Optimization of Bottom Ash Water Slurry Flow Characteristics by using Commercial Additive

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Abstract: - In this study, the rheological feature of bottom ash-water slurry was investigated by using NaCl as an additive. The additive was added into the bottom ash suspension with proportions of 0.2, 0.4, and 0.6% (by weight). The range of solid concentration in the suspension varied from 10 to 60 % (by weight). When compared to the normal condition or without additive, the addition of NaCl results in a very obvious reduction in the apparent viscosity of the solution. The addition of 0.4% additive shows good agreement with the reduction of energy consumption as compared to the rest of the range of velocities. Because of the reduction in energy consumption, the required pump power decreased up to a remarkable limit of approximately 20%. Sensitivity analysis demonstrates that increasing NaCl concentration reduces apparent viscosity, pressure drop, and specific energy consumption, leading to improved flow efficiency. According to the findings of the investigation, the suspension of bottom ash slurry described in the above manner has the potential to be transported in a slurry pipeline using the least amount of energy.

Key-Words: - Additive, Rheology, Energy consumption, Pressure drop, Sustainability, Sensitivity.

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1 Introduction

In India, about 70% of the country's electricity comes from thermal power plants, where pulverized coal is burned to generate heat. The burning of coal results in the production of a significant volume of ash, [1], [2]. Fly ash is fine particles that are collected from electrostatic precipitators (ESP) and that are released along with the flue gases when coal ash is burned, while bottom ash is the coarser particles of coal ash that are collected from the bottom of the boiler furnace. Thermal power plants in India generate roughly 1,200,000 megawatts (MW) of electricity and produce 240 million tonnes (MT) of ash annually. Fly ash will account for around 180 million tonnes of this total, while bottom ash will be the remainder, [3]. Fly ash is transported using pneumatic mode in some of the plants, whilst bottom ash is transported through hydraulic mode via pipes from the plant to ash ponds. Pipelines are used to connect the plant and the ash ponds. At this time, bottom ash is being carried to the ash disposal system in the form of a lean mixture via pumps and pipelines. The approximate concentration range for this mixture is between 10-15% (by weight). Hydraulic characteristics such as carrier fluid, particle size, rheology, specific gravity, and solid concentration of the slurry are the fundamental components of every slurry transportation system. When it comes to the design of a slurry transportation system, the rheology of the slurry suspension plays a vital role. The rheology of the slurry suspension can be influenced by several features of solid particles, including form, size, concentration, and chemical composition, etc.

The rheological properties of ash slurry suspensions have been investigated by several different researchers, [4], [5], [6], [7]. On the other hand, there is no such thing as a universal correlation that can be found for the rheological behavior of slurry suspension. Additionally, the fact that it is dependent on a large number of circumstances makes it more complicated. It has been reported by several authors [8], [9] that fly ash exhibits non-Newtonian flow properties at higher concentrations (more than solid concentration 40% by weight). The incorporation of a particular ingredient into coal ash slurry has the potential to bring about dramatic alterations in the substance's rheological properties, [10], [11].

Electrolyte additives play a crucial role in modifying the rheological and flow properties of fluids, as highlighted by various studies. It also examined how ionic interactions in colloidal suspensions influence viscosity, demonstrating that electrolytes reduce internal resistance by screening inter-particle forces, [12], [13]. Similarly, explored drag modifications in fiber suspensions, showing that additives alter turbulence and flow resistance, [14], [15]. More recently, reviewed industrial applications of friction reduction techniques, emphasizing the benefits of additives in pipeline transport,[16], [17], [18]. Also, some research investigated the role of ionic additives in optimizing fluid transport, confirming their potential for reducing energy consumption in industrial processes, [19], [20], [21]. These studies collectively highlight the significance of electrolyte additives in enhancing flow efficiency and minimizing energy losses in various fluid transport systems. There are many reports available in the published literature on the rheological properties of fly ash slurry at high concentrations with and without additives. However, relatively few studies have been available on the rheological consideration of bottom ash slurry. The primary objective of this research was to compare the rheological and settling properties of bottom ash suspensions made with and without the addition of additives. As an addition, a common salt or NaCl solution was used.

2 Materials and Methods

2.1 Properties of Bottom Ash

The sample of bottom ash was taken from the RGTPS Hisar, which is located in the state of Haryana in India and mainly utilized coal from the coalfield of Odisha (India) for the production of electricity. The findings of an examination using a scanning electron microscope on a sample of bottom ash are depicted in Figure 1. The sample consists of irregular and more substantial particles that have a rough surface roughness. Particle size distribution of the bottom ash sample was evaluated using the sieve analysis method and shown in Figure 2(a). Around 62.50 % of particles are observed coarser than 150 µm, 30.10% of particles are in the range of 53-150 µm and only 7.40% of particles are finer than 53 µm. The weighted mean diameter of bottom ash was found as 148 µm. The specific gravity of bottom ash was measured as 1.94 by using the pycnometer method. To determine the particle size distribution of the bottom ash sample, the sieve analysis method was utilized. It was found that approximately 62.50 % of the particles had a size that was coarser than 150 µm, 30.10 % of the particles had a size that was between 53 and 150 µm, and 7.40 % of the particles had a size that was finer than 53 µm. The weighted mean diameter of bottom ash was determined to be 148 µm using various measurements. The pycnometer method was utilized to determine the specific gravity of bottom ash as 1.94.

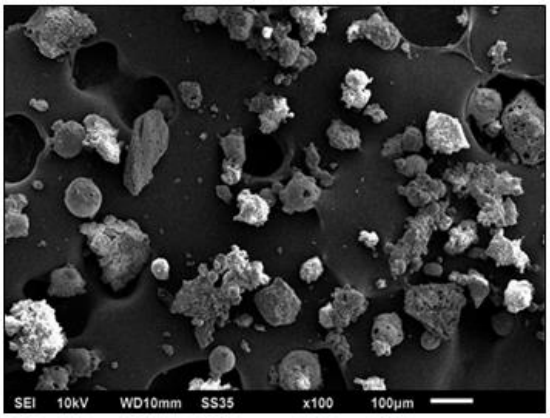

Fig. 1: Morphology of bottom ash sample

The use of Energy-dispersive X-ray spectroscopy allowed for the analysis of the sample of bottom ash to determine its constituent chemical elements as shown in Figure 2(b). It has been observed that the bottom ash sample has SiO2, Al2O3, FeO, and CaO at 53.3, 34.2, 3, and 3.4 % respectively. As was just illustrated, the particle surfaces are covered with a significant amount of aluminum and silicon. Also, it has been demonstrated that particles with a high surface enrichment of Al/Si have a significant impact, in the form of drag, on the flow behavior of coal ash slurry, [22], [23], [24].

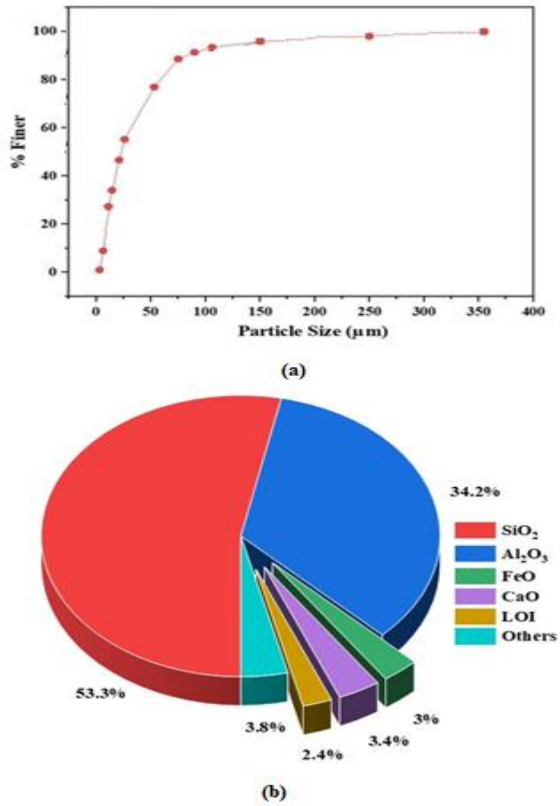

Fig. 2: (a) Equivalent diameter of particles and (b) chemical composition of bottom ash sample

A digital pH meter was utilized to get an accurate reading of the suspension's pH value. For solid concentrations ranging from 10 to 60 % (by weight), the bottom ash suspension had pH values in the range from 7.75 to 7.38, showing that it was chemically inert.

2.2 Properties of Additive

The use of Energy-dispersive X-ray spectroscopy allowed for the analysis of the constituent chemical elements present in the additive. The brief chemical composition of the additive sample is shown in Figure 3. When compared to those of Fe, Ca, Cu, and Mg, the percentages of Na and Cl are significantly greater.

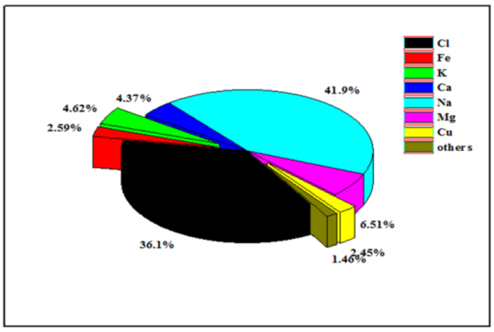

Fig. 3: Chemical composition of additive

It was represented that the commercially available NaCl powder is predominantly enriched with Na and Cl elements with the proportion of 41.9% and Cl respectively. The XRD studies were conducted on a commercial NaCl sample. The sample was cooked in the furnace for half an hour at a temperature of 200˚C to conduct a structure investigation. The structural analysis for the sample was carried out using the X-ray diffraction method on a copper target within a diffractometer 6000 X-ray diffraction spectrometer. The wavelength of the incident X-rays was 1.542 A˚. All of the measurements were carried out at room temperature, in the range of 2-Theta, degrees varies from 4 to 90˚C. IR radiation of the material with gamma rays was performed using a CO 60 gamma source at a dose rate of 2 kGy/h. The XRD analysis of the additive sample is shown in Figure 4. The maximum peak was observed at $2\theta = 32.4$ for Na, while some small peaks were also observed at 44.35 and 65.23 for Cl.

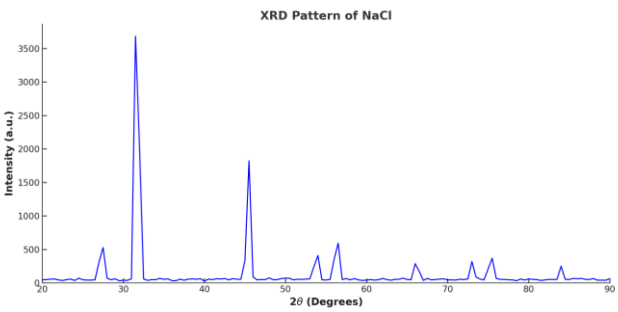

Fig. 4: XRD analysis of additive

2.3 Experimental Procedure

The rheological behavior of bottom ash suspension was measured utilizing a standard rheometer (Rheolab Q-C, Anton Paar Company Ltd, Germany) that functions according to the Searle principle. The schematic diagram of the rheometer is shown in Figure 5. While the rheometer's parameters are broken down in great depth in Table 1.

To calculate the rheological parameters for the ash suspension, shear stress was applied at a constant shear rate. A total of one hundred milliliters of ash was suspended in 100 ml of distilled water. It was discovered with the help of an electronic type single pan balance that the mass of the bottom ash suspension was (least count 0.001 mg). The bottom ash suspension was well-mixed thanks to the use of the glass rod, which enabled accurate mixing.

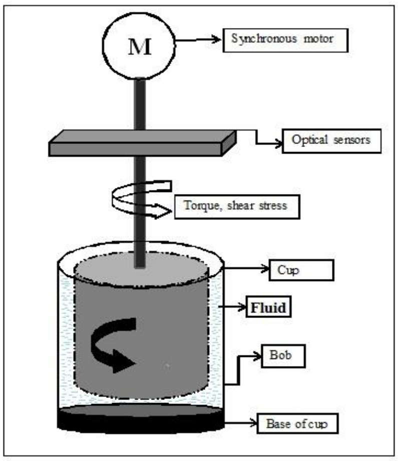

Fig. 5: Schematic of rheometer

Table 1. Specification of the rheometer (Rheolab QC)

S.No.	Component	Specifications
1	Motor type	Synchronous EC motor
2	Torque range	0.25-75 (mNm)
3	Speed range	0.01 to 1200 (min^{-1})
4	Shear stress range	0.5 to 3 x 107 (mPa)
5	Shear rate range	0.01 to 4000 sec^{-1}
6	Viscosity range	0.1 to 109 (mPas)
7	Motor type	Synchronous EC motor
8	Temperature Range	-20 to 180 (ºC)

Before beginning the rheological tests, a locking device was utilized so that the bob and cup assembly would not move while it was being held in place. After reaching the desired height, a suspension of bottom ash was added to the contents of a cup (or cylinder). To carry out rheological testing, all concentrations were subjected to shear rates ranging from 0 to 200 s^{-1} at a temperature that was held constant at 25°C. The experimental study was conducted for bottom ash suspensions both with and without the inclusion of additives. To use as an addition, we decided to go with NaCl solution. Water was utilized appropriately with varying solid concentrations of 10, 20, 30, 40, 50, and 60% (by weight) accordingly to make individual suspensions for each dried sample of bottom ash. This was done to produce individual samples of each dried sample.

Experiments were carried out a second time using bottom ash suspensions that also contained an additive. To the bottom ash suspension, an additive of NaCl was added in the following proportions of percentage by weight: 0.2%, 0.4%, and 0.6% respectively. Experiments in rheology were carried out multiple times using the same shear rate. This was done so that the data could be as accurate as possible.

3 Result and Discussion

During the experimentation, evaluation of the apparent viscosity of a bottom ash suspension has been done at a constant temperature of 25˚C. The concentration of the suspension ranged from ten to sixty percent (by weight). The shear stress and shear rate of each sample of bottom ash were determined. This result is indicative of the suspensions' non-Newtonian nature and conforms to the Bingham fluid behavior provided in the equation below:

$$\tau = \tau_\circ + \eta_p\dot{\gamma}, \quad \text{for } \tau \geq \tau_\circ \tag{1}$$

For shear stress below $\tau_\circ$, the material does not flow ($\dot{\gamma}$= 0).

In a pipe flow scenario, the momentum equation in cylindrical coordinates is:

$$\frac{d\tau}{dr} = -\frac{dP}{dz}\tau \tag{2}$$

Integrating and applying the boundary condition gives the velocity profile, consisting of;

- Shear Flow Region: Velocity follows the Bingham equation.
- Plug Flow Region: Velocity remains constant in the core region where $\tau < \tau_\circ$

$$Q = \frac{\pi R^4}{8\eta_p}\left(-\frac{dP}{dz} - \frac{d\tau_\circ}{R}\right) \tag{3}$$

For Newtonian fluids: $\tau = \mu\,\dot{\gamma}$
where μ is the dynamic viscosity (Pa\c.s)

For Bingham plastic fluids: $\tau = \tau_\circ + \eta_p\dot{\gamma}$ for $\tau \geq \tau_\circ$ and $\dot{\gamma}$ =0 otherwise.

The transition from Newtonian to Bingham behavior occurs when τ surpasses $\tau_\circ$.

The viscosities of all of the suspensions were determined by assuming that the obtained data could be fit into a straight-line equation. Figure 6 illustrates the range of shear stress and shear rate that bottom ash experiences across the solid concentration range that was previously discussed. Up to a solid concentration of 40%, the shear stress values increase linearly with the strain rate (by weight). Bottom ash suspensions exhibit non-Newtonian flow behaviour above a concentration of 40% (by weight), but the stress-strain rate relationship indicates.

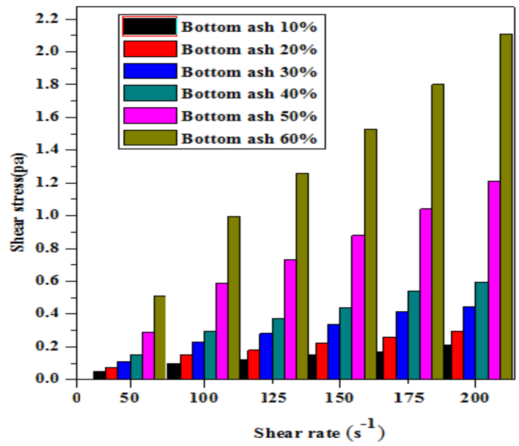

Fig. 6: Rheology of bottom ash sample

Newtonian flow characteristics up to that concentration. Non-Newtonian flow behavior in bottom ash suspensions occurs when the concentration is higher than 40% (by weight). The relative viscosity of the bottom ash was determined to be 1.02, 1.49, 2.26, 4.38, 5.69, and 9.95 after being tested at a range of solid concentrations ranging from 10% to 60% by weight. These percentages refer to the weight of the sample. The findings indicate that the viscosity of a suspension is exactly proportional to the amount of solid that is present in the solution. Because there are proportionally more solid particles in suspensions when the solid concentration is high, the shear tension (both particle-fluid and particle-particle) must be high to commence the shearing process. This is true for both particle-fluid and particle-particle interactions. When considering fly ash slurry, several studies, including [1], [14], [19], [20], came to the same conclusions.

3.1 Effect on the Rheological Character of Bottom Ash Suspension with Additive

At a solid concentration of 60%, the rheological characteristics of a bottom ash suspension with additives were investigated (by weight). The results of the measurements were taken at a room temperature of 25˚C degrees Celsius. It has been determined from the collected data that an increase in shear rate results in a reduction in the apparent viscosity of the bottom ash suspension. Additionally, the presence of additives in suspension promotes particle dispersion and enables a reduction in surface tension in addition to a reduction in the interparticulate forces of particles, which ultimately results in a reduction in Bingham viscosity, [21].

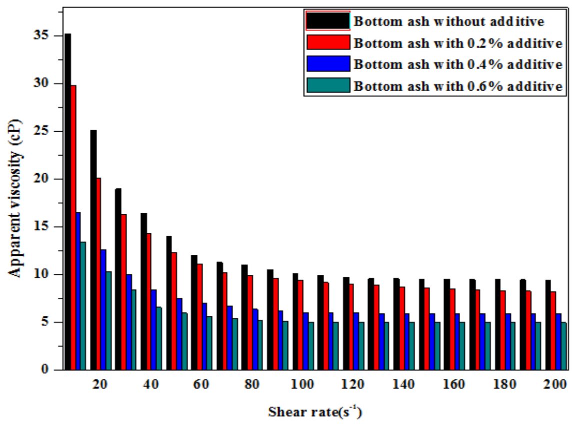

Fig. 7: Influence of shear rate on apparent viscosity for bottom ash suspension with and without additive

The effect of additive on the apparent viscosity of bottom ash suspension in proportion by weight (0.2-0.6% of total solids) is depicted in Figure 7. It was noticed that the additive of NaCl reduced the apparent viscosity of slurry up to a remarkable limit. With NaCl as an addition in the proportions of 0.2, 0.4, and 0.6%, the apparent viscosity was found to fall by 13.40, 42.47, and 17.08% at 10 s^{-1} shear rate, but only 10.79, 26.61, and 13.11% at 100 s^{-1} shear rate respectively. The experimental data make it abundantly clear that a decreasing trend of apparent viscosity is highly pronounced for the range of shear rate 10–100 s^{-1}, changes are marginal beyond shear rate 100 s^{-1}. Based on the findings presented above, it is possible to draw the conclusion that the apparent viscosity of bottom ash suspension decreases as the fraction of additives increases from 0.2 to 0.6%. As a result of the addition of additives, the molecular structure of the bottom ash suspension transforms tube shape into a globular structure. Because of this alteration, the drag friction between molecules has decreased, which in turn has led to a reduction in viscosity. The inclusion of additives at a percentage of 0.4% brings about the maximum reduction in apparent viscosity that can be achieved in a bottom ash suspension.

The tendency of decreased viscosity helps to reduce the pressure drop and the amount of energy required to maintain flow suspension in the pipeline. Researchers looked into how the addition of additives affected the rheological properties of fly ash slurry and found almost similar results, [14],[20]. The experimental rheological data were used to generate, a total of 80 apparent viscosity data points with a variation in shear rate for bottom ash suspension with and without additives in varying proportions. The findings of this study have been compared with the available data, [22]. The variation in relative viscosity for experimental and theoretical values derived with 80 data points for bottom ash suspension is shown below in Figure 8. The predicted relative viscosity values when compared with the experimental values, produce an excellent match at the 45° line. The result demonstrates that there was good agreement of relative viscosity within the deviation limits of ± 12%.

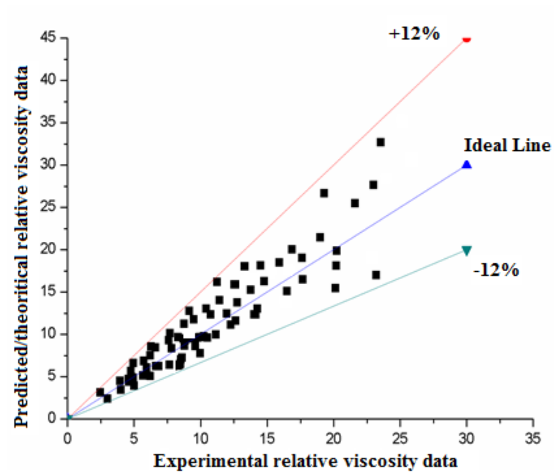

Fig. 8: Comparison of the experimental value of relative viscosity with predicted data

3.2 Effect of Additive on Settling Characteristics of Bottom Ash Suspension

The highest value of the solid concentration attained by using the gravitational settling method is referred to as the static settled concentration of the suspension and the behavior of the suspension of bottom ash about settling is dependent on the solid content as well as the viscosity, [22], [23]. Figure 9 represents the settling of the bottom ash suspension changes with time. It was determined that the initial solid content of the bottom ash suspension was 30%. (by weight). It was determined that the final static settled concentration of bottom ash suspension was 52.14 %.

The findings make it abundantly evident that the settling concentration of bottom ash suspension drops with increasing passage of time. It has been noticed that the concentration of the sediment that settles initially exhibits a significant increase with time but then almost returns to its original value after some time has passed.

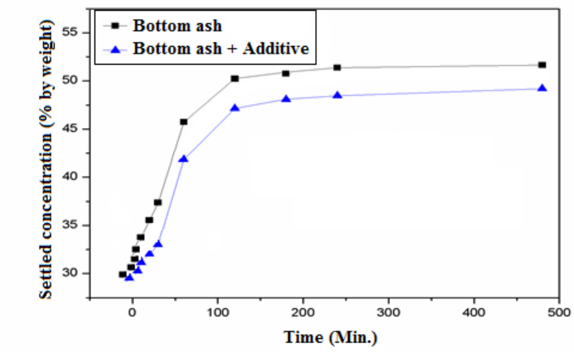

Fig. 9: Effect of additive on the settled concentration of bottom ash

Researchers also reported a similar pattern of settling behavior of slurry suspension, [18], [21]. The inclusion of additives results in a reduction in the static settling concentration of bottom ash in suspension. The final static settling of bottom ash suspension was reported to be 48.11 % with the addition of NaCl additive. The addition of an additive to the bottom ash suspension leads less settling of solid particles. This is accomplished by reducing friction between neighboring layers, which in turn tends to result in a reduction in the settling of bottom ash suspension. Because of this, the flow of the suspension will be smooth. Similar conclusions were drawn by researchers about the fly and bottom ash slurry, [25], [26], [27], [28].

3.3 Calculation of Specific Energy Consumption

The power that is necessary to move one tonne of solid-liquid suspension every kilometer is often regarded as specific energy consumption (SEC). The solid concentration of the suspension is taken as 60% to calculate the amount of energy that can be saved during the transit of bottom ash suspension in the pipeline (by weight). The flow of the suspension demonstrates characteristics of Bingham plastic flow. The Darby and Melson empirical approach was utilized to conduct the pressure drop in the pipeline analysis (1982). The pressure drop in a pipeline with a smooth interior and a diameter of 50 mm was measured. 100 meters was taken as the length of the pipe. The pressure drop is measured in meters of water column (mwc) and is determined for a pipeline that is 1 kilometre long across a wide variety of flow parameters.

For pressure – driven flow in a pipe, the energy dissipation per unit volume is given by:

$$E = \tau_\circ \dot{\gamma} \tag{4}$$

The pressure drop for Bingham plastic flow is:

$$\Delta P = \left(\frac{8\eta_p U}{D^2} + \frac{4\tau_\circ}{D}\right) L \tag{5}$$

where:
U = mean velocity (m/s)
D = pipe diameter (m)
L = pipe length (m)

At a solid concentration of 60% (by weight), the velocity of the suspension varied between 1.0 to 3.0 m/s. The additive named as NaCl solution, was put into the bottom ash slurry in the following proportions: 0.2, 0.4, and 0.6. (% by weight). The relationship between the pressure drop and the flow velocity is illustrated in Figure 10.

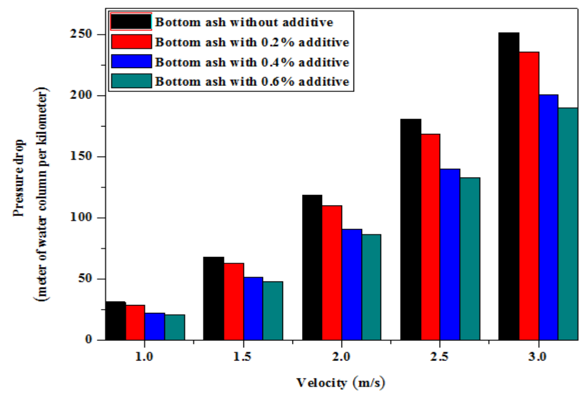

Fig. 10: Relationship between pressure drop and flow velocity

At a given solid concentration, it has been shown that the pressure drop increases with an increase in velocity, and the rate of increase is extremely noticeable at high velocities.

When 0.2, 0.4, and 0.6 (% by weight) of additive were added in the suspension, the values of pressure drop with a velocity of 1 meter per second are 28.60, 22.60, and 21.20 meters of water column per Km respectively. While values for the drop in pressure at a velocity of 3 m/s are 236.20, 201.20, and 190.20 respectively. Additionally, the maximum pressure drop was investigated using a 0.4% additive mixed in with the bottom ash suspension. Using fly ash slurry suspension, researchers acquire almost similar results, [12], [14], [24]. It is possible to calculate the particular energy consumption of the suspension by applying the following relation:

$$SEC = \frac{P}{\dot{m}} \tag{6}$$

For pipe flow, power is given by:

$$P = \Delta P Q \tag{7}$$

Substituting for ΔP:

$$SEC = \frac{\left(\frac{8\eta_p U}{D^2} + \frac{4\tau_\circ}{D}\right)LQ}{\rho Q} \quad (8)$$

Simplifying:

$$SEC = \frac{L}{\rho}\left(\frac{8\eta_p U}{D^2} + \frac{4\tau_\circ}{D}\right) \quad (9)$$

where ρ is the slurry density (kg/m^3)

Equations 6-9 were used to calculate the Specific Energy Consumption (SEC). Figure 11 displays the computed values of specific power consumption with and without the addition of additive in bottom ash suspension at a solid concentration of 60% (by weight) with various velocities ranging from 1 to 3 m/s.

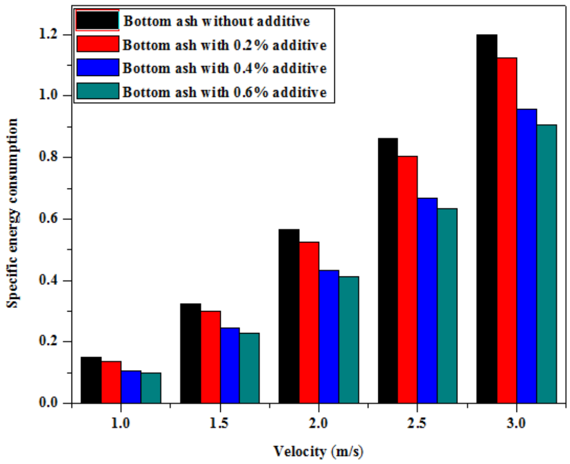

Fig. 11: Specific power consumption with and without the addition of additive at a solid concentration of 60% (by weight)

It has been shown that even a low dosage of the additive mixed to the bottom ash suspension, shows a significant impact on the SPC. The SPC for the bottom ash suspension drops by 10.14%, 21.97%, and 7.19%, respectively, after the addition of 0.2, 0.4, and 0.6% additive at a velocity of 1 m/s. Likewise, at a velocity of 3 m/s, the SPC of bottom ash suspension is decreased by approximately 7.23, 15.81, and 6.26% respectively. According to the results, the addition of 0.4% additive displays the greatest possible decrease in SPC at each of the relevant velocities. Because of the reduction in energy consumption, the pump power is roughly 22 and 16% lower at 1 and 3 ms^{-1} velocity respectively. As a result, the high-concentration suspension will be able to be disposed of through the pipeline system at a lower principal investment cost, or the bottom ash suspension will be able to be transported economically with the addition of a small dosage of additive. Both of these outcomes will be possible as a result of the effective pipeline system. However, it was also reported that additives affect the performance of pumps up to remarkable limits, [13], [15], [20], [21], [22], [23]. Researchers also reported similar trends for energy consumption by using different computational models and experimental analysis, [12], [17], [19], [24], [25].

3.4 Sensitivity Analysis

In order to check the effect of additives in slurry suspension, Sensitivity analysis has been conducted for the results and observations found from different mathematical and experimental analyses. The sensitivity analysis presented in the figures investigates the impact of NaCl concentration on apparent viscosity, pressure drop, and specific energy consumption in a flowing fluid system. The results indicate that the presence of NaCl significantly alters the fluid's rheological and hydrodynamic behavior, making it more efficient for flow applications.

3.4.1 Apparent Viscosity to Shear Rate

The variation of apparent viscosity with shear rate is shown in Figure 12(a). It is evident that as the shear rate increases, the apparent viscosity decreases for all cases, which is a typical characteristic of shear-thinning fluids. However, the presence of NaCl reduces the viscosity significantly compared to the no-additive case. The highest reduction in viscosity is observed at 0.6% NaCl concentration, suggesting that NaCl weakens the intermolecular forces within the fluid, thereby facilitating smoother flow. This behavior can be attributed to electrostatic interactions that alter molecular dispersion and hydration layers around the particles. Studies on polymer and colloidal suspensions have shown that electrolyte additives can reduce viscosity due to charge screening effects, which weaken inter-particle interactions and promote a more fluidized state, [26], [27].

3.4.2 Pressure Drop to Flow Velocity

The relationship between pressure drop and flow velocity is shown in Figure 12(b). A linear increase in pressure drop with velocity is observed, which is expected based on classical hydrodynamic principles. However, the fluids with NaCl additives exhibit a lower pressure drop compared to the no-additive case. This reduction in pressure drop correlates well with the decrease in viscosity seen in Figure 12(a), confirming that NaCl enhances flow efficiency by minimizing internal resistance.

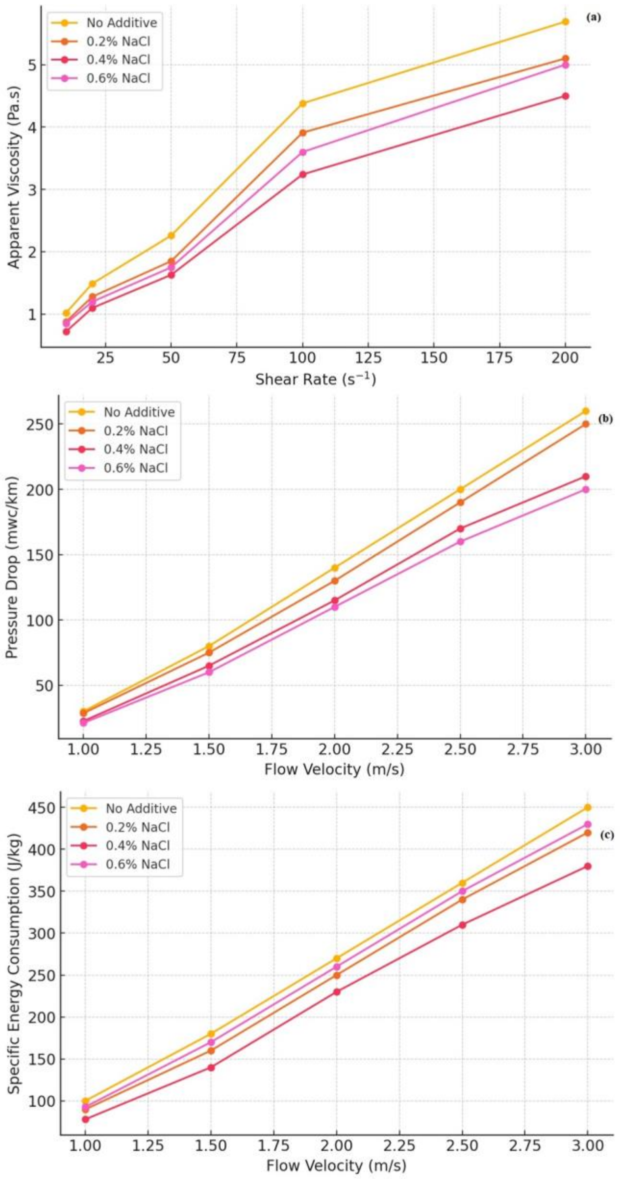

Fig. 12: Sensitivity analysis for the various parameters (a) Apparent Viscosity and shear rate (b) Pressure drop to flow velocity (c) Specific energy consumption to Apparent flow velocity

The reduction in pressure loss is particularly relevant for industrial applications where minimizing energy dissipation is crucial for cost-effective pipeline transport. Previous studies have reported similar drag reduction effects in polymeric and saline solutions, where the presence of salt alters the microstructure of the fluid, reducing turbulence and friction losses, [29].

3.4.3 Specific Energy Consumption to Apparent Flow Velocity

The specific energy consumption as a function of flow velocity shown in Figure 12(c). As expected, energy consumption increases with velocity, reflecting the growing power requirement for fluid transport. However, the fluids with NaCl exhibit lower specific energy consumption compared to the no-additive case, with the most significant reduction observed at 0.6% NaCl concentration. This result is consistent with the trends in Figure 12(a) and Figure 12(b), where viscosity and pressure drop reductions contribute to an overall decrease in energy demand. Research on energy-efficient fluid transport has highlighted that additives such as NaCl can optimize flow properties, leading to substantial savings in operational costs, [30], [31]

The sensitivity analysis demonstrates that increasing NaCl concentration reduces apparent viscosity, pressure drop, and specific energy consumption, leading to improved flow efficiency. These findings align with existing research on the role of electrolytes in modifying fluid behavior, particularly in non-Newtonian systems. The results suggest that optimizing NaCl concentration could be a practical strategy for reducing energy losses in industrial applications. Future studies could further investigate the combined effects of different electrolytes and additives to enhance flow performance while maintaining system stability and sustainability.

4 Conclusion

This study investigated the optimization of bottom ash-water slurry flow characteristics using NaCl as a commercial additive. Rheological analysis indicated a notable reduction in apparent viscosity, particularly at a concentration of 0.4% NaCl by weight. This optimized concentration significantly improved the slurry transport characteristics, resulting in approximately a 20% reduction in energy consumption. Moreover, sensitivity analysis of slurry flow indicated that the reduction in viscosity directly correlates with decreased pressure drop across the pipeline. This, in turn, substantially lowered the specific power consumption required to maintain slurry flow, demonstrating economic and environmental advantages in slurry transportation systems. Therefore, incorporating an optimal dosage of additive not only enhances the flow performance but also significantly contributes to sustainability by reducing both operational energy costs and the associated environmental impact.

Nomenclature:

SEC	Specific energy consumption (J/kg)
P	Power (W)
$\dot{m}$	Mass flow rate (kg/s)
ΔP	Pressure drop (Pa)
Q	Volumetric flow rate (m^3/s)

η	Dynamic viscosity/ plastic viscosity of the fluid (Pa·s)
U	Mean velocity of fluid (m/s)
D	Diameter of the pipe (m)
τ_0	Shear stress at the wall (Pa)
L	Length of the pipe (m)
ρ	Density of the fluid (kg/m³)
E	Energy dissipation per unit volume (W/m³)
τ_0	Shear Stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})
τ	Shear stress (Pa)
$\tau_\circ$	yield stress (Pa)
NaCl	Sodium chloride (Common salt)
pH	Phase of Hydrogen
C_W	Solid mass concentration (by weight %)
P_B	Power required for suspension flow
C_W	Solid mass concentration (by weight %)
^{o}	Degree

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