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EXPERIMENTAL INVESTIGATION OF THE PHYSICAL AND RHEOLOGICAL BEHAVIOUR OF FLY ASH AND BOTTOM ASH SLURRIES AT HIGHER SOLID CONCENTRATIONS

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Abstract

In India, thermal energy accounts for more than 70% of electricity production and millions of tons of coal are burned in these thermal power plants. Thus, large quantities of coal ash (fly ash and heavy ash) are produced and the current level of production is about 120 million tons per year. Out of this, approximately 20% is bottom ash and the rest 80% is fly ash. The ash produced in India usually has higher specific gravity as Indian coal has much higher content of non-combustible matter. Also, majority of the thermal power plant in India dispose both the materials namely fly ash and bottom ash to ash ponds using the same pipeline. This has motivated the author to carry out a systematic study on the flow of Indian coal ash (FA and BA) slurries at higher concentrations. The knowledge of slurry rheology is very vital for the design of slurry pipeline particularly for the dense phase conveying system. Since the pilot plant loop tests at these concentrations are tedious, time consuming and complex in nature, the slurry pipeline designers have been adopting the empirical approach for slurry pipeline design based on the rheological model of the slurry. In the current research it is observed that at higher concentration of solid the shear stress and apparent viscosity of the coal ash slurries are highly influenced.

Keywords: *fly ash, bottom ash, slurry, rheological behaviour, shear rate, shear stress.*

1. Introduction

A slurry pipeline system is used for conveying solid particles using fluid which is generally water as a carrier. Slurry pipeline transportation has been one of the progressive technologies for conveying large quantity of materials over long distances (Baker *et al* 1979; Brown *et al.* 1991 and Abulnaga 2002). The mineral ores in mining and process industries, coal ash in thermal power plants disposal of waste materials like tailing and waste materials are a few examples that can be mentioned. These materials need to be stored or transported in industries for processing purposes or disposal to nearby locations. Compared to the conventional mode of transport, slurry transportation has been established as an economic and ecological method. The fly ash produced is a very fine powder where as bottom ash is coarse. About a decade ago, utilization of power generation waste which is primarily coal ash was one of the major problems of thermal power plants especially for solid-fuel power plants. But now a day it is possible to utilize the coal ash for road embankments, cement bricks etc. Efforts are being made to utilize all the ash being produced in power plants and it is estimated that in our country about 35% of the production of ash is being utilized at present. The remaining 65% still needs to be transported and stored safely for subsequent consumption. At present, these materials are being transported by slurry pipelines at low concentration (10-20% by weight). This leads to very high power consumption excessive erosion wear due to higher transportation velocity and the existence of highly skewed concentration profile making the system very uneconomical. Today, many industries are adopting this mode of transport for both standard and long-haul transport because it offers many advantages such as reliability, reduced availability, year-round availability, access to a remote location and automation possibilities. Additional features of these pipelines, which make them more attractive as a means of transportation, include traffic congestion, air and noise pollution and accidents. The long-distance transport of solids by pipelines is generally more economical than the conventional mode of transport (Link *et al.* 1974 and Seshadri *et al.* 1975).

2. Literature review

Slurry flow is a complex flow of a continuous liquid that transports the dispersed solid in suspension and is transported by the drag forces of the liquid acting on the particles. It depends on the properties of the solid particles in relation to the properties of the liquids. It influences the dependence of the pressure drop as a function of the flow rate and the magnitude of the pressure drop, as well as other performance characteristics. Knowing the different regimes of slurry flow is very important to understand the behavior of slurry. Rheological behaviour of the slurry is mainly expressed by (apparent, plastic, zero, or infinite) viscosity and (shear, or yield) stress. These behaviors are significantly influenced by physical and chemical properties such as solids concentration, particle size and distribution, particle shape, pH, shear rate, slurry temperature, and chemical reagents (He *et al.,* 2004). When solid particles are added to the transport liquid by increasing the solids concentration), the viscosity of the suspension is increased. This is due to the physical particle interactions that occur when a solid is dispersed in a liquid. At low solids concentration, the viscosity appears to increase linearly with increasing solids concentration and after a certain solids concentration, the viscosity of the slurry increases considerably with small increases in concentration (Rutgers, 1962).This is because at high concentration the inter-particle distance becomes smaller and increases the attractive potential and collisions between the particles. Rutgers concluded that the effect of hydrodynamic interactions dominate at low to medium solids concentration. According to Cheng (1980) the particle frictional contact dominates for solid concentration ranging from medium to high and at very high solids concentration the particle effect dominates the hydrodynamic effects. The other key parameters affecting the rheological properties of the slurry are Particle size and distribution. The smaller the particle size and the narrower the size distribution, the higher will be the shear stress and apparent viscosity at a given range of shear rate. According to (He *et al.,* 2006), it is because for slurries with finer particles the surface area per unit mass increases providing greater inter-particle attractions than for the coarser ones at a fixed solids concentration. Working temperature is also another important factor which affects the rheological properties of slurry. The values of apparent viscosity and shear stress decreases with increase in temperature. This is due to the formation of aggregates which grow continually in size with the increase of temperature until they no longer grow (Shenoy 1976). Studies carried out in the last phase of previous century with other materials have shown that at higher concentrations ($C_w > 50\%$, by weight) slurry behaves as non-Newtonian fluid with rheological equation showing Bingham behaviour (Bunn and Chambers 1993). For the case of slurry flow at very high concentration, the flow regime becomes homogeneous and the fluid becomes highly non-Newtonian. Hence it is possible to operate the pipeline al velocities in the laminar flow regime. High concentration slurry transportation (50 % by weight) reduces the skewness in concentration profile. Reduction in skewness of concentration profile and velocity is expected to reduce the erosion wear of pipeline and hence increase the lifespan of the pipeline (Seshadri 1979, 1982).

On the basis of extensive literature survey, it is seen that there is still significant gap in knowledge on selection of optimized parameters for hydraulic design of slurry pipeline, especially at high concentrations for fine slurries Indian fly ash being one of them. It is well known that coal ash (FA and BA) produced in various thermal power plants across India vary widely in their physical and chemical properties due to thee variation in the combustion efficiency and quality of the coal used. Literature reveals that different rheological models proposed are not universal due to complex dependence of rheological properties on several parameters namely particle size distribution, concentration and other chemical properties. The existing flow models are not applicable to all slurries at high concentrations. This shortcoming has motivated the author to study the rheology of fly ash slurries at high concentrations. Studies are also undertaken to achieve the reduction in the values of rheological parameters by using additives and to investigate their impact on slurry pipeline design.

3. Experimental setup

To determine the physical and rheological properties of the suspension, a standard laboratory scale test was performed. These in-depth experiments were conducted in the Water Resources Simulation Laboratory of the Department of Civil Engineering at IIT Delhi. The rheological data are obtained for FA and BA slurries at high concentrations. Rheological experiments were conducted with RheolabQC. This rheometer uses a paddle technique which has become a simple and effective method for the direct measurement of the stress properties of minerals and other suspensions, as it eliminates the serious effects of slippage. In this study, a RheolabQC with a CC27 measuring cup and an ST22-4V-40 sensor system with 4-blade pallet geometry were used. The diameter and length of the paddle rotor were 22 mm and 40 mm respectively. The geometry of the blades and the measuring cup were cleaned and air dried. For each oven-dried sample, several suspensions were prepared with distilled water at different concentrations of solid. To avoid any undesirable influence of the sedimentation of particles, the measurement of each sample is initiated at the highest shear rate, from 300 to 30 s^{-1}, which corresponds to the same order of magnitude as expected in the control system of slurry pipeline. About 60 ml of suspension was prepared for each sample and rheological measurements of slurry with different concentrations of solids were made. The shear rate was applied for a period of 2 minutes to measure the corresponding viscosity and shear stress under the control of the shear rate. Constant shear measurements were performed at room temperature. All rheological measurements were repeated for each suspension to minimize and avoid experimental errors in rheological tests.

3.1 Test materials and Range of parameters

The material used in this specific study was coal ash (fly ash and Bottom ash) taken from Ahmadabad power plant, Gujrat (India). Since the suspension must be transported through normal water in the pipes, normal tap water was chosen for the preparation of the suspension sample. Solid mass concentrations of 30, 40 and 50% were selected for FA and BA slurry. Shear rate during measurements ranged from 30 s-1 to 300 s-1 in 30 s-1 steps each.

4. Basic bench scale test for physical and rheological properties of coal ash

4.1 Physical properties of solid materials

FA and BA samples were obtained from the Ahmadabad thermal power station in the state of Gujarat, India (Figure 2). The physical properties of the samples were determined and reported in Table 1. The density was measured with the standard method of the pycnometer. The mean density of FA and BA is 2.1 and 2.13 respectively. The settling behavior of a suspended solid sample is determined by preparing a mass concentration of 30%, mixing thoroughly and letting it settle into a graduated jar until the level of the deposited material becomes constant and called static settled concentration. Meanwhile, the suspension level was recorded at regular intervals during the sedimentation process to determine the sedimentation rate of the suspension. Table 1 shows the maximum static concentrations of the FA and BA slurry samples. The measured pH values of FA and BA for various particle ranges are presented in Table 2.

The particle size distribution (PSD) was obtained by two methods: sieve analysis and hydrometer analysis. At the beginning, the sample is washed with water on a BS 350 mesh and then oven-dried. Sieve analysis was performed for particles larger than 45 μm and the percentage of solids retained was calculated according to standard procedures. The standard hydrometer technique was used for the finest particles (<45 μm). The PSD of all samples was presented in Figures 1 (a and b). The maximum particle size of FA is 300 μm and 600 μm for BA. For FA 70% of the particle size is less than 75 μm and the average particle diameter (d_{50}) of the FA sample is 45 μm and for BA d_{50} it is 172 μm. The static concentration of FA at the initial concentration of 30% is Cw = 72.1% and for BA Cw it is 58.33%.

Table 1. *The static settled concentration of FA & BA at 30% Cw slurry sample*

Time (min)	0	0.5	2	4	8	30	60	120	480	720	1440
Cw(%) BA	30	42	55.3	56.7	56.7	56.7	57	57.5	58.33	58.33	58.33
Cw(%) FA	30	31.5	34.1	37.3	42.2	58.5	60.1	61.2	70.1	72.1	72.1

Table 2. *pH values for FA and BA slurries at various solid mass concentrations.*

Cw (%)	0	30	40	50
pH value of FA	7.02	7.36	7.33	7.29
pH value of BA	7.02	7.12	7.31	7.34

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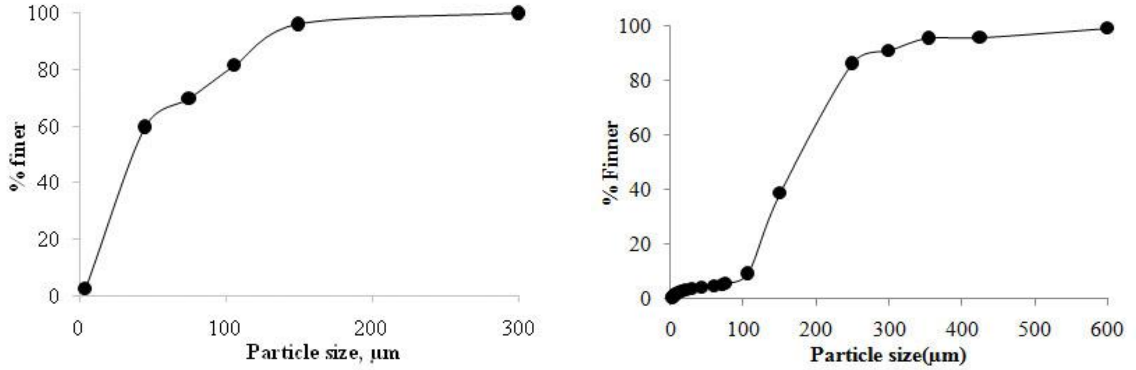

Fig.1(a & b) particle size distribution of FA ash and BA ash sample.

Figure 2. FA and BA samples

4.2 Rheological Properties of the Slurry

4.2.1 Effect of solid concentration on viscosity and shear stress of FA slurry

Figure 3 (a & b) shows the rheological properties of FA slurry at solid concentration of 30%, 40% and 50% by mass. It follows the Herschel-Bulkley model, which includes the shear-thinning or shear-thickening behaviour of power-law fluids and the yield-stress effects. The data showed that the variation of shear stress with shear rate at all concentration follow a shear thickening behavior. The model is formulated as:

$$\tau = \tau_o + K\gamma^n$$

From the experimental results it is seen that the shear stress increases with increment in shear rate; particularly at high shear rate the increment in shear stress is more and follows the similar pattern for 30% and 40% concentration of solid. At 50% solid concentration there is marginally high increment in shear stress values with increase in shear rate. It is also seen from the result that the apparent viscosity of sample increases rapidly at low shear rate excepting at 50% solid concentration and as the shear rate increases it increases slowly.

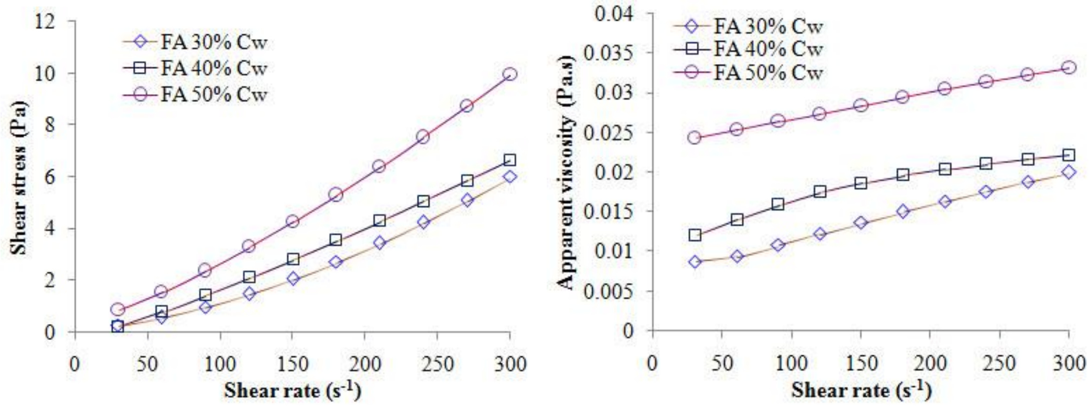

Figure 3(a & b) Rheogram of FA slurry at various solid concentration.

4.2.2 Effect of solid concentration on rheological behavior of the BA slurry

Figure 4 (a & b) shows the rheological properties of BA slurry at solid concentration of 30%, 40% and 50% by mass. The result showed that the entire slurry samples exhibits a non-Newtonian behavior and follows the Herschel-Bulkley model. The experimental data shows that the shear stress variations with shear rate follow a shear thickening behavior at all concentrations. From the experimental results it is observed that the shear stress decreases with increment in shear rate; particularly at high shear rate the decrement in shear stress is less and at low shear rate the decrement is comparatively high at 30% and 40% concentration of solid. At 50% solid concentration (Cw) there is marginally high decrement in shear stress values with increase in shear rate. It is also seen from the result that the apparent viscosity of sample decreases rapidly at low shear rate excepting at 50% Cw and as the shear rate increases it decreases slowly. At 50% Cw the decrement of shear stress and apparent viscosity at low shear rate is marginally very rapid although at higher shear rate there is slow decrement in values of shear rate and apparent viscosity.

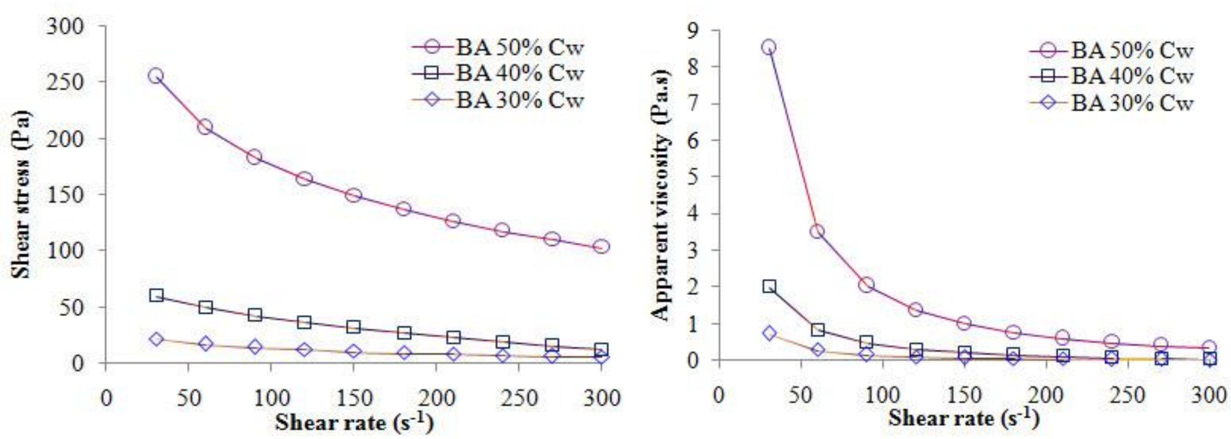

Figure 4(a & b).Rheogram of BA slurry at different solid mass concentrations.

5. Conclusions

The purpose of this study is to evaluate the effect of solid concentration and shear rate on the physical and rheological properties of FA and BA slurry. The FA and BA ash slurry samples were chosen with a solid mass concentration of 30-50%. The physical properties of the samples such as pH, PSD, density and static concentration were also studied. A computerized rotary rheometer was used to determine the rheological behavior of the slurry. The following outcomes have been observed from the experimental results and data:

a. The variation of shear stress with shear rate follows the Herschel-Bulkley model with shear thickening behavior.
b. The rheological behaviour of BA slurry changes with increase in shear rate. The shear stress and apparent viscosity decreases rapidly at low shear rate (up to 200 s^{-1}) and beyond that the decrement rate is low with increase in shear rate (200 -300 s^{-1}).
c. Shear stress and apparent viscosity increase with solid mass concentration.

Nomenclature

τ	= Shear stress
τ_o	= Yield stress,
n	= flow behavior index
K	= Consistency index
γ	= Shear rate
D	= Diameter of Pipe
ρ_m	= Density of slurry
d_{50}	= Mean diameter of FA particles
C_w	= Solid particle concentration by weight
PSD	= Particle size distribution

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