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Brief note

RHEOLOGICAL BEHAVIOR OF FLY ASH SUSPENSION WITH ADDITIVE FOR HYDRAULIC CONVEYANCE

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In the present work, rheological behaviour of a fine particulate fly ash slurry suspension is studied with and without addition of an additive. Rheological experiments are performed for the range of shear rate from *50* to *200* s^1. Sodium sulfate is used as an additive in the fraction of *0.2*, *0.4* and *0.6*% (by weight). Addition of sodium sulfate to the fly ash slurry suspension leads to an improvement of its rheological characteristics. A reduction in relative viscosity and pressure drop is more pronounced with the addition of sodium sulfate in proportion of *0.4*%, while marginal with *0.2* and *0.6*% (by weight). The analysis reveals that the fly ash suspension has a potential to for being transported in a slurry pipeline with higher concentration and minimum energy consumption.

Key words: fly ash, rheology, relative viscosity, pressure drop, energy consumption.

1. Introduction

Coal based Indian thermal power plants produce about 135 million tonnes of fly ash annually [1]. The slurry pipelines are used for the transportation of fly ash slurry suspension as a lean concentration from the generation unit to a disposal area. During the transportation of fly ash a large amount of water and pumping power is required [2-5]. So, an adequate design of the slurry transportation system is needed. Rheological behaviour of slurry suspension plays a vital role in the design of its transportation system [5, 6]. Many researchers have studied the rheological behavior of ash slurry suspensions [7-14]. Researchers reported that addition of an additive improves rheological characteristics of the coal ash slurry [13-17]. However, limited data base is available to predict rheological behaviour of the fly ash suspension with and without an additive. In the present investigation, the rheological behaviour of fly ash slurry was studied with and without an additive. Sodium sulfate is used as an additive in proportion of *0.2*, *0.4* and *0.6* (% by weight). On the basis of the study, an effort has been made to study the possibility of transporting the fly ash slurry suspension at higher concentration with minimum power consumptions.

2. Material and methods

2.1. Characterization of fly ash

A fly ash sample was collected from an electrostatic precipitator (ESP) of Rajiv Gandhi thermal power plant Hisar (India). A number of laboratory scale tests were conducted to analyze the physio-chemical characteristics of the fly ash sample. A mechanical sieve shaker with standard sieves was used to determine the particle size distribution of the fly ash sample. It was found that about *37.20*% particles were coarser than $75\mu m$ and only *17.35*% particles were finer than $53\mu m$. The scanning electron microscopy-energy dispersive X-ray spectroscope (JEOL, 6510LV model) was used to analyze the surface morphology and chemical composition of the fly ash sample. The scanning electron micrograph (SEM) of the fly ash is shown in Fig.1.

It has been shown that particles of fly ash having smooth surfaces, spherical shapes and are usually found as agglomerates. Chemical composition of the fly ash sample is shown in Fig.2. It was found that the proportion of aluminum oxide (Al_2O_3) and silica oxide (SiO_2) were higher as compared to other elements.

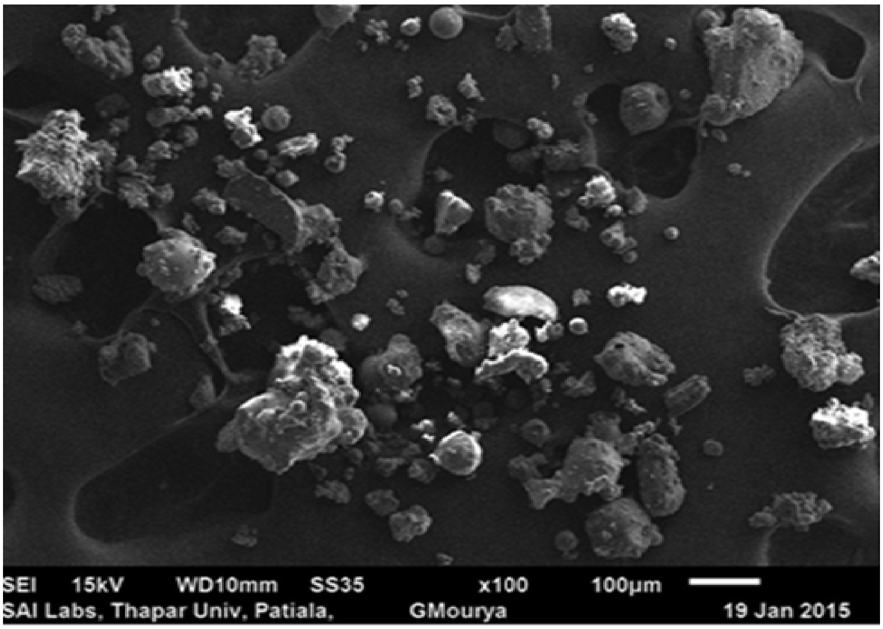

Fig.1. SEM of fly ash sample.

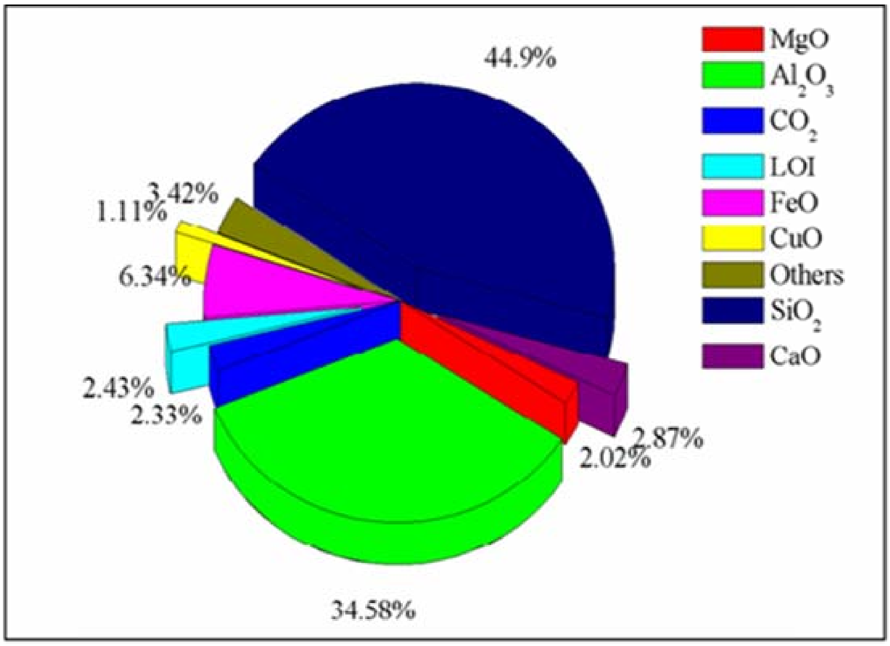

Fig.2. Chemical composition of fly ash sample.

The specific gravity of the fly ash sample was measured as *2.10* by using a pycnometer method. Static settled concentration of the fly ash suspension was measured by gravitational method with initial solid concentration, i.e. *30*% (by weight). During the settling process of slurry suspension at fixed interval of time, slurry level was recorded. The final static settled concentration of the fly ash slurry suspension was recorded as *59.68%* (by weight) as shown in Fig.3. A digital electrode pH meter was used for measuring the pH value of the slurry suspension. The pH values of different concentrations of the fly ash from *10* to *60%* (by weight) are in the range of *6.55* to *6.10*, respectively, as shown in Fig.4. The pH values indicate a non-reactive nature of the fly ash slurry suspension.

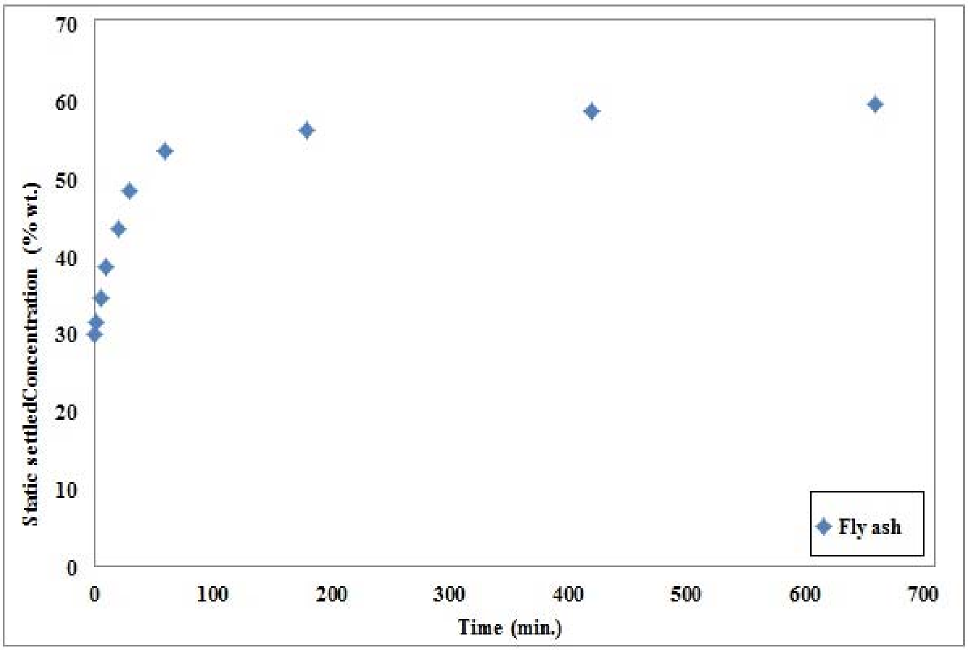

Fig.3. Final static settled concentration of fly ash sample.

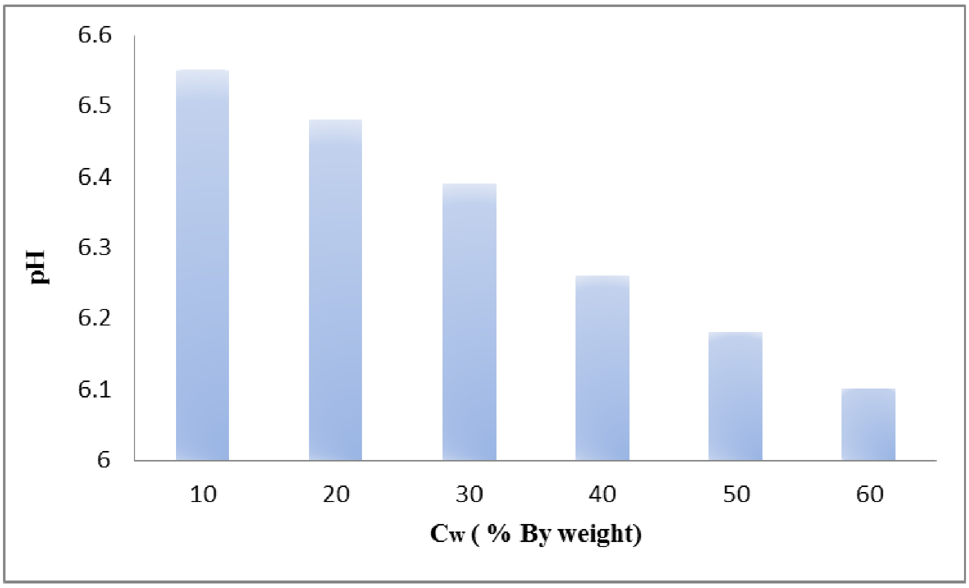

Fig.4. pH of fly ash sample.

2.2. Rheological experimentation

Rheological experiments were conducted with a certified rheometer (Manufactured by: Rheolab Q-C, APC Ltd. Germany). This rheometer works on the principle of Searle. The rheology of fly ash was determined by calculating shear stress at a particular value of shear rate. Initially, the rheometer was calibrated by using tap water for its reliability. A locking device enables the fixing of rotating bob and cup which was done before laboratory testing. For rheological tests, a *100 ml* fly ash slurry sample was prepared through proper mixing of water and ash with the help of a glass rod. The suspension was poured out in the cup of rheometer at level of specified mark after weighing on an electronic type pan balance with least count of ± *0.001 mg*. The fly ash slurry was in the gap between two cylinders. The rotary cylinder (bob) was moved up by a motor while the other cylinder was stationary. Shearing action of the slurry suspension begins with the rotation of the bob under the action of drag force applied by the motor. A Similar procedure was also repeated for the fly ash slurry suspension with addition of an additive. Experiments were repeated to ensure the precision of measured data and average value was considered. Specification of the Rheometer (Rheolab QC) is given in Tab.1.

Table 1. Specification of the rheometer (Rheolab QC).

1. S. No.	**2. Component**	**3. Specifications/Range**
4. 1	5. Motor type	6. Synchronous EC motor
7. 2	8. Torque range	9. *0.25–75* (*mNm*)
10. 3	11. Speed range	12. *0.01 to 1200* (*min–1*)
13. 4	14. Shear rate range	15. *0.5 to 3 × 107* (*mPa*)
16. 5	17. Shear stress range	18. *0.01 to 4000 sec–1*
19. 6	20. Viscosity range	21. *0.1 to 109* (*mPas*)
22. 7	23. Temperature range	24. *–20 to 180* (*°C*)

2.3. Range of parameters

The rheological properties such as the shear stress and viscosity were measured at a fixed shear rate for all slurry samples. Rheological tests were conducted for the value of shear rate in the range of $50\text{-}200\ s^{-1}$ at solid concentration of *30* to *60*% (by weight). A similar procedure was also repeated for the fly ash slurry suspension with addition of an additive. Sodium sulfate was used as an additive with proportion *0.2*, *0.4*, *0.6* (% by weight) in all solid concentrations of fly ash slurries. The pressure drop in a *100m* long pipeline having diameter of *50 mm*, was calculated in terms of meter of water column per kilometer (*mWc/km*).

3. Results and discussions

The rheology of fly ash is determined by calculation of the shear stress at a particular value of the shear rate. The measure of shear stress - shear rate represents the rheological behaviour of any liquid or solid-liquid. The rheological behaviour of fly ash suspensions is evaluated for solid concentration of *30-60* (% by weight). Figure 5 shows shear stress vs. shear rate curves for the fly ash slurry for different solid concentrations. Results represent the non-Newtonian nature of the slurry suspension which follows Bingham fluid behavior as shown in the equation mentioned below

$$\tau = \tau_v + \eta \frac{du}{dy} \tag{2.1}$$

where, τ is the shear stress (Pa), τ_v is the Bingham yield stress (Pa), and η is the coefficient of rigidity or Bingham viscosity.

The coefficient of rigidity is used in the case of Bingham fluid for measuring the relative viscosity. The obtained data follow the straight line equation which is used to find viscosity for each slurry suspension sample. The fly ash slurry suspension shows a Newtonian behaviour up to *30*% solid concentration (by weight) and beyond shows non-Newtonian flow characteristics. The value of shear stress at the shear rate of $50\ s^{-1}$ is observed as *0.14*, *0.39*, *0.85* and *1.42* Pascal, whereas at the shear rate of $200\ s^{-1}$, it is observed as *0.69*, *1.90*, *3.79* and *6.10* Pascal for solid concentration of *30*, *40*, *50* and *60*% (by weight), respectively. The shear stress value increases about *9.29* and *8.89* times with an increase in the value of C_w from *30* to *60%* at the shear rate of *50* and *200* s^{-1}, respectively. Similar observations are also made by other researchers [12-16].

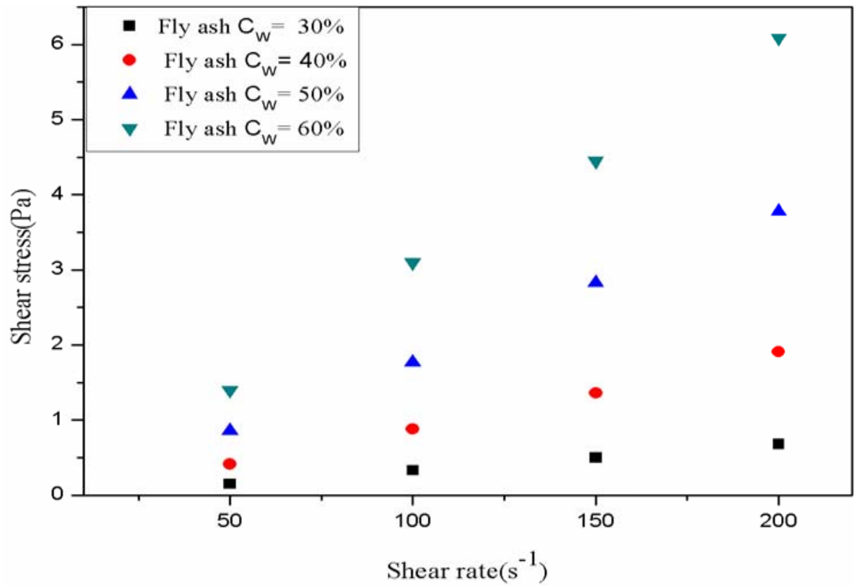

Fig.5. Shear stress-shear rate curve of fly ash.

3.1. Influence of additive on relative viscosity

Experiments were carried out to investigate the influence of an additive on the relative viscosity of fly ash slurry suspension at solid concentration (C_w) ranging from *30* to *60%* (by weight). Sodium sulphate was used as an additive with fraction of *0.2*, *0.4* and *0.6* (% by weight). Variations of relative viscosity for the fly ash suspension with and without additives are shown in Fig. 6.

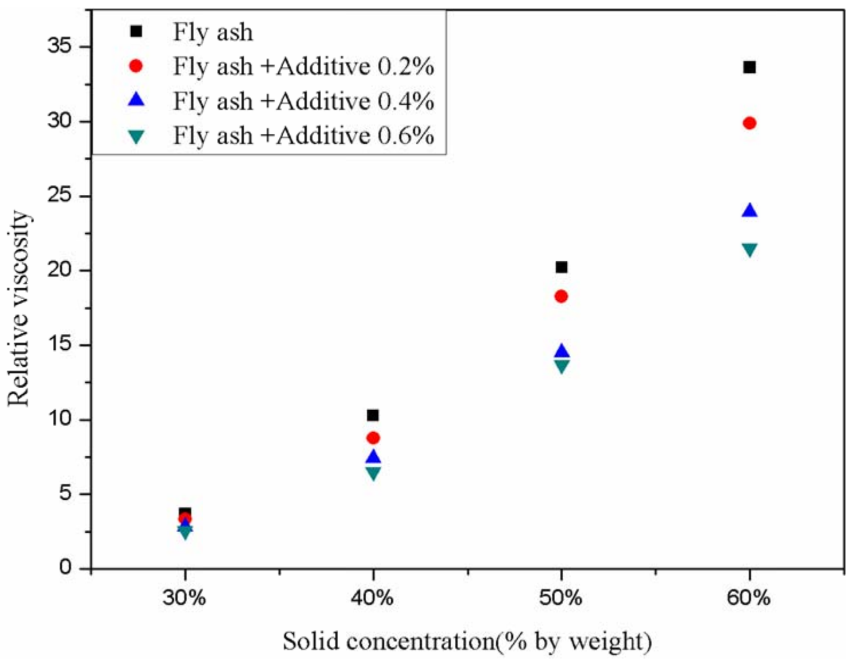

Fig.6. Variations in relative viscosity of fly ash suspension with and without additive.

Experimental results reveal that the relative viscosity of fly ash suspensions is highly dependent on their solid concentration. It also seems that the relative viscosity increases monotonically with a slight increase in solid concentration. In other words, the relative viscosity of fly ash increases more rapidly at higher solid concentration as compared to lower solid concentrations. Due to the increase in solid concentration of the slurry suspension, the quantity of solid particles in the slurry suspension also increases. Thus for starting the shear process, more shear stress is required. A similar type of phenomenon has been observed by investigators [1, 12, 13, 17] with the fly ash slurry. However, a reduction in the relative viscosity is observed by adding a high proportion of additive to the ash slurry at a fixed value of shear rate. The addition of sodium sulphate changes the molecular structure of the fly ash suspension. These changes lead to a decrease in the drag friction between molecules of the fly ash particle, hence viscosity of the suspension is reduced. The addition of a small quantity of the additive may influence the extent of the particle-particle and fluid-particle interaction in the slurry suspension. The influence generated by the addition of additives in rheological characteristics of coal ash slurry suspensions has already studied by many investigators [12-14]. A reduction in the relative viscosity is observed by adding an additive to the fly ash suspension. The following reduction in the relative viscosity of fly ash is observed: *11.14%*, *17.31*% and *12.30* % at solid concentration *30*% (by weight), whereas it decreases by about *13.34%*, *24.71%* and *16.36*% at solid concentration of *60*% (by weight) with addition of additive by weightage of *0.2*, *0.4* and *0.6*%, respectively. It is observed that the reduction in the relative viscosity is more pronounced with addition of *0.4*% additive as compared to *0.2* and *0.6*% (by weight) addition.

4. Mathematical method for prediction of pressure drop

A friction factor is considered to be the most important parameter of pressure drop in pipelines. The flow behaviour of any solid liquid flow is mainly divided into three types: laminar, transition, and turbulent flow depending on the value of the Reynolds number. The fanning friction factor value for laminar flows can be obtained analytically. However, the value of the fanning friction factor for transition and turbulent flows depends on empirical formulae. The Darby and Melson (1981) empirical approach was used to predict the pressure drop in the slurry pipeline. To determine a single expression for the friction factor for all flow regimes, modified friction was devolped in [15]. The fanning friction factor and pressure drop for a straight pipeline are predicted for fly ash slurries at high concentrations.

5. Effect of additive on pressure drop characteristics

The pressure drop characteristics for the fly ash suspension with additive were measured. Sodium sulfate was used as an additive with proportion of *0.2*, *0.4* and *0.6*% (by weight). The effects of the additive were investigated by comparing pressure drop results for slurry suspensions with and without addition of an additive. Results revealed that addition of an additive significantly affects the pressure drop at higher concentrations. The effect of the additive on the pressure drop of fly ash suspensions at solid concentration of *60*% (by weight) is shown in Fig.7. It was observed that the pressure drop increases with an increase in flow velocities for slurry suspensions. However, a remarkable reduction in the pressure drop was observed with addition of the additive. In other words, the pressure drop decreases with an increase in the proportion of additive in slurry suspensions. This may be attributed to a reduction of the inter-particle friction and surface tension among the particles of ash, which leads to a decrease in the pressure drop. Similar observations were also made by other investigators [13, 17]. For velocity $1\ ms^{-1}$, a reduction in the pressure drop was observed: *7.9*, *13.51* and *4.21* (*mWc/km*) with addition of the additive in proportion of *0.2*, *0.4* and *0.6*% (by weight), respectively. It was also observed that a reduction in the pressure drop for fly ash was highly pronounced with addition of the additive in proportion of *0.4*% (by weight) as compared to *0.2* and *0.6*% (by weight).

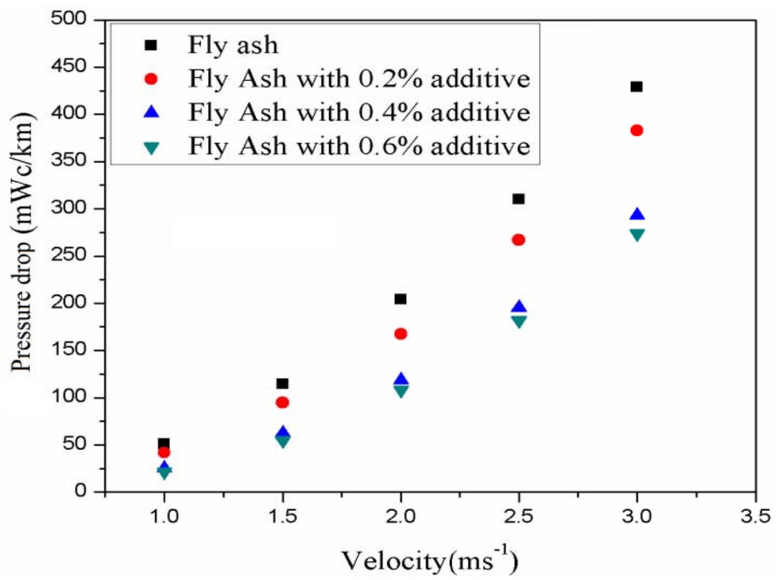

Fig.7. Variations in pressure drop of fly ash suspension with and without additive.

6. Effect of additive on specific energy consumption

Specific energy consumption (SEC) was also measured for transporting fly ash slurry suspensions by using an additive at varying range of flow velocities (*1-3*ms^{-1}). The effect of the additive on specific energy consumption was shown in Fig.8. SEC was very much affected by a small dosage of the additive in fly ash suspensions. SEC for fly ash suspensions decreases by *17.74*, *38.94* and *16.08*% with addition of the addive in proportion of *0.2*, *0.4* and *0.6*% (by weight) at flow velocity of $1\ ms^{-1}$, respectively. A maximum reduction in SEC was observed with addition of the additive in proportion of *0.4*% (by weight). This decrease in power consumption results in a reduction of pump power required for transportation of the fly ash suspension. About *36*% of pump power is reduced. Thus, the high concentration suspension can be disposed of through a pipeline system with a lesser principal investment cost or it will be possible to transport the coal ash slurry suspension economically with addition of a small dosage of additive.

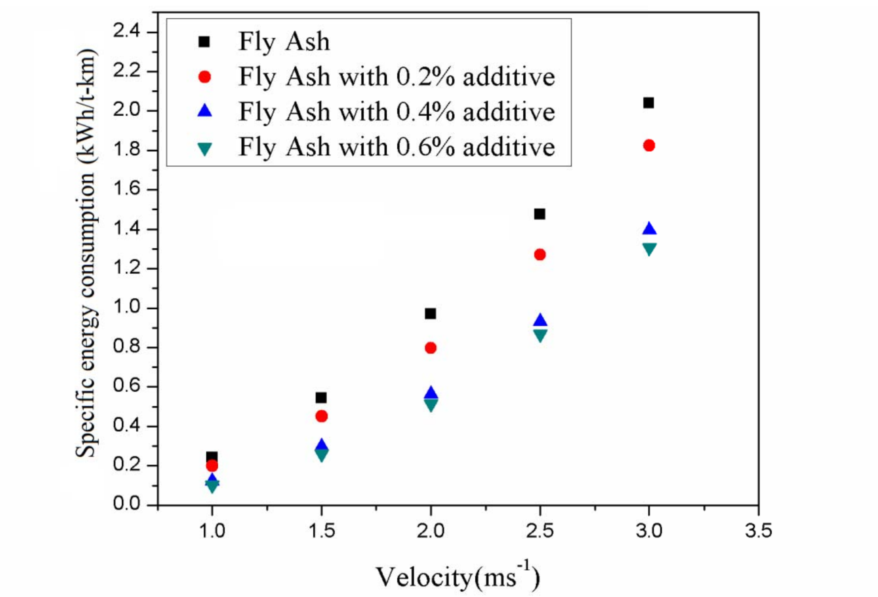

Fig.8. Variations in specific energy consumption for fly ash suspension with additive.

7. Conclusion

The following conclusions are drawn on the basis of the present study which deals with rheological characteristics of fly ash slurry suspensions with and without an additive.

- Addition of an additive improves the rheological behavior of the fly ash suspension.The slurry suspension shows a Newtonian behaviour up to solid concentration of *30*% (by weight), beyond it shows non-Newtonian flow characteristics.
- A higher reduction in the relative viscosity of fly ash slurry suspension is noticeable with a higher concentration of the additive. However, the reduction rate is more pronounced with the additive in proportion of *0.4* (% by weight).
- Power required to transport the fly ash slurry gets reduced by up to *36*%.

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