Experimental Investigation on the Rheological Behaviours of Fly Ash Slurries without and with the Addition of Chemical Agents

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Abstract- **In India the demand of transporting large quantities fly ash slurries through pipeline to the disposal sites is increased very rapidly in the last decades. But the main difficulties on which the investigators encountered are that the pressure drop and pump capacity are drastically increased. Currently it is believe that adding some selective chemicals may change the rheological properties of the slurry and hence pressure drops. Due to the above notions, this particular study is aimed on experimentally investigating the rheological properties of fly ash slurries with and without the addition of chemical at solid concentration ranging from 10 to 50% by weight. Two chemicals namely Cetyl Trimethyl Ammonium Bromide (CTAB) as a cationic surfactant and Sodium Salicylate (NaSal) as a counter ion (1:1) at mixing proportions ranging from 0.01 to 0.07% by weight of total slurry were used. It has been shown that up to solid concentration of 50% by mass all the samples behave as non-Newtonian and follows a Herschel-Bulkley model with shear thickening behaviours except for additive concentration of 0.07% which shows shear thinning behaviour. Furthermore, beyond 10% concentration of solids the result shows yield stress. The results also indicate that the shear stress and viscosity decrease up to 0.06% of chemical additives and then increase. Hence, the optimum chemical additives are at a concentration of 0.06% by weight of total slurries. From this investigation it can be concluded that the FA Slurry rheology is highly dependent on chemical additives at the chosen additive proportions and slurry concentration.**

Keywords: Slurry transportation; non-Newtonian fluid; rheological behaviour; chemical additive

I. INTRODUCTION

Thermal power is the largest source of power in India. Coal is used widely as a thermal energy source and also as fuel for thermal power plants for power generation with 272000 MW installed capacity for electric power generation. More than 75% of electricity consumed in India is generated by thermal power plants out of which 51% of India's commercial energy demand is met through the country's vast coal reserves. The problems associated with the use of coal are low calorific value and very high ash content. The ash content is as high as 55–60%, with an average value of about 35–40% (Mishra et al 2004). Thus huge amount of ash is generated in power plants that are transported through pipelines in slurry form at a very lean solids concentration (around 20% by weight) to the disposal sites. The rheology and transport of suspensions are a matter of widespread interest. The disposal of fly ash as a dense slurry from coal fired power stations is gaining popularity because it leading to high energy and water consumption. Therefore, there is a requirement for a proper handling, disposal and utilization of the ash being produced in large quantity. In India, at present, the majority portion of fly ash produced goes for disposal in ash ponds and landfills and only a small fraction of it is utilized. Several studies conducted on pipeline transportation of fly ash slurry as a backfill material at higher solids concentration clearly shows the advantage that the flow can take place under laminar conditions thereby reducing specific power consumption. . It is conceived that the design of fly ash slurry disposal pipelines can be carried out at high solids concentration (>50% by weight) to have favorable pipe economics. But the flow behaviour of the slurry changes drastically at high solids concentration affecting the viscosity due to fineness of fly ash particle size (Parida et al 2003).

A number of factors influence the rheological behaviours namely solids contents, particle size, particle size distribution, the surface chemistry of the particles, chemical additives and so on (He, Wang, and Forssberg, 2004). Certain chemical additives enhance the fluidity of the slurries and hence enable the slurries to be pumped at much higher concentrations thus reducing the water requirements. So, the selection of appropriate additives should be recognized as one of the most essential factors in the preparation of highly concentrated slurries. It is, therefore, relevant to investigate the effects of chemical additives on the rheological behaviours of slurries.

Hence, in the present study, an attempt has been made to evaluate the rheological behaviour of FA slurry at 10% to 50% mass concentration with and without addition of chemicals. The chemical additives used in the study are Cetyl Trimethyl Ammonium Bromide (CTAB) and Sodium Salicylate (NaSal) in 1:1. Based on the rheological data, suitable discussions and conclusions have been made for its effective transportation through hydraulic pipelines.

II. LITERATURE REVIEW

The flow behaviour of the slurry changes drastically at high solids concentration affecting the viscosity due to fineness of fly ash particle size. Literature reveals that addition of some agents/surface-active agents markedly affects the rheological behaviour of the slurry. Seshadri et al. (2005) investigated pipeline transportation of the FA slurry with Sodium hexa-metaphosphate added at 0.1% concentration by mass and they found that there is a significant reduction in the viscosity of the slurry. Verma et al. (2006) studied the rheological behaviour of FA slurry without and with the addition of Sodium hexa-metaphosphate at 0.1% concentration by mass for different particle size distributions and concentrations and they found that particle size distribution and concentration of solids affected more to the slurry rheology in non-Newtonian comparison to the Newtonian nature of slurry. Mosa et al. (2008) assessed the effect of three types of additives, namely-sulphuric acid, sodium tripolyphosphate and sodium carbonate at mass concentrations from 0.5 to 1.5% on the rheological characteristics of coal-water slurry. They found that apparent viscosity and flow properties decreases with an increase in additives. According to Chandel et al. (2009a) investigation, adding 0.2% by mass of sodium carbonate and Henko detergent (5:1) could drastically reduce the yield stress and Bingham plastic viscosity of FA at concentration ranging from 50 to 70% by mass. Naik et al. (2009a, 2009b, 2011) studied the effects of addition of Cetyl Trimethyl Ammonium Bromide and Sodium Salicylate on the rheological Properties of FA-water suspensions for 20% to 40% concentration at temperature ranging from 200C to 400C and found that the viscosity and shear stress decreased for all the cases with increase in temperature and the slurry without additive showed shear thickening behaviour but exhibited almost Newtonian pattern with a zero yield stress when the concentration of the additive solution increased gradually with an incremental value of 0.1% by mass. According to their investigation the effective additive concentration range was found to be from 0.2% to 0.3% by mass and the slurry exhibits Newtonian properties of shear thinning behavior in the presence of additives with input shear rate 100s-1 to 1000s-1 at 40% solid concentration. Senapati et al (2010, 2012) investigated over a range of volumetric solids concentration (ϕ=0.32–0.4945) in shear rate range of 10–200 s−1. The slurry was highly pseudo-plastic whose behavior can be described by a non-Newtonian power law model in the range of solids concentration studied. The flow behaviour of ash slurry in the concentration range of 50–60% by weight) using sodium silicate as an additive is described by a Bingham-plastic model. The addition of sodium silicate (0.2–0.6% of the total solids) reduced both the slurry viscosity and the yield stress. Kunal and Kundan (2012) experimentally evaluated the effects of three types of additives (cationic, anionic and non-ionic polymer) on the rheological behaviour of FA slurry at 40% slurry mass concentration and found that all the additives reduce the viscosity and shear stress of the FA slurry.

III. EXPERIMETAL SETUP AND MEASUREMENTS

Standard bench scale test was carried out to determine the physical and rheological properties of the slurry. These extensive experiments were done in the Water Resources Simulation Laboratory of Civil Engineering Department, IIT Delhi. The rheological analysis was conducted by using an advanced computerized rotational rheometer, RheolabQC manufactured by Anton Paar Company Ltd., Germany. The rheometer consists of a high-precision encoder and a highly dynamic EC motor. It can be operated either via the robust keypad or via an external keyboard connected to the interface. The data can be read out immediately, stored for reading out later, or sent to a connected printer by a software program called RheoPlus. The rheometer consists of measuring cup CC27 and a sensor system ST22 – 4V – 40 having four bladed Vane rotors, with 40 mm length and 22 mm diameter.For the tests, around 70 g of the slurry was prepared by mixing the required quantity of solid materials with tap water to obtain the desired mass concentration (Cm). An electronic balance with a deviation of ±10–4 g was used for weighing the solid materials accurately. Shear rate under the controlled rate ranging from 30 s^{-1} to 300 s^{-1} at 10 measuring intervals was applied for about 2 minutes to measure the corresponding shear stress and viscosity. All the measurements were repeated several times to minimize errors occur during tests. Further, at each concentration, measurements were done at least two samples of the same material to assess the extent of repeatability. The repeated sets of sample data on shear stress and viscosity at any given shear rate agreed within ±3%.

A. Test materials and Range of parameters

The material used in this specific study was fly ash (FA) which is obtained from the Ahmedabad thermal power plant in Gujarat state, India. Since the slurry is to be transported through ordinary water medium in the pipelines, so ordinary tap water was chosen for the preparation of slurry sample. The solid mass concentrations of 10, 20, 30, 40, and 50% were chosen for FA slurry. The shear rates during the measurements were varied from 30 s−1 to 300 s−1 with a step of 30 each.

B. Additive Chemicals

Two chemicals namely Cetyl Trimethyl Ammonium Bromide (CTAB) and Sodium Salicylate (NaSal) were chosen. CTAB, $CH_3(CH_2)_{15}N(CH_3)_3Br$, is a cationic surfactant of ammonium compounds and soluble in water. As any surfactant, it forms micelles in aqueous solutions. This cationic surfactant is known to its being very effective for drag reduction when accompanied with suitable counter-ions. On the other hand, NaSal ($C_7H_5NaO_3$) is a Sodium salt of salicylic acid and can be prepared from sodium phenolate and carbon dioxide under higher temperature and pressure. It contains both a hydroxyl and a carboxyl group, which react with either an acid or an alcohol. It commonly used as a counter-ions for the cationic surfactant and acts as a reagent to reduce ion

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radius of the surfactant to deform micellar shape. The two chemicals were added to the slurry in equal proportion of weight concentration base (1:1).

IV. RESULT & DISCUSSION

A. Physical properties of solid materials

The samples of FA were obtained from the Ahmedabad thermal power plant in Gujarat state, India. The physical properties of the samples have been determined and shown in Table 1. The specific gravity was measured by the standard Pycnometer method. The average specific gravity of FA is 2.1. The settling behaviour of solid sample in suspension is determined by preparing 30% mass concentration, mix thoroughly and allowing it to settle in a graduated measuring jar till the level of the settled solids become constant and is called static settled concentration. In a meantime, the level of the slurry was recorded at regular intervals of time during the process of settling to determine the settling rate of the slurry. The maximum static settled concentrations of the sample slurry is 72.1% for FA as shown in Table 1. The measured pH values of FA ranges from 7.5 to 7.45 for 10% to 50% mass concentrations (Table 2). The particle size distribution (PSD) was obtained by two methods namely, sieve analysis and hydrometer analysis. At first the sample is washed with water over a BS 350 mesh and then dried in oven. Sieve analysis has been done for particle size larger than 45 µm and the percentage of the solids retained was calculated following the standard procedures. Standard hydrometer technique was used for the finer particles (< 45 µm). The PSD for all samples in semi-log form was presented in Figure 1. The maximum particle size of FA were 300 µm. 70% of the particle sizes are below 75 µm and median particle diameter, d50, of sample is 8 µm.

Table 1. Settling characteristics of FA slurries.

Time (min)	Conc (%) FA
0	30
0.25	30.3
0.5	31.5
1.0	32.8
2.0	34.1
10	45.5
30	58.5
60	60.1
180	60.8
480	70.1
720	72.1
1440	72.1

The static settled concentration of FA at 30% initial concentration is Cm = 72.1% (Cv = 55.2%).

Table 2. pH values for FA slurries at various mass concentrations.

Cm (%)	0	20	30	40	50
pH of FA	7.02	7.41	7.36	7.33	7.29

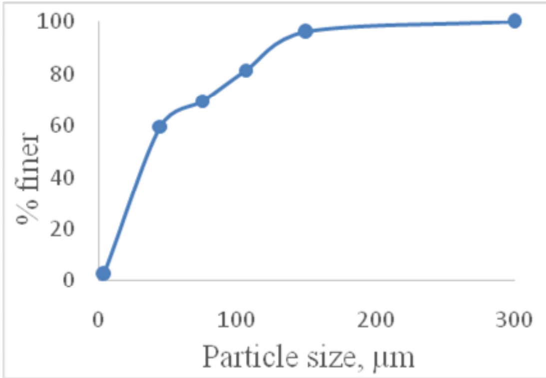

Fig.1 particle size distribution of Ash sample.

V. RHEOLOGICAL PROPERTIES OF THE SLURRY

A. Effect of solid concentration on viscosity and shear stress

Figure 2 (a & b) showed the rheological properties of FA at solid mass concentration of 10%, 20%, 30%, 40% and 50%. The results that the entire sample data presented show a non-Newtonian behavior. It follows the Herschel-Bulkley model, which includes the shear-thinning or shear-thickening behavior 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:

$$\tau = \tau_y + K\dot{\gamma}^n$$

Where, is the yield stress

When $n > 1$, the flow is called yield-shear thickening

$n < 1$, the flow is called yield-shear thinning

$n = 1$, the flow is called Bingham fluids

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 10% to 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.

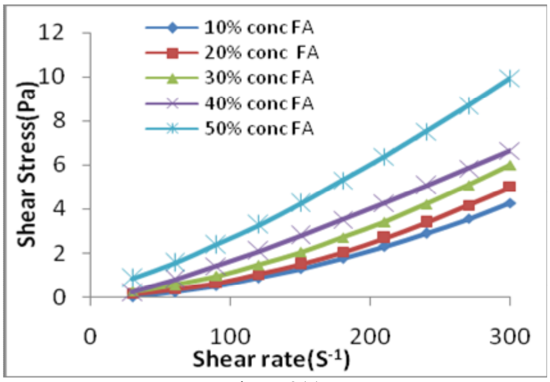

Figure 2(a)

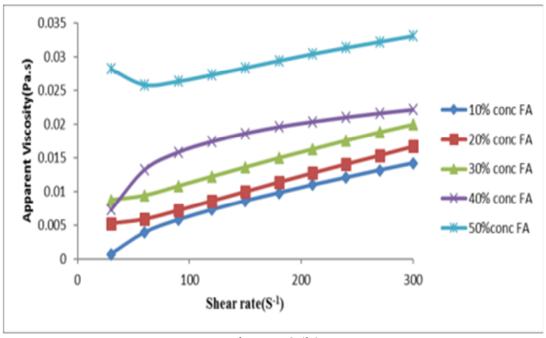

Figure 2(b)

Figure 2 (a and b). Rheogram of FA slurry at different solid mass concentrations.

% solid conc.	n (---)	K,10^{-3} (Pa.s^n)
10	1.6	0. 596
20	1.8	0. 18
30	1.6	0. 689
40	1.5	1.541
50	1.3	5.896

Table 3 values of n (flow behavior index), *K* (consistency index /coefficient) at various solid concentrations

The slurry behaves as non Newtonian with zero yield stress at 10% solid concentration by mass. As the solid concentration increase from 20% to 50% the slurry follows a Herschel-Bulkley model with shear thickening behaviours with yield stress. As shown in table 3, the value of K increases with increase in concentration except for 20% solid concentration. The value of n increases up to 20% solid concentration and then continuously decreases up to 50% solid concentration by weight.

B. Effect of chemical additives:

Figure 3(a-d) shows the relationship of shear rate with shear stress and apparent viscosity at 50% solid mass concentration with the addition of surfactant (0.01 to 0.07%) which is dispersing and drag reducing agent. The mass of added chemical additive was expressed as the percentage of total solid. It can be seen that the shear stress decreases up to 0.06% of chemical additives and shows the non-Newtonian behavior with nonzero yield stress. The data showed that the variation of shear stress with shear rate follow the Herschel-Bulkley model with shear thickening behavior and it changes to shear thinning at 0.07% of chemical additives.

From the result it is seen that with the addition of chemicals the value of shear stress increase slowly with increase in shear rate. It is also observed that the increment rate is high over 150 S^{-1} shear rate at all the range of chemical additives except 0.07%.it is also observed from the experimental data the increment in shear stress is less as the percentage of chemical additives increase at the same shear rate. Particularly at 0.06% chemical additives there is small increment in shear stress with the increase in shear rate. At 0.07% of chemical additives the curve of shear stress turns it behavior from shear thickening to shear thinning. The apparent viscosity decreases rapidly at little increase in shear rate up to 150S^{-1}. As we move above to 150S^{-1} the value of apparent viscosity decreases very slowly for all range of chemical additives.

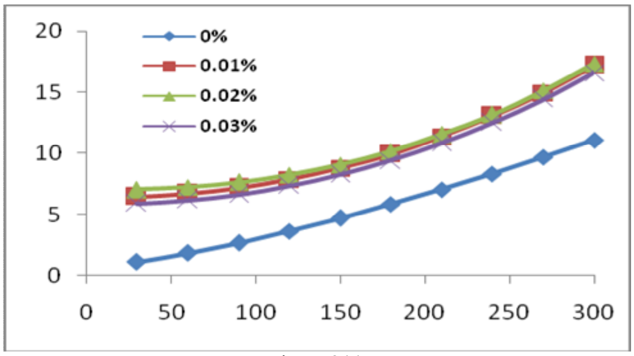

Figure 3(a)

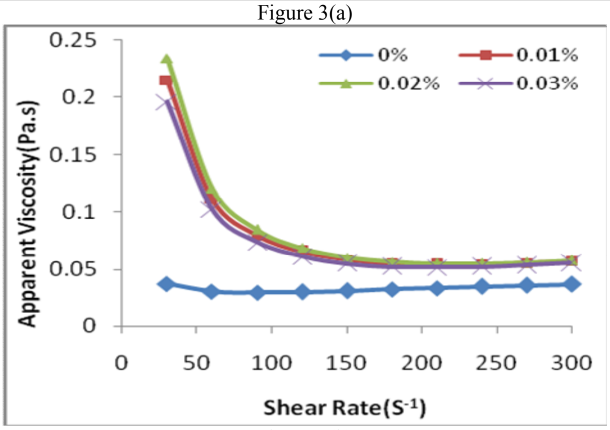

Figure 3(b)

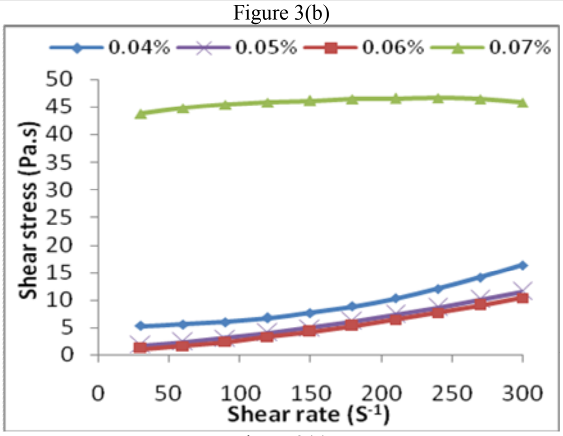

Figure 3(c)

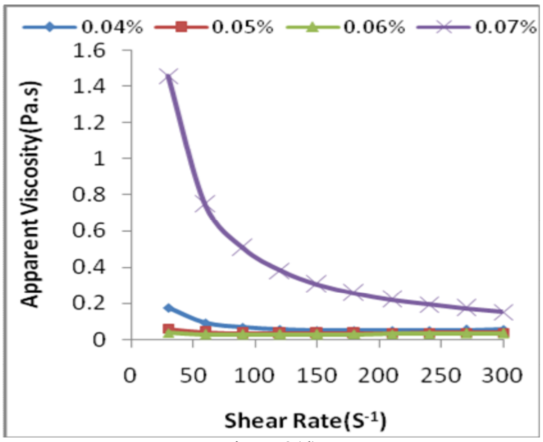

Figure 3(d)

Figure 3(a-d) shows the effect of chemical additives on rheological properties of FA slurry.

Effect of Chemical Additives on n & K values

Table 4 shows the result for n & K values at various percentages of chemical additives in 50% slurry.

Chemical additives (%)	n (---)	K, 10^{-3} Pa.s^n
0	1.4	4.645775
0.01	2.2	0.046109
0.02	2.3	0.020047
0.03	2.1	0.057329
0.04	2.2	0.037324
0.05	1.5	1.896949
0.06	1.5	2.175301
0.07	0.01	144920.5

It is clear from the result that the value of n increases with increase in chemical additives from 0% to 0.02% than it decreases continuously with a little exception at 0.04% of chemical additives. Similarly the value of K decreases with addition of chemical additives from 0% to 0.02%. The value of K continuously increases above 0.04% to 0.07% with exception at 0.003% addition of chemical additives.

VI. CONCLUSIONS

The aim of this investigation is to evaluate the rheological properties of the FA slurry without and with the addition of Chemical additives. The FA slurry samples has been made with 10 to 50% mass concentration and treated with chemical additives i.e. Cetyl Trimethyl Ammonium Bromide (CTAB) and Sodium Salicylate (NaSal) with solid mass percentage 0.01 to 0.07 in the FA slurry. The physical properties of the ashes such as pH, PSD, specific gravity and static settled concentration have also been studied. Computerized rotational Rheometer was used to determine the rheological behaviour of the slurries. The following outcomes have been observed from the experimental results and data:

- The result clearly indicates that the FA Slurry Rheology depends on chemical additives. The shear stress decreases up to 0.06% of chemical additives and shows the non-Newtonian behavior with non zero yield stress.
- The data showed that the variation of shear stress with shear rate follow the Herschel-Bulkley model with shear thickening behavior and it changes to shear thinning at 0.07% of chemical additives.
- Dispersing agent reduces the viscosity of slurry and the surface tension reduces with addition of cationic surfactant that also improves the surface properties of slurry.

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