Evaluation of Flow Characteristics of Fly Ash Slurry at 40% Solid Concentration with and without an Additive

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ABSTRACT

In India, about 75% of total electrical energy is generated from thermal power plants which in turn release about 130 million tones 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 being transported as lean slurry in pipe lines requiring about 80 to 85% of water with more energy input. The objective of the present study was to evaluate the rheological characteristics of fly ash slurry with and without an additive at varying temperature environment to facilitate smooth flow of materials in the pipeline. To achieve the objectives, six number of fly ash slurry samples were prepared from the fly ash obtained from a power station situated in the southern part of India. 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 100 to 1000s^{-1} for 40% solid concentration. Temperature was varied from 20^0C to 40^0C for all the shear rates investigated. Test results showed that all the slurries exhibited Newtonian properties of shear-thinning behavior in the presence of an additive. The influence of cationic tenside on drag reduction of fly ash slurry was also studied. The distinctive reduction of surface tension on colloidal disperse characteristics of the slurry was observed in the presence of the tenside. The study revealed that the slurry developed in the above manner has a potential to be transported through pipelines with minimal energy consumption.

1. Introduction

Fly ash is produced in large quantities in India (about 130 million tons per annum) from the thermal power stations situated across the country.[1] There are numerous successful case histories on the utilization of fly ash either alone or mixed with lime, gypsum or both.[2] In spite of efforts made by Government agencies and fly ash producers the fly ash utilization level has reached up to about 40 to 45% only. With increasing generation of fly ash, efforts are being made to transport it through pipelines. But it becomes complex due to 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.[3,4] 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.[5] Certain additives enable the slurries to be pumped at much higher concentration of solids, thus reducing the 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.[6,7,8,9] Fly ash slurries consist largely of silica with varying amounts of other materials as aluminum, iron, and alkaline earth materials. The presence of these materials introduces drag effects on the flow behavior of slurry.[10] Hydraulic pipelines are used widely to transport solid particulate materials using water or any other liquid as the carrier fluid. These pipelines are used either for long distance transportation of bulk materials, like mineral ore to processing plants, coal to power stations or for disposal of waste material like fly ash, mill tailings etc. Hydraulic pipelines today have also been accepted by various industries as an attractive mode of solid waste transportation within the plant and outside because of its low maintenance cost, round the year availability and being environment-friendly. In power stations, these pipelines are used prevalently for disposal of fly ash/bed ash/bottom ash to ash pond area. In India alone, approximately 130 million tones of fly ash are transported every year to disposal sites by pipelines at various power stations situated across the country.[1] However, these pipe lines carry lean slurry concentration with fly ash to water ratio at about 1:20. Therefore huge quantity of water is transported to the disposal site requiring vast stretch of valuable land area. In India about 65,000 acres of cultivable land is lying under the ash ponds. The transported water drains away from the ash pond area which in turn contaminates the surface water and ground water regime downstream. The presence of solid particles leads to drastic changes in the flow patterns, which in turn affects the pressure drop considerably across the pipeline. Fine particulate slurries generally show non-Newtonian flow behavior for concentrations above 40% by weight.[6] Coarse particulate slurries require high operating velocities for transportation resulting in higher specific energy consumption per unit solid throughput. On the other hand transportation of non-settling solids would result in lower energy consumption and better operational conditions. A surfactant is chosen for this investigation and added to the fly ash slurry to keep the solid particles water borne in the suspension during its transportation in hydraulic pipelines. These agents when added to a liquid, reduces its surface tension, thereby increasing its spreading and wetting properties. These aqueous solutions can even reduce up to 80% of the drag in a turbulent straight pipe flow in a wide range of temperature environment.[11] Many researchers have investigated the characteristics of such a dilute surfactant solution, but limited studies are reported about the use of these agents for the transportation of fly ash slurry in the pipe lines. In the present study, an attempt has been made to evaluate the flow properties of the fly ash slurry with and without an additive.

2. Background of the study

The surface nature of fly ash particles is very important in the preparation of high solid/ liquid ratio fly ash-water suspensions. In this investigation a cationic surfactant namely cetyltrimethyl ammonium bromide (CTAB) was used along with a counter-ion sodium salicylate (NaSal) to study the flow properties of fly ash slurry. By proper selection of a surfactant and treatment of fly ash powders, the authors obtained a high solid concentration, up to 40% by weight of the fly ash-water suspensions in the present study. The authors in their earlier investigations reported the results of 20% and 30% solid concentration showing positive improvement in the flow properties.[12, 13] Seshadri and co-authors[12] also studied the effect of sodium hexametaphosphate as a dispersing agent on rheology of fly ash water slurries. Encouraging results were obtained at a dispersant dosage less than 1 wt. % of the solids. Nigle and Neil reported that reducing friction in non-settling slurry pipe flow is obtained by reducing the viscosity of the slurry by adding suitable chemicals and additives.[14] In their work, the effects of different chemical additives have been studied on a number of mineral slurries including drilling mud slurries (using sodium acid pyrophosphate and sodium hexametaphosphate), phosphate rock slurries (using caustic soda), limestone cement feed slurries (using a combination of sodium tripolyphosphate and sodium carbonate). Their work was aimed at to reduce the viscosity of the investigated slurries to facilitate long-distance pumping and reducing energy requirements. Boylu and co-authors[15] studied the effect of caboxymethyl cellulose (CMC) on the stability of the coal water slurry using different coal ranks. The results depicted that polymeric anionic CMC agent has higher effect on the stability of coal-water slurry, in particular, that prepared from bituminous coal. Cassasa and co-authors[16] also studied the rheological behavior, sedimentation stability and electrophoretic mobility of four bituminous coals in water and in solutions of simple well-characterized surfactants. It was found from their study that slurry rheology and stability depend on coal particle surface charge. It was claimed that additives may be chosen to modify the surface charge and hence improve slurry rheology. Huynh and co-authors[17] illustrated the effect of dispersants on the rheological properties of copper concentrate slurries. Mingzhao and co-authors[18] reported some guidelines in selecting dispersants in order to have suitable chemically controlled viscosity. The guidelines include : (a) dispersant must be absorbed by enough solid surfaces to affect slurry viscosity, (b) slurry viscosity must be as high that the utilization of the dispersant can help reducing or control slurry viscosity, (c) dispersant must be consistent in its ability to decrease viscosity as a function of changing dispersant concentration, pH value and water quality, (d) dispersant must be nontoxic and degradable, and (e) dispersant must not adversely affect or contaminate downstream operations. Keeping the above literature in mind we have chosen a cationic surfactant to modify the surface charge of fly ash particles so that they can remain water borne while being transported in pipelines which in turn can modify the flow properties of fly ash water suspensions.

3. Rheological models

There are many rheological models available to study the flow behavior of concentrated particulate slurries. Among them, the power law model has a wider application. The model can be mathematically expressed as given below:

$$\tau = K\, r^{n} \;\ldots\ldots.\; (1)$$

The apparent viscosity can be estimated from the power-law model as

$$\mu a = \frac{\gamma}{r} = K(r)^{n-1} \;\ldots\;\ldots.\,(2)$$

Where μ_a is the apparent viscosity (poise), γ shear stress (dyne/ cm^2), r 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 behavior index, which is a measure of the degree of departure from the Newtonian fluid flow. Lester[19] reported that the power law describes three flow behaviors. These behaviors include pseudoplastic ($n < 1.0$) – the effective viscosity decreases with shear rate, Newtonian ($n=1.0$) – the viscosity does not change with shear rate and dilatants ($n>1.0$) - the effective viscosity increases with the shear rate. This model was selected and applied throughout this work to estimate the apparent viscosity of fly ash slurries.

3. Experimental Work

3.1 Material and methods

3.1.1 Fly ash

The material used in this study was lignite fly ash. It was obtained directly from the hoppers of Ennore Thermal Power Station, Tamilnadu, India. The physico-chemical analysis of the sample is shown in Table-1.

Table 1.Physical and chemical properties of fly ash sample

<table>
<tr><td>Sample</td><td>Specific Gravity</td><td colspan="2">Specific surface area (m^2/g)</td><td colspan="2">Moisture content (%)</td><td colspan="2">Wet density (gram/cc)</td><td>Turbidity (NTU)</td><td>pH</td></tr>
<tr><td rowspan="4">Fly Ash</td><td>2.20</td><td colspan="2">1.240</td><td colspan="2">0.200</td><td colspan="2">1.75</td><td>459</td><td>7.3</td></tr>
<tr><td colspan="9">Chemical Composition, Elements (weight %)</td></tr>
<tr><td>SiO_2</td><td>Al_2O_3</td><td>Fe_2O_3</td><td>CaO</td><td>K_2O</td><td>TiO_2</td><td>Na_2O</td><td colspan="2">MgO</td></tr>
<tr><td>56.77</td><td>31.83</td><td>2.82</td><td>0.78</td><td>1.96</td><td>2.77</td><td>0.68</td><td colspan="2">2.39</td></tr>
</table>

3.1.2 Reagents

Additives used in this study namely, cetyltrimethyl ammonium bromide (CTAB) – a cationic surfactant which is a well known drag reducing and dispersing agent along with a counter-ion. The counter-ion used in this study was NaSal.

3.2 Fly ash-water slurry (FWS) preparation

The solid concentration was kept constant at 40% solids by weight through all the tests. The procedure of preparation of the fly ash water suspensions was standardized for all tested samples. Weighed amount of tap water was transferred into a 500cm^3 glass beaker, and then the weighed fly ash sample was slowly transferred into the beaker. The contents were stirred by magnetic stirrer for about 20-30 minutes after adding the entire fly ash sample. The fly ash water suspension was then allowed to stand in the beaker for about 10 minutes to ensure release of entrapped air. Before testing, the slurries were always thoroughly mixed by hand shaking and stirring to ensure homogeneity of the slurry. The same procedure was repeated with different test conditions. The dosages of CTAB and NaSal ranged from 0.1 to 0.5 wt. % of solids. The selected additives were prepared in the predetermined ratio and dissolved in a little amount of water before adding them to the fly ash slurry. Table 2 shows the sample ID, parametric variations and suspension characteristic features.

Table 2.Sample ID, Parametric variations and suspension characteristics

Sample ID	Fly ash (gram)	Surfactant (gm)	Counter-ion (gm)	Water (ml)	Solid Conc. C_w (by wt.)
40.1	39.0	0.5	0.5	60	40
40.2	39.2	0.4	0.4	60	40
40.3	39.4	0.3	0.3	60	40
40.4	39.6	0.2	0.2	60	40
40.5	39.8	0.1	0.1	60	40
40.6	40.0	0.0	0.0	60	40

4. Rheological measurements

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 25s^{-1} to 1000s^{-1}. It is considered as a concentric cylindrical rotational rheometer with a wide shear rate range, i.e., from 0-1000 s^{-1}. The temperature was varied from 20^{0}C to 40^{0}C by a water bath circulator. The physical parameters for the rheometer measuring system are given in Table-3.

Table-3: Physical parameters of the sensor system for the Anton Paar Rheometer

Measuring system	Rotor Radius, R_i, mm	Cup radius, R_a, mm	Ra/ Ri	Measuring Gap, mm
CC 27	13.332	14.461	1.0846835	1.129

5. Results and Discussion

5.1 Effect of surfactant on slurry rheology

Figures (1-7) illustrates the relationship between shear stress and shear rate at 40% solids by wt. using different dosages of surfactant which is a dispersing and drag reducing agent. The surfactant dosage was expressed as percentage of total solids. It can be seen that the shear stress decreases with the increase in the amount of surfactant and then increases with increasing surfactant concentration from 0.3% to 0.5% wt. of solids. The best surfactant dosage is 0.3% as it gives the lowest shear stress at all studied shear rates. Increasing the dosage of dispersant beyond this value does not lead to an improvement in flow properties of considered slurries. Figure 5 illustrates the relationship between shear stress and shear rate at 40% solids by wt. using different dosages of surfactant at varying temperature environment. It can be seen that shear thinning behavior is observed at 20^{0}C, 25^{0}C and 30^{0}C which is a desirable feature for any slurry pipeline system. The comparison between the use of surfactant at 0.1% to 0.5% concentration and at different shear rates was carried out. As it is observed from the figures, the type of additive is an important factor affecting the rheological properties of the slurry. It is shown that the use of CTAB is better because the slurry becomes less viscous at all studied shear rates.

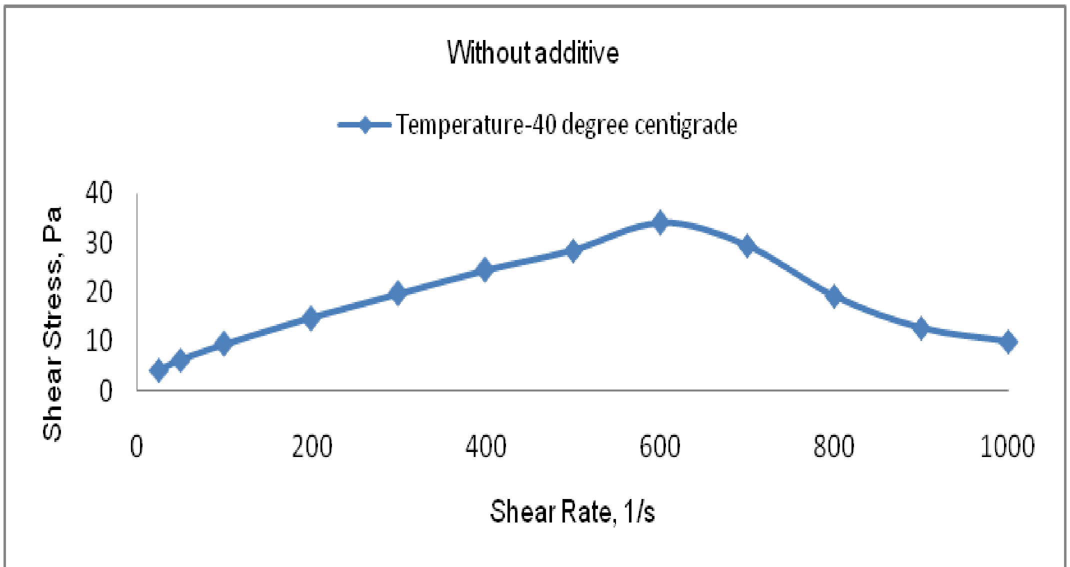

Figure 1. Rheogram of fly ash slurry at 40^0 C without additive

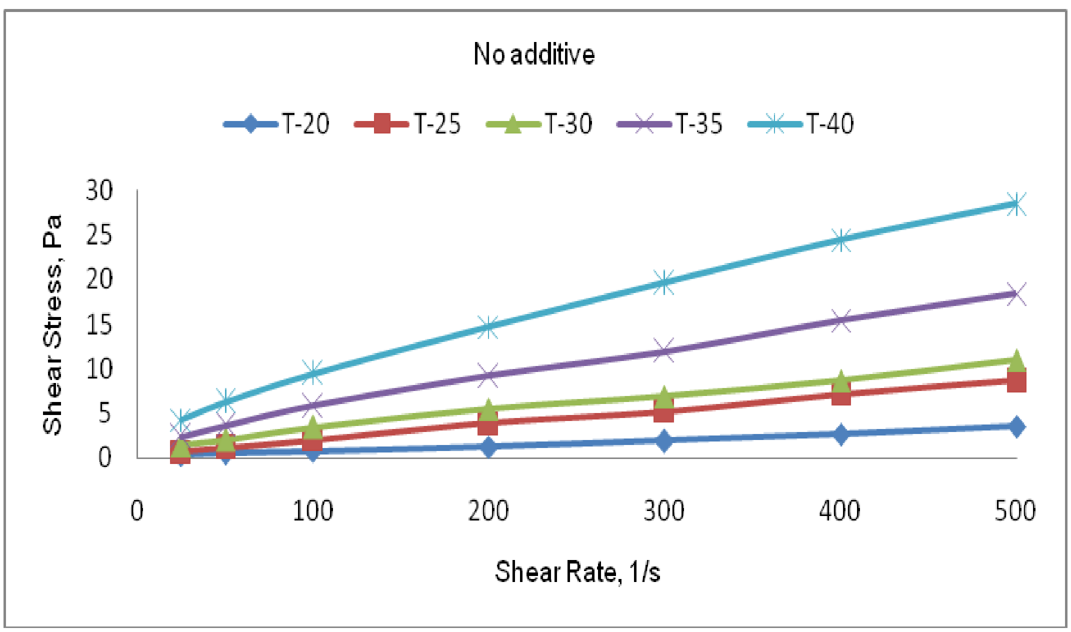

Figure 2. Rheogram of fly ash slurry without additive

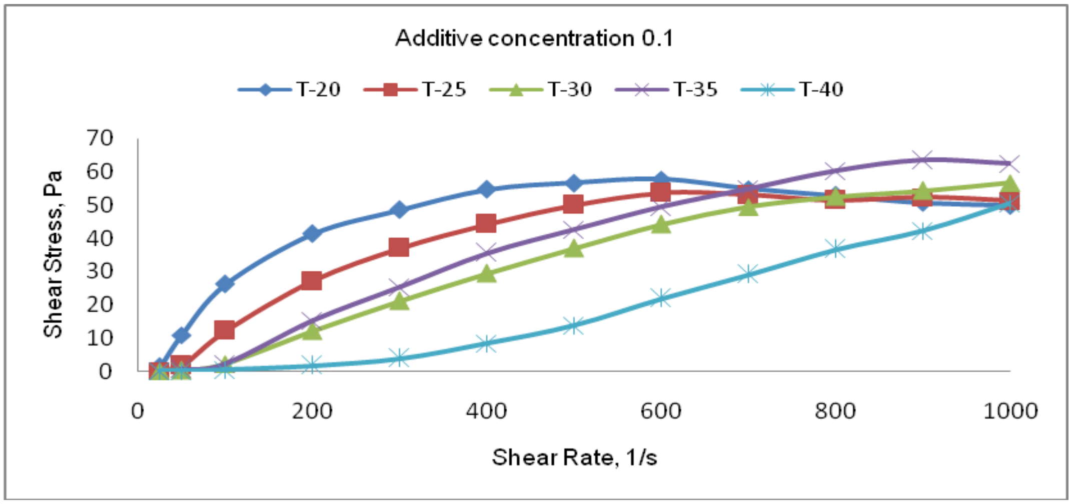

Figure 3. Rheogram of fly ash slurry with 0.1% additive

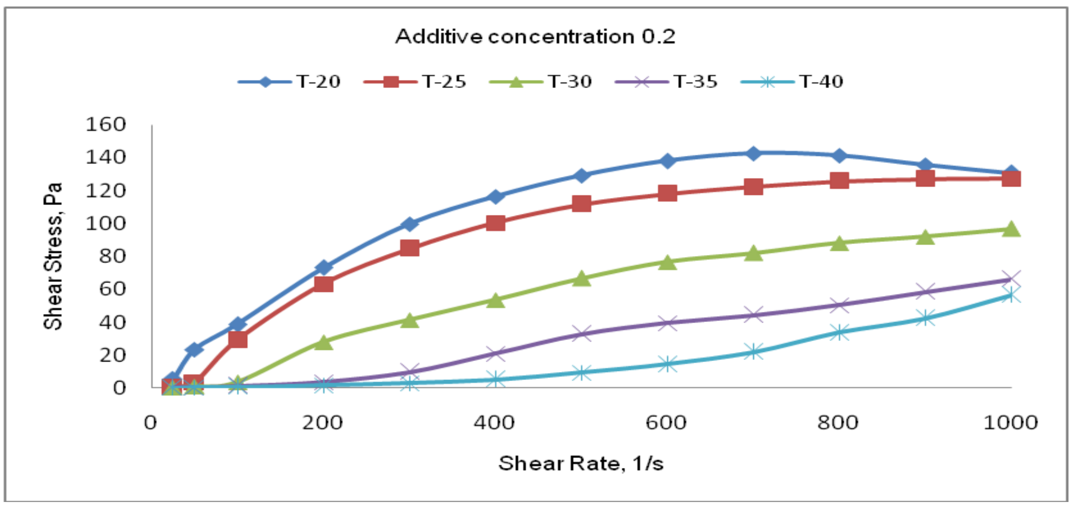

Figure 4. Rheogram of fly ash slurry with 0.2% additive

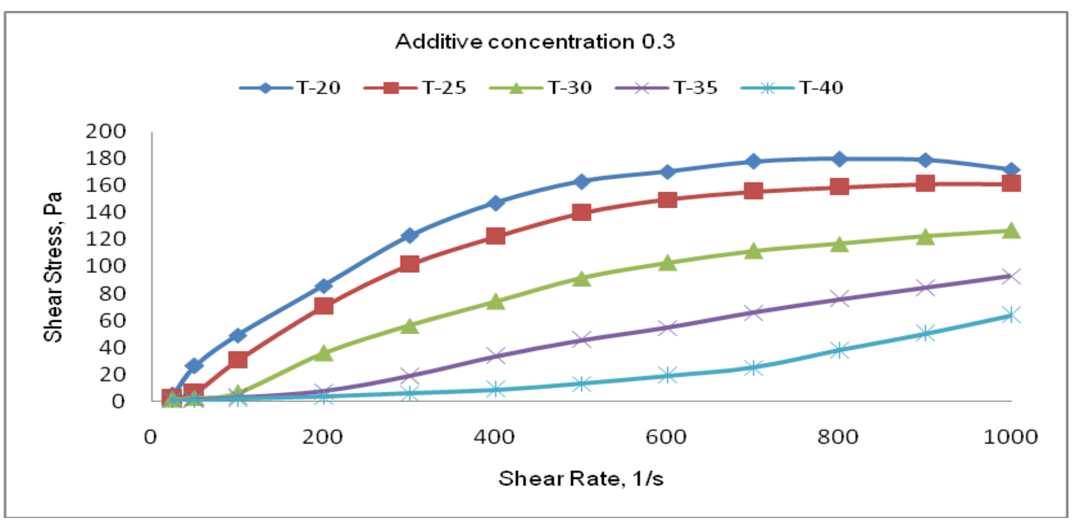

Figure 5. Rheogram of fly ash slurry with 0.3% additive

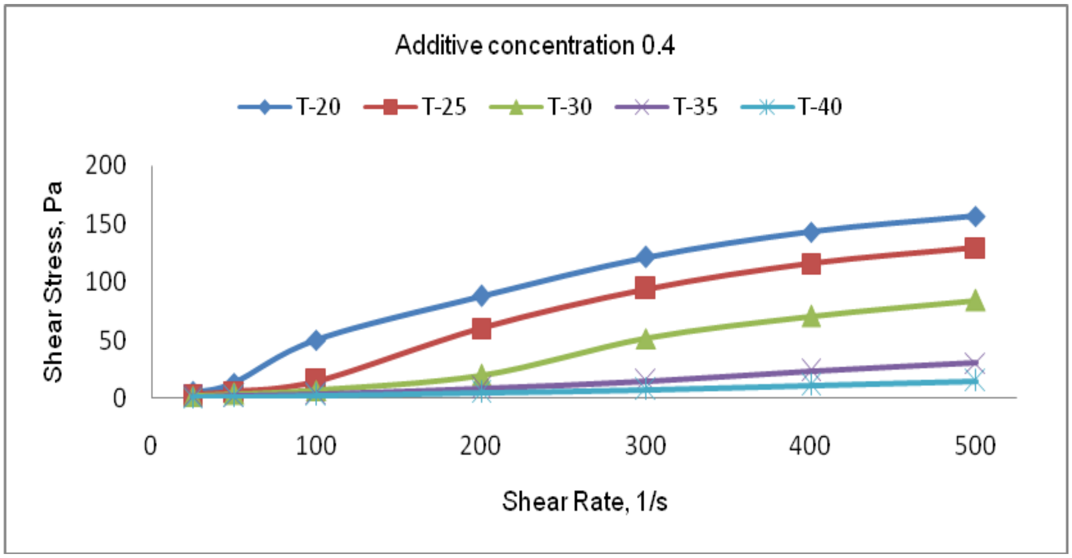

Figure 6. Rheogram of fly ash slurry with 0.4% additive

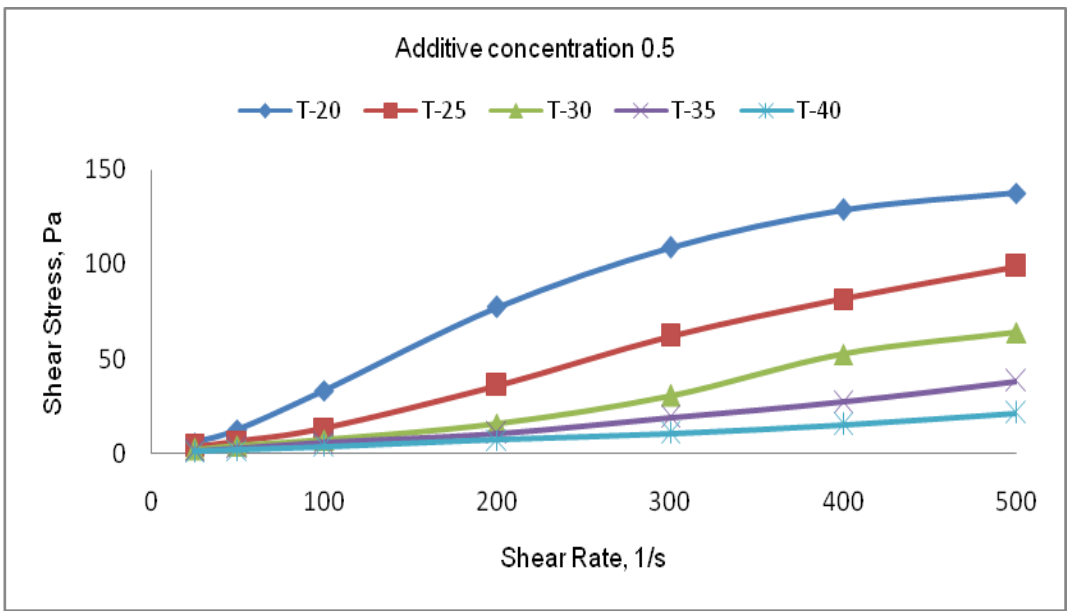

Figure 7. Rheogram of fly ash slurry with 0.5% additive

5.2 Viscosity of fly ash slurry

In this study, flow properties of fly ash slurry samples in the presence and absence of chemical additives were also investigated. The applied dispersant was CTAB at 0.1 to 0.5% wt. of solids. The mentioned counter-ion was used at same concentration as that of the surfactant. The results are presented in Figures (8-14). It is clear that the surfactant addition is an important factor for improving the rheological properties of the fly ash slurry.

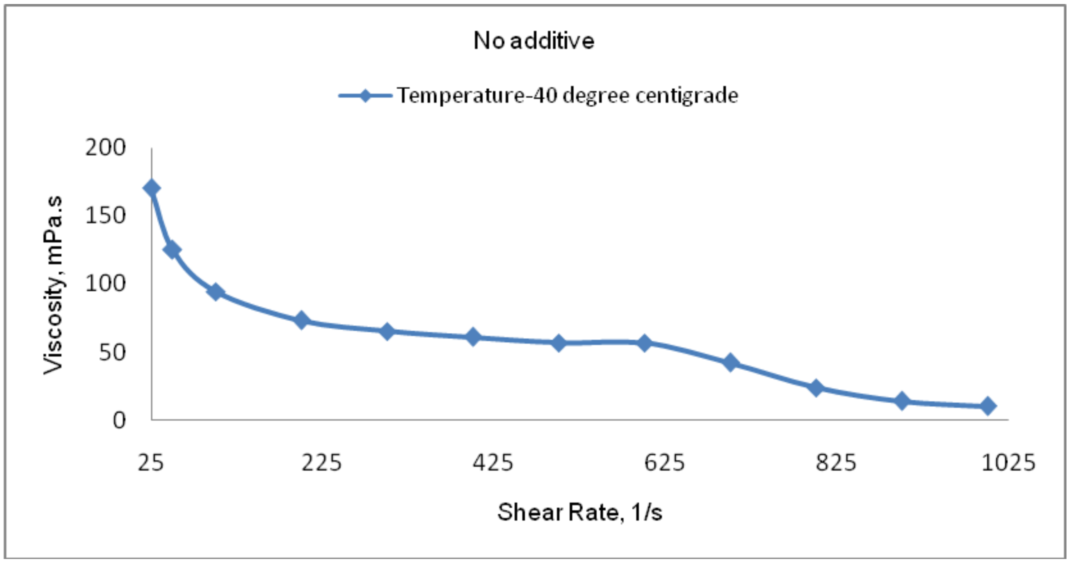

Figure 8. Flow curve of fly ash slurry without additive

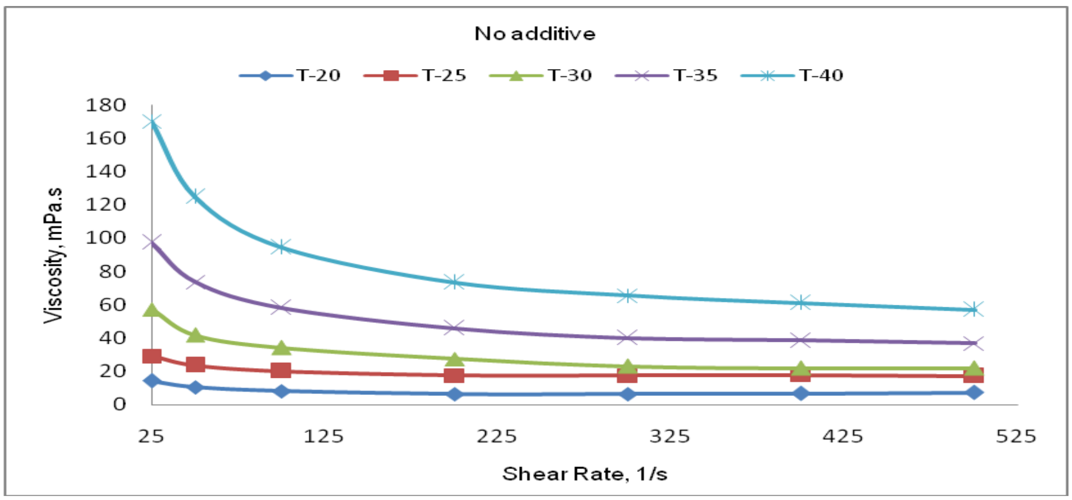

Figure 9. Flow curve of fly ash slurry without additive

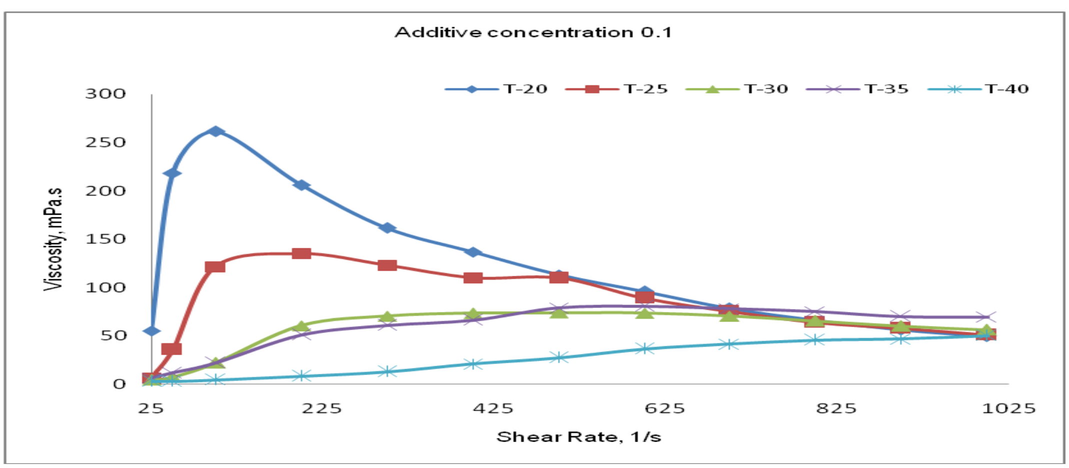

Figure 10. Flow curve of fly ash slurry with 0.1% additive

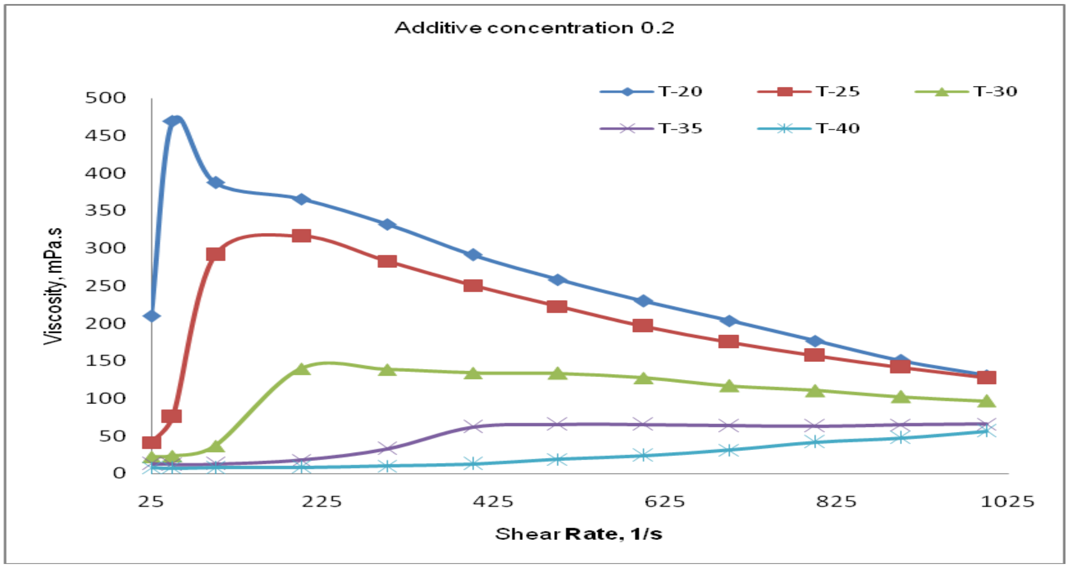

Figure 11. Flow curve of fly ash slurry with 0.2% additive

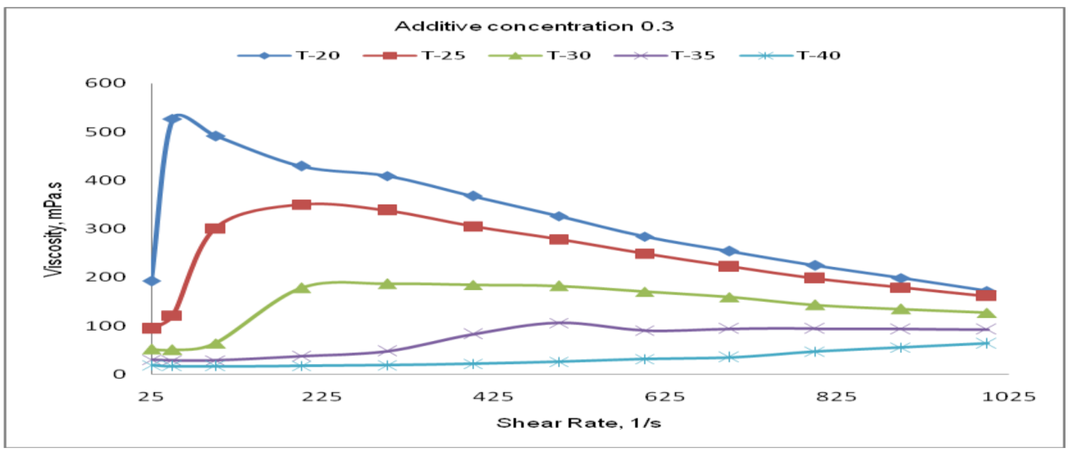

Figure 12. Flow curve of fly ash slurry with 0.3% additive

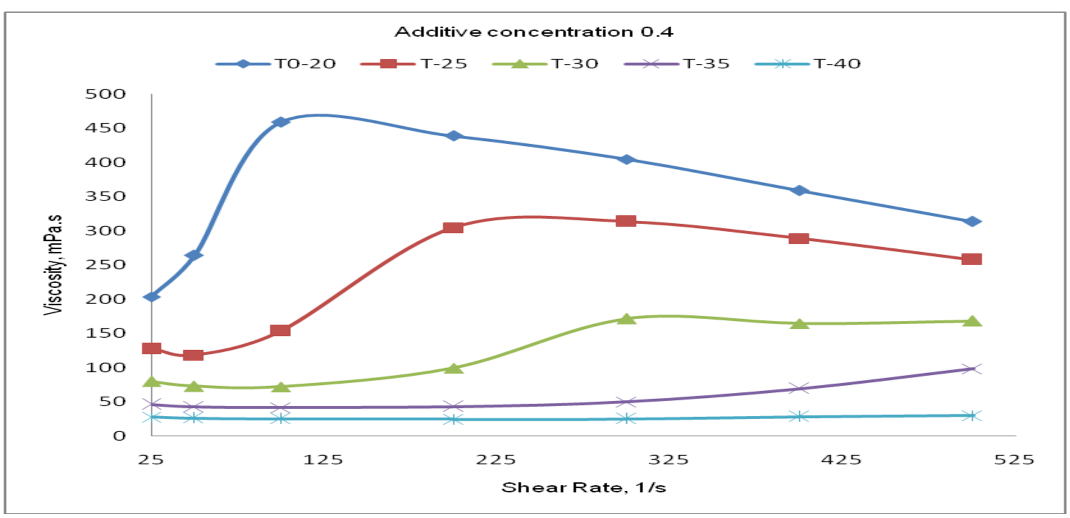

Figure 13. Flow curve of fly ash slurry with 0.4% additive

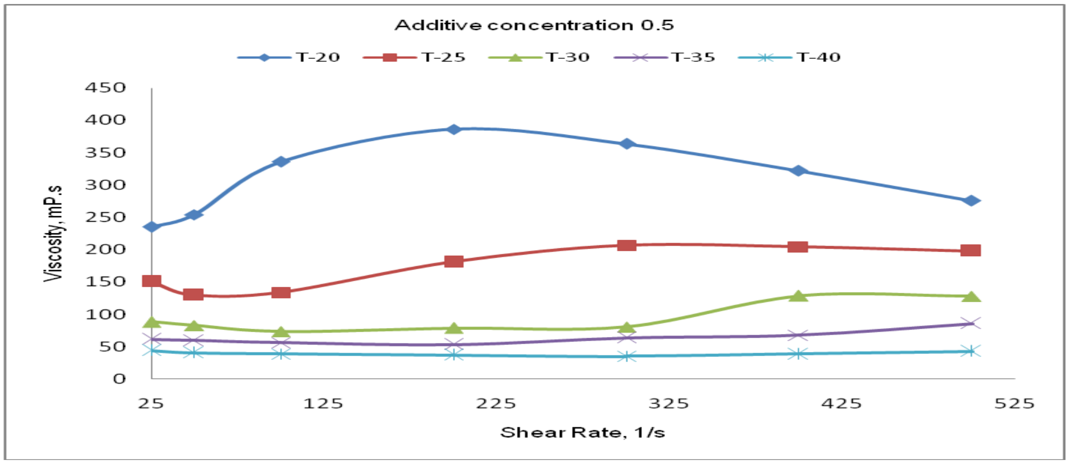

Figure 14. Flow curve of fly ash slurry with 0.5% additive

5.3 Effect of temperature on slurry viscosity

Generally, particulate slurries exhibit non-Newtonian flow behavior because of the inter-particle forces that act between the particles in these chemically complex systems. Various chemical treatments are used to alter the surface chemistry and then the interactions between particles within the slurry. It is expected that the surface chemistry of particles affect rheological behavior of the slurry to a great extent. These surface forces arise from chemistry of solid-solution interface and dominate the interaction between neighboring particles. Hence the surface species will dictate the inter-particle forces between fly ash particles in the slurry. When the electrostatic repulsive forces between the particles are weak and insufficient, the aggregation of the particles occurs and the result is aggregated slurry with increase in rheological parameters. However, when the electrostatic repulsion between particles are sufficient to prevent the Van der Waals attractive forces from operation, a well dispersed slurry with reduced rheological parameters is obtained. Such surface forces depend on adsorption of reagent ions on solid surfaces which, in turn, depend on slurry pH. Figures (15-21) depicts the flow behavior with and without an additive at varying temperature environment.

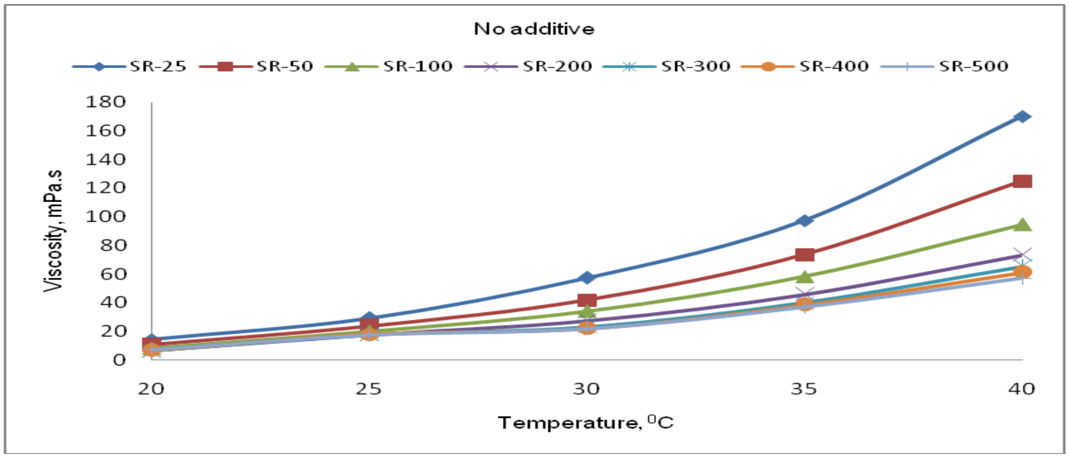

Figure 15. Viscosity vs. Temperature plot of fly ash slurry without additive

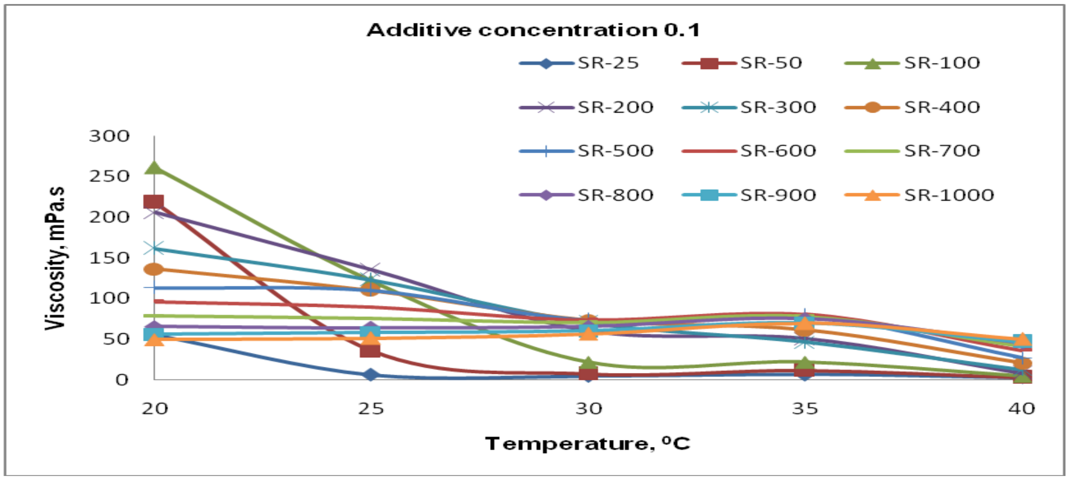

Figure 16. Viscosity vs. Temperature plot of fly ash slurry with 0.1% additive

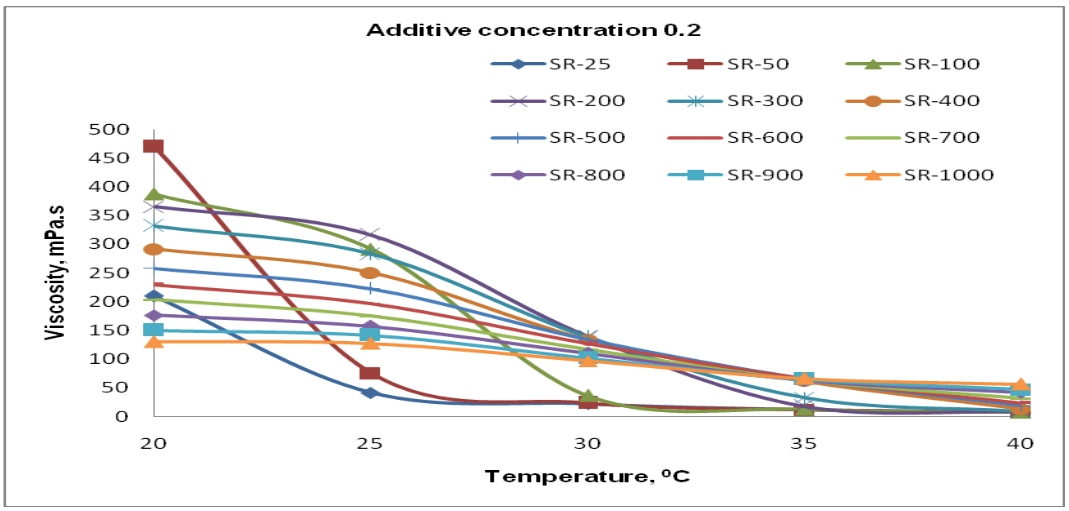

Figure 17. Viscosity vs. Temperature plot of fly ash slurry with 0.2% additive

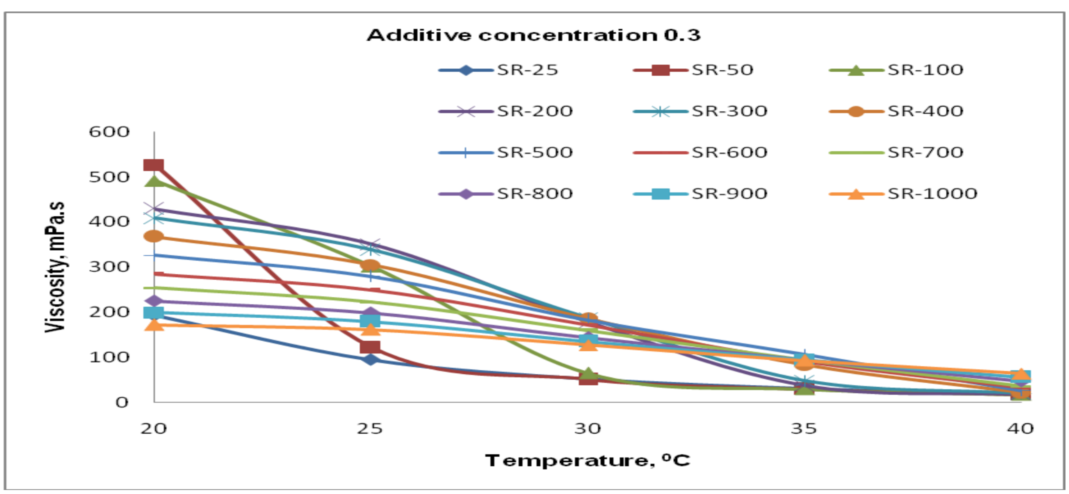

Figure 18. Viscosity vs. Temperature plot of fly ash slurry with 0.3% additive

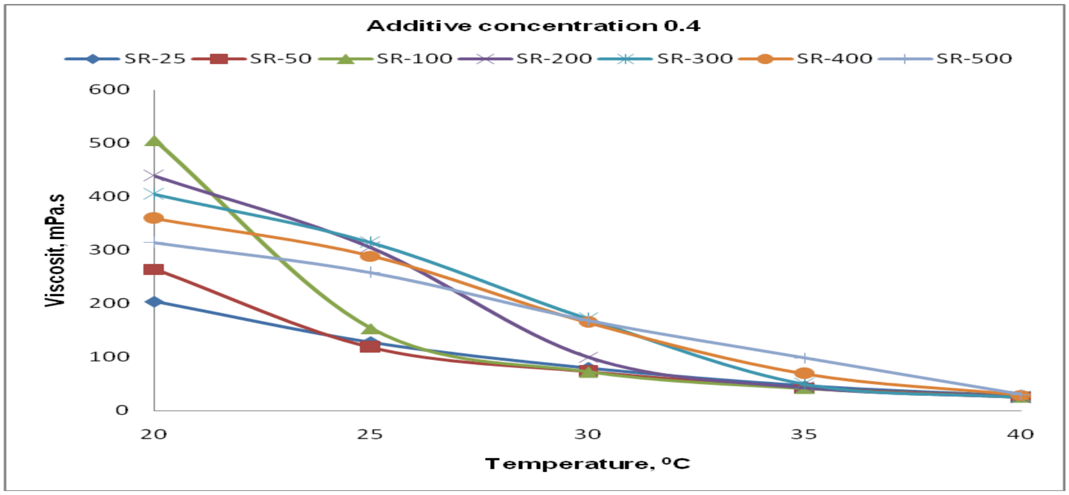

Figure 19. Viscosity vs. Temperature plot of fly ash slurry with 0.4% additive

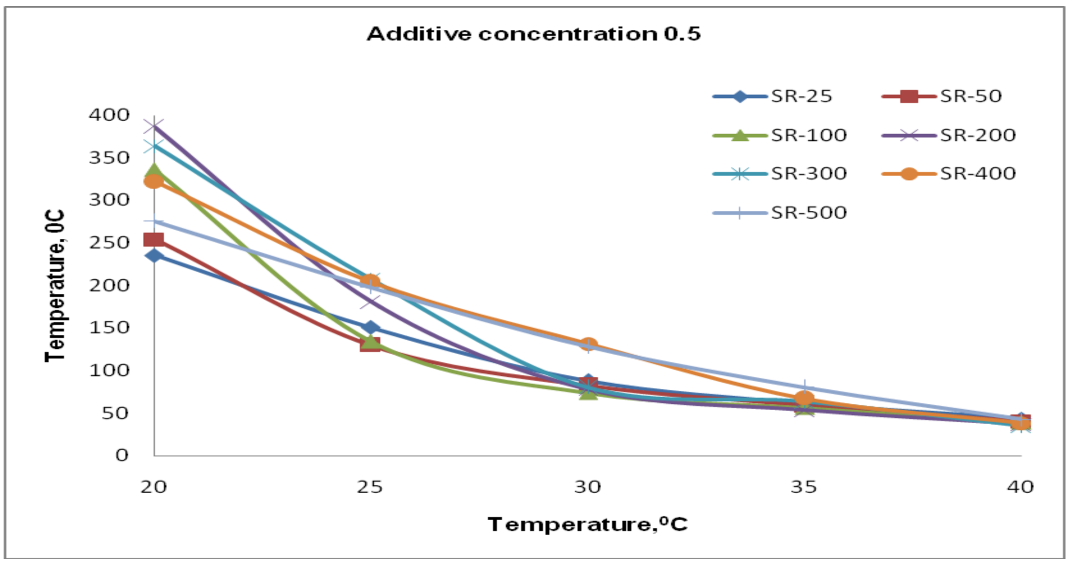

Figure 20. Viscosity vs. Temperature plot of fly ash slurry with 0.5% additive

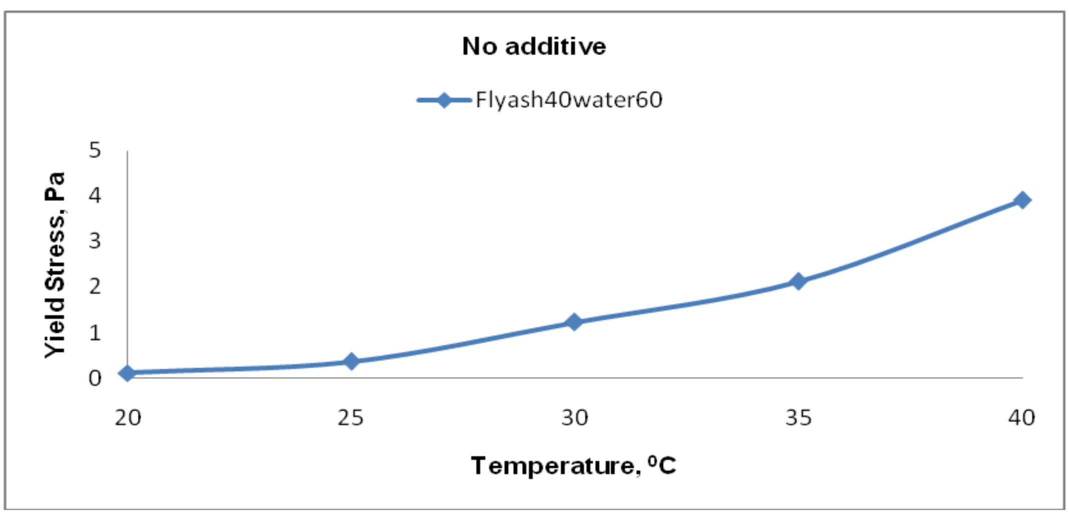

Figure 21. Yield stress vs. Temperature plot of fly ash slurry without additive

6. Conclusion

The test results clearly indicate that the fly ash-water slurry rheology depends on chemical additives. The presence of elements such as iron oxide, aluminum oxide and other 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. The untreated fly ash slurry exhibited turbulent flow behavior where as by addition of the surfactant to the slurry the rheological characteristics were improved. All the treated slurries exhibited shear-thinning and Newtonian properties. The surfactant also modified the surface properties of the fly ash particles and suspension stability of the slurry was improved. Another important conclusion from this study is 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) which implies that fly ash has got 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. It was found that the flow properties and viscosity of the fly ash water suspensions are very sensitive to the use of chemical additives. Using a dispersing agent is very important as it reduces the viscosity of the slurry.

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