Influence of Chemical Reagents on Rheological Properties of Fly Ash-Water Slurry at Varying Temperature Environment

H.K. Naik1,*, M.K. Mishra1, Karanam U.M. Rao2
1 Department of Mining Engineering, National Institute of Technology, Rourkela, India
2 Department of Mining Engineering, Indian Institute of Technology, Kharagpur, India
Email: hrushi1920033@gmail.com, mkmishra@nitrkl.ac.in, umakaranam@gmail.com

ABSTRACT

About 70% of total electrical energy is generated from thermal power plants in India which in turn release about 160 Mt of fly ash as solid waste annually. Transportation and disposal of such a huge amount of fly ash is a major problem faced by the power plants. Presently fly ash is transported as lean slurry in pipe lines requiring about 80 to 85% of water with high energy input. A major impediment in high volume transportation of fly ash is its high specific gravity as compared to that of water. The objective of the present study was to evaluate the rheological characteristics of high concentration fly ash slurry with and without a chemical reagent at varying temperature environment to facilitate smooth flow of materials in the pipelines. Six different composition of fly ash slurry samples were considered for investigation. The main constituents of the slurry were fly ash, water, a cationic surfactant, and a counter-ion. Detailed rheological properties were determined using a cylindrical co-axial rotational rheometer at shear rates varying from 25s^{-1} to 1000s^{-1} for 40% solid concentration (by weight). Temperature was varied from 20°C to 40°C for all the shear rates investigated. Test results showed that all the slurries exhibited shear-thinning behaviour in the presence of the surfactant. The influence of cationic tenside on drag reduction of fly ash slurry was also studied. The distinctive reduction of surface tension on colloidal dispersion characteristics of the fly ash slurry was observed in the presence of the tenside. It revealed that the slurry developed in the above manner has a potential to be transported through pipelines with minimal energy consumption.

© 2011 The University of Kentucky Center for Applied Energy Research and the American Coal Ash Association
All rights reserved.

ARTICLE INFO

Article history: Received 2 September 2011; Received in revised form 5 October 2011; Accepted 8 November 2011

Keywords: Rheology; Fly Ash; Slurry; Shear Stress; Viscosity; Shear Rate

1. Introduction

Fly ash is produced in large quantities in India (about 160 Mt per annum) from the thermal power stations located across the country (Behera and Mishra, 2011). It is projected to be about 300 Mt by 2017 and 1000 Mt per year by 2032 (Kumar, 2010). At present about 50% of the fly ash is being gainfully utilized in India (Sahay, 2010). The rest is dumped nearby in ash ponds that occupy huge land area. There are numerous successful attempts on the utilization of fly ash either alone or mixed with lime, gypsum, or both (Mishra and Rao, 2006). In spite of all efforts, fly ash utilization level is not increasing at par with its production. The problem will be acute with increasing coal-fired power production. Both abandoned as well as operating underground mine voids have the potential to accommodate huge quantities of fly ash. Fly ash has to be transported to the mines in pipelines, but transport is problematical due to the quick settling nature of fly ash particles because of its higher specific gravity as compared to that of water. This problem is normally addressed by pumping of solids as a lean aqueous suspension or slurry (usually 15 to 20% by mass) to ash pond area (Bun, 1989; Bun and Chambers, 1993). The economic
efficiency of this process depends on the power requirements for pumping, which in turn depend on the concentration, viscosity, and yield stress of concentrated slurries (Horsely, 1982). Certain chemical additives enable the slurries to be pumped at much higher concentration of solids, thus reducing the energy consumption and water requirements, which is an important consideration in power stations in view of the reduced size of the ash ponds to accommodate the fly ash slurry (Biswas et al., 2000; Seshadri et al., 2005; Matras et al., 2007; Verma et al., 2008).

Fly ash largely consists of silica with varying amounts of other materials as Al, Fe, and alkaline earth materials. The presence of these materials introduces drag effects on the flow behaviour of fly ash slurry (Jones and Chandler, 1989). Fine particulate slurries generally show non-Newtonian flow behaviour for concentrations above 40% by weight (Seshadri et al., 2005). Coarse particulate slurries require high operating velocities for transportation, resulting in higher specific energy consumption per unit solid throughput. Transportation of non-settling solids would result in lower energy consumption and better operational conditions. Surface active agents (Surfactants) are known to be good drag reducers. These agents, when added to a liquid, reduce surface tension, thereby increasing spreading and wetting properties of the constituent particles. These aqueous solutions reduce up to 80% of the drag in a turbulent straight pipe flow in a wide range of temperature environment. This turbulent drag reduction phenomenon implies that pipe flow containing these additives requires a lower pressure drop for a given flow rate (Rozenblit et al., 2006, Nguyen et al., 2006). The characteristics of such a dilute surfactant solution have been investigated in oil well fracturing operations (Ousterhout and Hall, 1961), increasing the output of the water jet during fire fighting (Fabula, 1971), in transportation of crude oil in the Alaska and Norwegian pipelines (Sellin and Ollis, 1980; Burger et al., 1980), sewage systems to prevent overflow during heavy rains (Sellin and Ollis, 1980), in water supply and irrigation systems (Sellin et al. 1982 a, b; Shenoy, 1984), hydraulic transportation of solid particle suspensions (Golida, 1986), and closed-circuit pumping installations (Choi et al., 2000; Suzuki et al., 2005). A similar application is the addition of polymers to oil being pumped from offshore platforms to shore facilities (Beaty et al., 1984). Limited studies are available in the open literature about the use of these reagents for the transportation of fly ash slurries in the pipe lines. Therefore, in the present study, an attempt has been made to evaluate the flow properties of the fly ash slurry with and without a chemical reagent to reduce drag friction in the hydraulic pipelines.

A number of factors influence the rheological behaviour of slurries such as weight % of solids, particle shape, particle size, and the surface chemistry of the particles. Colloidal (surface) forces, which arise because of the chemistry of solid-liquid interface, increasingly dominate the interaction between neighbouring particles as the particle size of the slurry decreases. The rheological behaviour of the slurry may be favourably altered by manipulation of the surface chemistry of the particle surfaces. Some of the methods are: (1) alteration of solution conditions, e.g. pH, and (2) addition of polymeric reagents (Huynh et al., 2000).

The identification of optimum conditions for hydraulic transportation of fly ash needs to evaluate its rheological behaviour. The energy required to pump slurries is related to the concentration, yield stress, and viscosity of the slurry (Jones and Chandler, 1989). Certain surfactants, such as cetyl trimethyl ammonium bromide (CTAB) and cetyl trimethyl ammonium chloride (CTAC), with the addition of appropriate counter-ions such as sodium salicylate (NaSal), form network microstructures at very low concentrations and are very effective in reducing friction factors in turbulent flow (Qi and Zakin, 2002; Zhang et al., 2005). In this paper, the influence of a cationic surfactant (CTAB) on the rheological behaviour of fly ash slurry has been investigated in terms of shear rates, viscosity, temperature, and concentration.

The main objective of the present study was to keep the fly ash particles water borne during their transportation in pipelines and reduce the drag friction. This paper reports the results of determination of a few rheological parameters of the developed fly ash slurry. The changes in the surface chemistry of the slurry under the chemical treatments were also investigated by zeta potential as well as surface tension measurements and the results are co-related with the changes in the observed rheological properties.

2. Background of the Study

The surface nature of fly ash particles is an important factor in the high solid/liquid ratio (fly ash-water) suspensions behaviour. In this investigation, a cationic surfactant was used along with a counter-ion sodium salicylate (NaSal) to study the rheological properties of fly ash slurry. A high solid concentration with 40% by weight of fly ash-water suspensions was treated with surfactant and analysed. There were encouraging results of 20% and 30% fly ash concentration with addition of a surfactant and a counter-ion (Naik et al., 2009 a, b). Seshadri et al., (2005) obtained favourable results for slurry transportation with addition of about 1% of sodium hexametaphosphate as a dispersing agent on rheology of fly ash-water slurries. Nigle and Neil (2003) observed that friction reduction in non-settling pipe flow occurred when viscosity was changed with chemical reagents and additives. They studied the effects of different chemical reagents on drilling mud slurries (using sodium acid pyrophosphate and sodium hexametaphosphate), phosphate rock slurries (using caustic soda), and limestone cement feed slurries (using a combination of sodium tripolyphosphate and sodium carbonate). Their work was aimed at reducing the viscosity of the investigated slurries to facilitate long-distance pumping and reducing energy requirements. Boylu et al., (2005) studied the effect of cationic surfactants in the stability of coal-water slurry using different coal ranks. The results depicted that polymeric anionic CMC agent had higher effect on the stability of coal-water slurry, in particular, that was prepared from high rank bituminous coal (Thermal Code No. 434 of Turkish origin with medium volatile matter (30.3%)). Cassasa et al., (1984), studying the rheological behaviour, sedimentation stability, and electrophoretic mobility of four bituminous coals in water and in solutions of simple well-characterized surfactants, observed that slurry rheology and stability depended on coal particle surface charge and recommended the use of the additives to improve rheological parameters. Huynh et al., (2000) measured the rheological properties of chalcopyrite slurry with chemical treatments, showing that there was an increase in repulsive electrostatic forces between particles which, in turn, reduced the slurry viscosity and the solid content of the slurry was increased by over 10 wt. % for the same pumping energy input. He et al., (2004), using a cationic surfactant selected to modify fly ash particle behaviour recommended that the dispersing agents should be able to influence viscosity, pH, and be non-toxic, and biodegradable.
3. Materials and Experimental Procedures

3.1. Experimental Materials

3.1.1. Fly Ash

Fly ash samples collected from the Ennore Thermal Power Station (ETPS) located in Tamilnadu, India were used for the preparation of the slurry to investigate its rheological properties with and without the chemical reagent. About 50 kg of fresh fly ash sample was collected from the first field of storage silos in moisture proof gunny bags, tightened immediately, and transported to the laboratory for analysis. The result of physico-chemical analysis of the fly ash sample is shown in Table 1.

3.1.2. Water

Since the fly ash is to be transported through ordinary water medium in the pipelines, ordinary tap water (pH 7) was chosen for preparation of the fly ash slurry throughout this study.

3.1.3. Drag Reducing Reagents

The cationic surfactant cetyl trimethyl ammonium bromide (CTAB) (C19H42BrN; mol. wt. 364.46) (LOBA Chemie Pvt. Ltd., Mumbai, India) was selected for its eco-friendly attributes. It is less susceptible to mechanical degradation compared to that of polymers (Qi et al., 2003) and also has known potential to positively influence turbulent flow with very small parts (Ohlendorf et al., 1986). It is also least affected by Ca and Na ions present in tap water (Kawaguchi et al., 1997; Li et al., 2008). Figure 1 (a) and Table 2 presents the molecular structural diagram and physico-chemical properties of the surfactant respectively.

3.1.4. Other Reagents

For the surfactant drag-reducing additives, rod-like micelle structures are the key to produce complicated rheological fluid properties, including viscoelasticity. The counter-ion acts as a reagent to reduce ionic radius of the surfactant, deforming micellar shape from globular to rod-like micelles (Kawaguchi et al., 1997; Li et al., 2008). These rod-like micelles entangle together to bind strongly to micelle surface and facilitate the formation of large semiflexible worm like aggregates, at very low concentration (around 1 mM), which form an entangled network structure (Rehage and Hoffmann, 1991; Matras et al., 2007). These rod-like or thread like micelles can align along the flow direction in a pipeline like polymer chains and are the cause of the drag reduction ability of surfactant solutions (Qi and Zakin, 2002; Qi et al., 2003). Counter-ions can also act as catalysts for the breakdown and reformation of the entanglement points (Nguyen et al., 2006). Therefore, the counter-ion selected for this investigation was sodium salicylate (NaSal) (HOC6H4COONa) with molecular weight 160.1. Figure 1 (b) and Table 3 present the molecular structural diagram and physico-chemical properties of the counter-ion respectively.

![Molecular structure of (a) CTAB and (b) Sodium salicylate (NaSal).](image-url)
slurry and corresponding measured values of zeta potential and surface tension from the laboratory study.

3.3. Rheological Models used for this Study

There are many rheological models available to study the flow behaviour of concentrated particulate slurries. Among them, the power law model is well accepted for various applications (Chhabra and Richardson, 1999; George et al., 1984). The model is expressed as:

\[ \tau = K \gamma^n \]  

(1)

The apparent viscosity \( \eta_a \) is estimated from the power-law model as:

\[ \eta_a = \frac{\tau}{\gamma} = K(\gamma)^{n-1} \]  

(2)

Where \( \eta_a \) is the apparent viscosity (Pascal second), \( \tau \) shear stress (Pascal), \( \gamma \) shear rate (s\(^{-1}\)), \( K \) consistency coefficient of fluid (Pa/s) (the higher the value of \( K \) the more viscous the fluid), and \( n \) is the flow behaviour index, which is a measure of the degree of departure from the Newtonian fluid flow. The power law describes three flow behaviours (Lester, 1994): pseudoplastic (\( n < 1 \)) where the effective viscosity decreases with shear rate, Newtonian (\( n=1 \)) where the viscosity does not change with shear rate, and dilatants (\( n>1 \)) where the effective viscosity increases with the shear rate. This model has been used to estimate the apparent viscosity of fly ash slurries.

The data generated from the present study were fitted to a linear equation using ordinary least squares regression to determine a slope (plastic viscosity) and an intercept (yield stress), according to a Bingham model as below:

\[ \tau = \tau_0 + \eta_p \gamma \]  

(3)

Where \( \tau \) is the measured shear stress at a shear rate of \( \gamma \), \( \tau_0 \) is the yield stress, and \( \eta_p \) is the plastic viscosity. The apparent viscosity, \( \eta_a \), is typically reported as the ratio of the measured shear stress to the applied shear rate (\( \tau/\gamma \)) at a specific shear rate (Hackley and Ferraris, 2001).

3.4. Experimental Methods

Laboratory rheological data were obtained with an Anton Paar Rheometer (model Physica MCR 101) which measured the rheological properties of tested slurries by measuring shear stress at specific shear rates ranging from 25–1000 s\(^{-1}\). The rheometer consists of a motor with attached gear box system for varying the speed in steps of equal ratio. The cylindrical measuring bob is attached to a torsion bar and the concentric measuring cup can be rotated at a desired speed. Physical parameters of the measuring

### Table 2

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>% Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimum Assay value</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>Maximum limits of impurities</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Loss on drying at 105°C</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Chloride (Cl)</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>Sulphate (SO(_4))</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>Heavy metals (as Pb)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

#### 3.2. Parametric Variations and Sample Preparation

Slurry samples were prepared with 40 wt. % of fly ash with ordinary tap water. Temperature was varied from 20°C to 40°C at an interval of 5°C each by a temperature control circulator bath accurate up to ±0.5°C. The shear rates investigated varied from 25–1000 s\(^{-1}\) for each temperature. On the basis of previous studies, five different surfactant concentrations i.e. 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% of the total weight of the slurry were selected (Biswas et al., 2000; Usui et al., 2001; Li et al., 2002; Seshadri et al., 2005; Verma et al., 2008). An equal amount of a counter-ion equal to the surfactant concentration was also added to the slurry to prevent precipitation of surfactants due to the presence of Ca and Na ions in tap water (Munekata et al., 2006; Li et al., 2008). The counter-ion acts to reduce ion radius of the surfactant to deform micellar shape from globular to rod-like (Kawaguchi et al., 1997). The samples were prepared by adding the required amount of surfactant and the counter-ion to the required quantity of tap water and mixing thoroughly by a magnetic stirrer. Then the fly ash was added and kept the solution in a glass beaker. Stirring was done gently by a glass rod so as to avoid attrition of the particles.

The container was then covered tightly with aluminium foil to avoid evaporation of water as well as to enable uniform mixing of fly ash particles in the liquid medium. Tests were carried out after 1 h of sample preparation. For rheometric tests, about 19 ml of the slurry sample was poured into the measuring cup and the bob was lowered into the cup so that the free surface touched the top of the bob. Measurements were carried out as per standards (DIN EN ISO: 3219, 1993). Table 4 presents the different composition of fly ash

### Table 3

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>% Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Minimum Assay value (calculated to dried material)</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>Maximum limits of impurities</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Loss on drying at 105°C</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Chloride (Cl)</td>
<td>0.02</td>
</tr>
<tr>
<td>5</td>
<td>Sulphate (SO(_4))</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>Heavy metals (as Pb)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Fly ash (gm)</th>
<th>Surfactant (gm)</th>
<th>Counter-ion (gm)</th>
<th>Water (ml)</th>
<th>Solid Conc. ( C_w ) (by wt.)</th>
<th>Surface Tension (mN/m)</th>
<th>Zeta Potential (mV)</th>
<th>pH at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.1</td>
<td>39.0</td>
<td>0.5</td>
<td>0.5</td>
<td>60</td>
<td>40</td>
<td>33.119</td>
<td>+36.511</td>
<td>7.23</td>
</tr>
<tr>
<td>40.2</td>
<td>39.2</td>
<td>0.4</td>
<td>0.4</td>
<td>60</td>
<td>40</td>
<td>32.225</td>
<td>+35.679</td>
<td>7.33</td>
</tr>
<tr>
<td>40.3</td>
<td>39.4</td>
<td>0.3</td>
<td>0.3</td>
<td>60</td>
<td>40</td>
<td>31.645</td>
<td>+33.796</td>
<td>7.14</td>
</tr>
<tr>
<td>40.4</td>
<td>39.6</td>
<td>0.2</td>
<td>0.2</td>
<td>60</td>
<td>40</td>
<td>31.231</td>
<td>+32.678</td>
<td>7.34</td>
</tr>
<tr>
<td>40.5</td>
<td>39.8</td>
<td>0.1</td>
<td>0.1</td>
<td>60</td>
<td>40</td>
<td>33.265</td>
<td>+31.689</td>
<td>7.56</td>
</tr>
<tr>
<td>40.6</td>
<td>40.0</td>
<td>0.0</td>
<td>0.0</td>
<td>60</td>
<td>40</td>
<td>58.543</td>
<td>−25.000</td>
<td>7.40</td>
</tr>
</tbody>
</table>
tools and sensor system are presented in Table 5. In this instrument, the stationary cup, which houses the slurry, and into which the rotating bob, mounted vertically, was inserted. The shear rate was linearly increased from 25–1000 s⁻¹. The temperature was varied from 20°C to 40°C by a water bath circulator. The above temperature range was selected based on the average temperature variation during the various seasons of a year in India during which the fly ash slurry is to be transported. Shear viscosity was measured by a shear rate sweep experiment. The minimum waiting time was set at 20 s at each shear rate. The equipment was calibrated with standard Mobil oil, distilled water, Millipore water, and ordinary tap water of known viscosity. The rheological properties were determined for each sample and the reported values were the average of five measurements for each parameter.

Physical properties such as chemical composition, grain size analysis, particle size distribution, specific gravity, and specific surface area were determined following the procedures of Indian standards as per IS codes (1987). The grain size analysis of the untreated fly ash sample was carried out by Malvern particle size analyser (Mastersizer 2000 ver. 5.22, UK) laser diffraction apparatus. Zeta sizer (Nano-ZS, Malvern Instruments, UK) was used for zeta potential measurement of colloidal fly ash particles by electrophoretic mobility method. Surface tension was measured by Surface Tensiometer (Model: DCAT 11 EC, Data Physics, Germany).

4. Results and Discussion

4.1. Physical and Chemical Properties

The particle size analysis and physical and chemical properties of the untreated fly ash were determined as per standard procedure and reported (Table 1). About 88% of the fly ash particles are in the size range between 1 μm and 50 μm that possesses good gradational properties as per ASTM D422 63, (1994). The pH measurements were carried out as per the procedure outlined by Jackson (1958) at room temperature (25°C). The pH of the raw fly ash was 7.3 and did not change much after addition of the additives. This might be due to the non-toxic, bio-degradable, and non-reactive nature of the additive which was added to the slurry (Roi et al., 2004).

The fly ash consists of particles with diameters ranging from 0.02 μm to 2000 μm with D₁₀=3.8 μm, D₉₀=988.5 μm, and d₅₀ value of 11.2 μm (Figure 2.a). The size distribution of fly ash has a

![Fig. 2. a. Particle size distribution curve, b. SEM photomicrograph of untreated fly ash.](image-url)
fundamental bearing on their surface modification by an additive. The $D_{60}$ value of the fly ash sample was determined from the particle size distribution curve and the coefficient of uniformity ($C_u = D_{60} / D_{10}$) is found to be 14.8. The fly ash sample is well graded as per the classification and gradation of soils (ASTM D-2487, 1998), as $C_u > 6$. The SEM study showed the fly ash particles are round in shape which will help in smooth flow of particles in the hydraulic pipelines due to the well-known ball-bearing phenomena (Figure 2.b).

4.2. Influence of Surfactant on Slurry Rheology

Fly ash slurries exhibit strong flocculation behaviour in absence of chemical additives (Struble and Sun, 1995; Bentz, 2007). A yield stress is needed to break down this flocculated structure into smaller flocs or individual particles to induce flow. Slurries prepared with only the original fly ash and water exhibited excessive settlement and bleeding and a very low yield stress value. The rheological parameters, namely

---

**Fig. 1.** Rheogram of fly ash slurry without additive.

**Fig. 4.** Rheogram of fly ash slurry with 0.1% additive.
yield stress and plastic viscosity, were calculated from the measured shear stress–shear rate curves for each of the mixtures.

Figure 3(a) shows the relationship between shear stress and shear rate rheogram at 40°C for fly ash slurry at 40% solid concentration without any additive at shear rates varying from 25–1000 s⁻¹. Maximum shear rate observed was 600 s⁻¹, confirming observations reported by Shah and Jeong (2003). Figure 3(b) shows the shear stress–shear rate relationship without any additive at varying temperature. Slurry rheological parameters fit well to Bingham model with positive values of yield stress, whereas, addition of the surfactant to fly ash slurry completely eliminated the yield stress (Figures 4–5 a, b, c, d).

Therefore, the influence of the surfactant eliminated the yield stress of the slurries rather than the viscosity which compares favourably with the results obtained by Jones and Chandler (1989). The yield stress increased exponentially as the temperature increased from 20°C to 40°C at an interval of 5°C each for the fly ash slurry without any additive (Figure 6). Viscosity decreased as the shear rate increased for slurry without additive (Figure 7). The viscosity increased as the temperature was increased from 20°C to 40°C at an incremental value of 5°C each for slurry without additive (Figure 8). When the surfactant was added to the slurry the rheological properties changed drastically (Figure 9), the viscosity decreasing substantially as the temperature increased.

![Fig. 5. Rheogram of fly ash slurry with (a) 0.2%, (b) 0.3%, (c) 0.4%, and (d) 0.5% additive.](image1)

![Fig. 6. Yield stress vs. Temperature plot of fly ash slurry without additive.](image2)
was increased from 20°C to 40°C. These results compare favourably with the observations made by Shenoy (1976). This phenomenon is due to the formation of spherical micelles which grow continually in size with the increase of temperature until at the cloud point when they can no longer grow and phase separation occurs; this occurs only in relatively dilute surfactant solutions (Shenoy, 1976).

4.3. Influence of Surfactant on Shear Viscosity

At very low shear rates, from 25–50 s⁻¹, the slurry exhibited inconsistent results, because a minimum value of shear rate is required to start the flow. Figure 10 shows the shear viscosity of fly ash slurries with additive concentration ranging from 0.2% to 0.5% (by weight) at varying temperatures. Shear viscosity decreased sharply from 20°C to 40°C, with the shear rates varying from 25–1000 s⁻¹ for the entire additive ranges tested. Shear thinning behaviour, a favourable property for pipeline transport, was observed at 20°C and 25°C for all the slurries tested. The viscosity values of the slurries were nearly constant for the shear rates varying from 50–1000 s⁻¹ at 30°C, 35°C, and 40°C, confirming that the slurry showed Newtonian flow behaviour. In this case, the material would flow smoothly in pipelines. Best results are
obtained at 35°C and 40°C with additive concentration of 0.4% and 0.5% (Figure 10).

4.4. Surface Tension

Surface tensions of the six fly ash slurries with and without an additive were measured with a Surface Tensiometer (Model: DCAT 11 EC, Data Physics, Germany). The addition of surfactant reduced surface tension of fly ash slurries by 43% to 47% compared to untreated slurry and by 52% to 55% compared to plain tap water (Table 4). The surfactants facilitated easier spreading, leading to lower the interfacial tension between solid particles and the liquid.

4.5. Zeta Potential

The zeta potential of all the slurries was measured by using electrophoretic technique by Zeta Sizer-Nano Series (Malvern Instruments, UK). Zeta potential value of the untreated fly ash slurry was $-25\ \text{mV}$ at pH 7.4, increasing $\left(> +31\ \text{mV}\right)$ when the surfactant was added to the slurry (Table 4). From these results, it is...
confirmed that the fly ash slurry suspension is stable and the fly ash particles would repel each other and, therefore, flocculation would be prevented and dispersion achieved, facilitating smooth flow and reducing clogging.

5. Conclusions

Both yield stress and viscosity (apparent or plastic) strongly depends on the particle characteristics of the powders employed in preparing fly ash slurry with a constant volume fraction of water. As the yield stress is dominated by the characteristics of the fly ash particles, the additive acts as diluents, effectively decreasing the fly ash particle number density. The test results clearly indicated that the fly ash-water slurry rheology is strongly influenced by the chemical additives. The presence of elements such as iron oxide, aluminium oxide, and other alkaline earth materials in the fly ash slurry gives rise to adverse rheological properties, and these effects were negated by the addition of a surfactant (CTAB) that formed charged complexes with the fly ash particles. All the treated slurries exhibited shear-thinning and Newtonian properties. The surfactant modified the surface properties of the fly ash particles to improve its suspension stability. Another important conclusion derived from this study that the surface tension of the treated fly ash slurry is reduced compared to untreated fly ash slurry and that of the suspending medium (water). This implies that fly ash has greater potential to be transported in pipelines with the addition of a cationic surfactant and a counter-ion which will reduce specific energy consumption and water requirements. The flow properties and viscosity of the fly ash water suspensions were sensitive to the use of chemical additives.

Acknowledgments

The authors are grateful to the Ministry of Science and Technology, Department of Science and Technology, Government of India for its financial support under R & D project No: FAU/DST/600(19)/2008-09 dated 30.03.2009.

References


