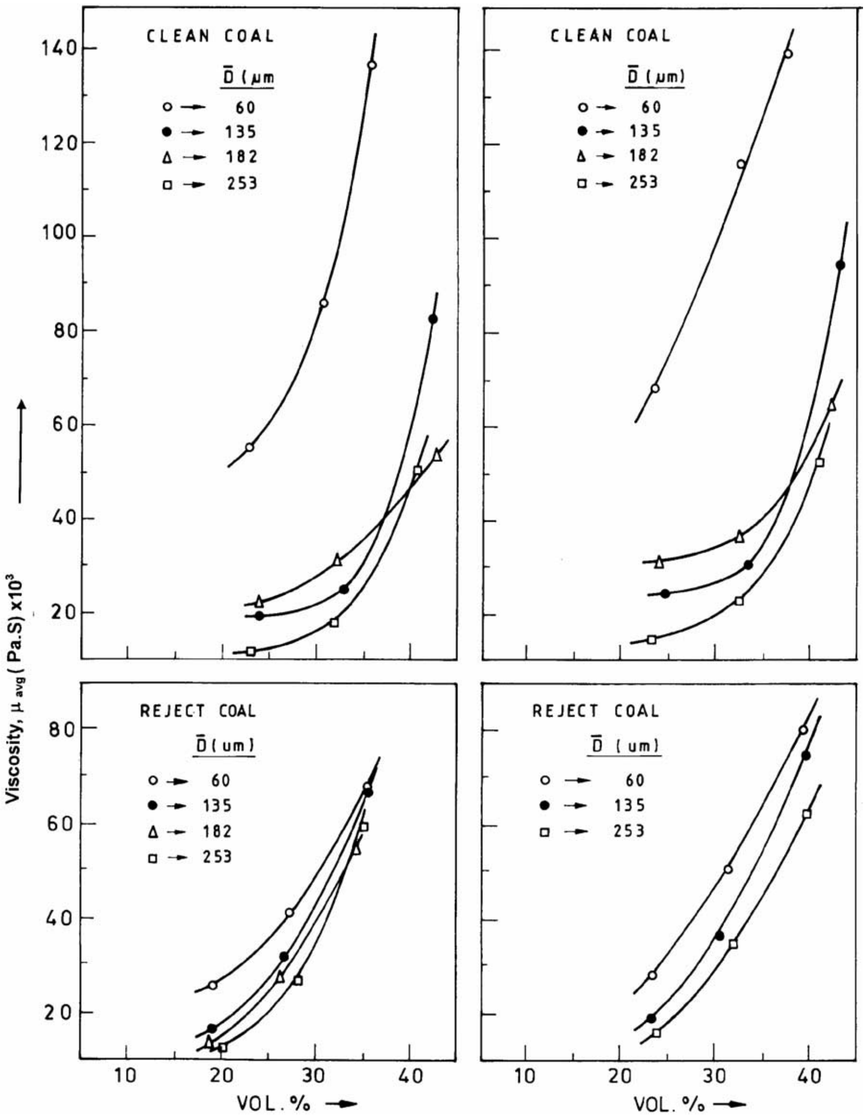


Fig. 7. Effect of slurry concentration on average viscosity for clean and reject coal for 60-, 135-, 182-, and 253-μm particles.

183-μm suspensions is less than that of the 253-μm suspension (Fig. 7). The high-ash rejects of both microwave-treated and untreated coals follow the same trend. The increase in viscosity with particle concentration can be attributed to increased in particle interaction of a hydrodynamic and/or colloidal nature. Viscosity increases with decreased particle size can be explained by the fact that the smaller particles have a lager surface area, with the result that more liquid is required to wet the surface and hence available fluid for flow is reduced and viscosity increased. This is in agreement with the findings of Wang and Tomita [25]. It has also been observed that for 60-μm particles the viscosity of suspensions increases with concentration at a constant shear rate, known as viscosity at infinite shear rate. At the same shear rate, the apparent viscosity of clean coal of diameter 60 μm is greater than that of 183-μm particles at all concentrations. The same trend has been observed for microwave-treated clean coals.

4.1.3. Effect of shear rate on apparent viscosity

Fig. 8 shows the effect of slurry concentration on apparent viscosity (point viscosity) for untreated and microwave-treated coals. This figure indicates an exponential decrease in viscosity with increased shear rate for all types of clean and rejects. From this figure it can be seen that the viscosity of microwave-treated coal is always lower than that of untreated coals. It is also clear from this figure that the viscosity of 135-μm clean is higher at 50% concentration than at 40% concentration. It is interesting to note that, the viscosity is always higher for 50% both treated and untreated slurries for 135 μm than that of 30% slurries at a constant shear rate. All suspensions show lower viscosity for microwave-treated coal than for untreated coal.

4.1.4. Effect of weight ratio on slurry viscosity

The effect of weight ratio on viscosity is shown in Fig. 9 for microwave-treated and untreated coal. It is possible,

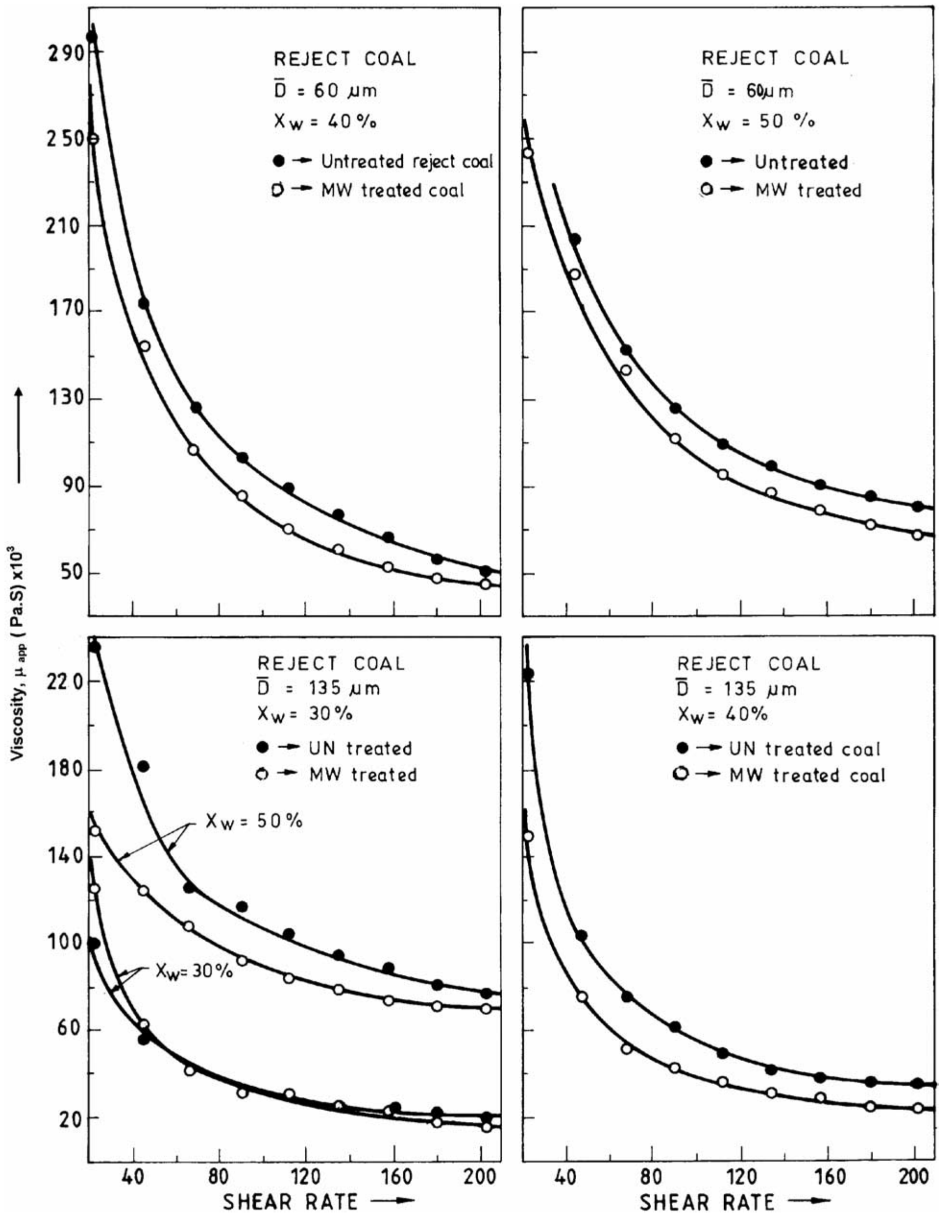


Fig. 8. Effect of slurry concentration on apparent viscosity for MW-treated and untreated coal.

as previously found by many workers, to obtain a mixed slurry with reduced viscosity by choosing a correct proportion and size ratio. It has been found that a mixture (1:1 by weight of 60- and 253-μm particles) of microwave-treated clean coal shows viscosity lower than that of untreated coal–water slurry with identical composition. It has been observed that a microwave-treated coal slurry showed viscosity almost 30% lower than that of untreated coal–water slurry. The reduction of viscosity by mixing different size particles may be due to the reorientation of smaller particles by entering into the molecular gap between the larger particles. As a result, reduction in viscosity occurs for different sizes of coal particles in coal–water suspensions.

4.1.5. Variation of shear rate with shear stress in log–log plot

A typical log–log plot of shear stress vs shear rate is shown in Fig. 10 and found linear. The same trend has been observed for all other samples of low- and high-ash coal of different particle diameters and slurry concentrations. From these figures it has been found that the value of n varies from 0.10–0.52 and $\log k$ varies from 1.20–4.50. However, most suspensions showed a value of $n = 0.20$. It has been also observed that 30% suspensions by weight showed a higher value of n than 50% suspensions. The regression analysis shows the values $n = 0.18$ and $\log k = 2.0$ and an empirical functional relation for power law to characterize the slurry type. The developed correlation is applicable to the microwave-treated clean and rejects for the 60- to 253-μm

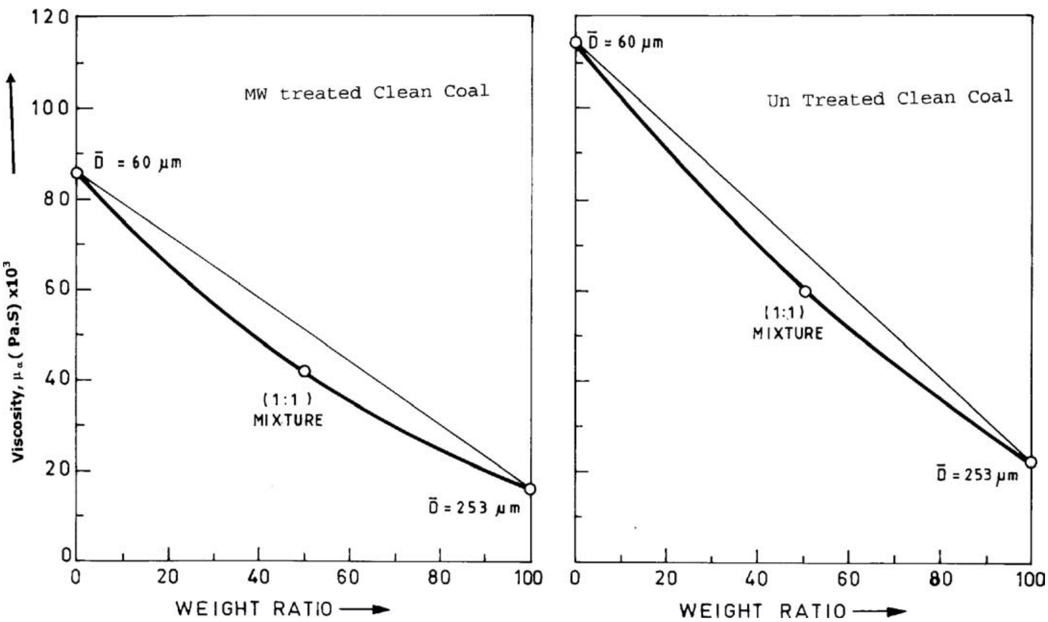


Fig. 9. Effect of weight ratio on slurry viscosity for MW-treated and untreated clean coal.

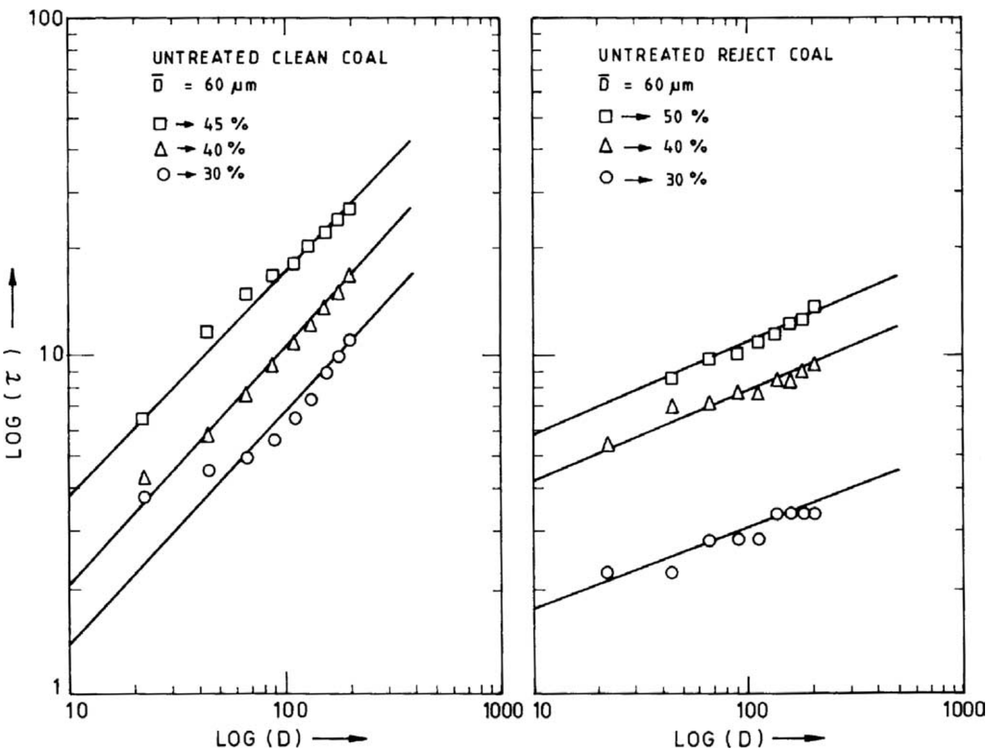


Fig. 10. Variation of shear rate with shear stress in log–log plot for untreated clean and reject coal.

coal particles and at a slurry concentration of 10–30% by weight:

$$\tau = 2.0[d]^{0.18}. \tag{5}$$

The constant k is the measure of the consistency of the fluid and the higher the value of k, the more viscous is the slurry. n is a measure of the degree of non-Newtonian behavior and the greater the departure from unity the more pronounced the non-Newtonian properties of the slurry. From experimental findings it is found that almost all the slurries are pseudo-plastic in nature and the 50% slurry behaves more long a non-Newtonian fluid than the 30% slurry. The value of n obtained for untreated reject coal seems to be much lower than for untreated clean coal. Probably this may be attributed to the difference in surface characteristics and condition.

5. Conclusion

Microwave pretreatment of Indian reject coal (high-ash coal) and clean coal (low-ash coal) was investigated and compared to that of untreated coal samples. Experimental investigation shows that there is a strong effect of microwave pretreatment on the rheological behavior of coal–water suspensions. The effect of microwave treatment resulted in a decrease in apparent viscosity of the suspensions, which reduces the pumping cost of slurry transportation. The effect is greater in the case of high-ash coal. Microwave treatment thus reduces the viscosity and naturally increases the solid concentration for slurry handling at identical energy consumption.

Acknowledgments

The authors thankfully acknowledge the reviewers of this paper for important comments and suggestions. The author also thank the Regional Research Laboratory, CSIR, Bhubaneswar, India for extending laboratory facilities to carry out part of the research.

Appendix A. Nomenclature

A	constant for Hakke Rotovisco
D	shear rate (1/s)
D_{avg}	average particle diameter (μm)
k	constant in power law, consistency index
k_1	constant in Eq. (1)
k_2	constant in Eq. (1)
M	constant for Hakke Rotovisco
n	viscosity index
$S\tau$	rate of shear parameter (Pa)
S_b	rate of shear rate (1/s)
X_v	volume fraction of solid in suspension
X_w	weight percentage of coal in slurry

Greek letters

α	one form of silica in mineral matter of coal, dimensionless
β	another form of silica in mineral matter of coal, dimensionless
μ	viscosity (Pa s)
μ_∞	slurry viscosity at infinite shear rate (Pa s)
μ_{app}	apparent viscosity (Pa s)
μ_l	viscosity of suspending medium (Pa s)
μ_{sl}	slurry viscosity (Pa s)
μ_{sl}	viscosity of suspension (Pa s)
μ_{sp}	specific viscosity ($\mu_{sl} - \mu_l/\mu_l$), dimensionless
ρ	density (kg/m^3)
τ	shear stress (Pa)
τ_0	yield stress

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