Stabilization and Rheological Behavior of Fly Ash–Water Slurry Using a Natural Dispersant in Pipeline Transportation

Debadutta Das,§,⊥ Swetashree Pattanaik,§ Pankaj Kumar Parhi,§,∥ Ranjan Kumar Mohapatra,⊥ Rajesh Kumar Jyothi,⊥ Jin-Young Lee,∥ and Hong In Kim∥

†Department of Chemistry, Sukanti Degree College, Subarnapur 767017, Odisha, India
‡Department of Chemistry, Trident Academy of Technology, Bhubaneswar 751024, Odisha, India
§School of Chemical Technology and School of Biotechnology, KIIT Deemed to be University, Bhubaneswar 751024, India
∥Convergence Research Center for Development of Mineral Resources (DMR), Korea Institute of Geosciences and Mineral Resources (KIGAM), Daejeon 34132, South Korea
⊥Department of Chemistry, Government College of Engineering, Keonjhar 758002, Odisha, India

ABSTRACT: Effective transportation of fly ash–water slurry through a pipeline from its generation site, a power plant, to a storage site by replacing commercial surfactants such as cetyl trimethyl ammonium bromide and sodium dodecyl sulfate by a natural dispersant extracted from Sapindus laurifolia was studied. The stability of fly ash slurry was determined from its rheological parameters, dispersant concentration, and stabilization mechanism. From surface tensiometric data, the critical micelle concentration of the dispersant was obtained to be 0.017 g/cc. The stabilization of high-concentration fly ash slurry has been studied through its rheological behavior by variation of temperature and dispersant and ash concentration. The rheological result obtained for fly ash concentrations in the range of 50–65% slurry was best justified by the Bingham plastic model. The wettability of fly ash particles is increased in the presence of dispersants, which is inferred from reduction of the surface tension value. The stabilization mechanism of the slurry is explained by a steric factor as indicated by the decrease in the zeta potential value. Air pollution is minimized at its destination site due to agglomeration of fly ash particles, which is confirmed from the SEM micrograph.

INTRODUCTION

Most of the energy requirement of India comes from burning fossil fuel. In more than 60% of the thermal power plants in India, a fine-grained particulate material known as fly ash is produced from burning of coal in a coal-fired boiler in the power plant and gets carried off in the flue gas. The fly ash is collected from the flue gas before it is released into the atmosphere, causing air pollution by means of particulate air pollution control equipment. Even though the massive production rate of fly ash in India attained only a utilization rate of around 45% in the cement industry, those from the production of building materials and others are disposed of onto land through landfills or ash ponds. It has been reported by some researchers that fly ash-derived particles may be used in potential drug delivery systems, anti-biofouling systems, and low-cost adsorbents for removal of organic dyes and geolite synthesis. Many environmental problems related to soil, air, and water pollution escalate due to fly ash. Fly ashes are usually disposed of onto ash ponds in a slurry form through pipelines from thermal power plants. Such a type of disposal system requires a large amount of water and energy, which makes the process uneconomical as fly ashes with concentrations varying from 10 to 15% are transported. The economical transportation of solid concentration slurry should be high, which in turn requires less amount of water, a low energy requirement for pumping, and low-energy wastage, which is an environmentally friendly and emerging trend. This causes an increase in slurry viscosity and yield stress; therefore, more pumping power is required for transportation and it is very much essential to know the rheological behavior of the slurry at various ash concentrations. Furthermore, it is also necessary to study the surface effect of the surfactant and other microscopic particles. The transportation of high-volume fly ash slurry through long distances in pipelines is always challenged by friction loss, elevated energy consumption, and high settlement rate in the pipelines. There have been several attempts to transport high-concentration fly ash slurry in pipelines all over the world. In the past decade, a number of techniques have been investigated, which alter the flow behavior of slurry either by reducing the pressure drop or...
reducing adversely the impact of rheological properties. The flow behavior of fly ash slurry depends on different factors, for instance, shape of particles, particle size distribution, solid concentration in slurry, and slurry viscosity.\textsuperscript{9} Viscosity and shear stress of slurry could be decreased by adding different additives, thereby enhancing the possibilities of a high percentage of solids in the slurry transportation.\textsuperscript{10} Many investigators have examined the effects of various additives on the rheological behavior of fly ash slurry at high concentrations during pipeline transportation. A substantial reduction in the viscosity of the slurry was observed by using 0.1% sodium hexametaphosphate by mass.\textsuperscript{6} The fly ash slurry stabilization by considering the combined effect of 0.1% sodium hexametaphosphate and particle size distribution at different ash concentrations were reported, which ensue non-Newtonian rheology of the slurry.\textsuperscript{11} The reduction of Bingham plastic viscosity, yield stress by using sodium carbonate (0.2% by mass) and Henko detergent (5:1) as an additive in fly ash concentration from 50 to 70% by mass.\textsuperscript{12} The outcomes of dispersants such as cetyl trimethyl ammonium bromide (CTAB) and sodium salicylate on stabilization of fly ash slurry in the solid concentration range from 20 to 40% at varying temperatures from 20 to 40 °C reported that the apparent viscosity and shear stress decrease with the increase in temperature even without an additive and the optimized additive concentration in the range of 0.2 to 0.3% by mass.\textsuperscript{13–16}

With respect to the charge on the surface, three types of dispersants (cationic, anionic, and nonionic polymers such as cetylpyridinium chloride, sodium dodecyl sulfate (SDS), and Triton X-100, respectively) are established to reduce viscosity, and a shear stress of 40% mass concentration of fly ash slurry was reported.\textsuperscript{17} The flow behaviors of high-concentration fly ash slurries with a solid concentration of 32 to 49% can be illustrated by the non-Newtonian power law model as they are greatly pseudo-plastic in nature and the relative viscosity of slurry depends on the concentration of the solid volume fraction, particle size, and their distribution as examined by Senapati et al.\textsuperscript{18} They have developed a model for power plant ash slurry, integrating the maximum solid fraction, median particle size, coefficient of uniformity, and shear rate power law index to predict the apparent viscosity. Particle gradation has a remarkable effect on the ash concentration and pressure drop observed by Kumar et al.\textsuperscript{19} that comparatively less energy required for transportation and even less energy than fine ash slurry for optimized particle size distribution that is the ratio of fly ash and bottom ash in the range 4:1 to 3:2. The mixture of surfactants tris(2-hydroxy-ethyl) tallow alkyl ammonium acetate [tallow alkyl N-(C\textsubscript{2}H\textsubscript{4})(OH)\textsubscript{3}], sodium salicylate used as a counterion, and copper hydroxide [Cu(OH)\textsubscript{2}] in a certain ratio can stabilize the fly ash slurry to a considerable extent.\textsuperscript{20} Elizabet et al.\textsuperscript{21} have investigated the effect of an anionic surfactant, sodium lauryl sulfate, on the fly ash surface at different concentrations and a temperature range from 50 to 80 °C. They reported that fly ash treated with a surfactant was more hydrophobic than untreated fly ash due to the remarkable reduction of the degree of agglomeration.

A high concentration of ~300 g/L fly ash slurry can competently be stabilized by an equimolar mixture of biopolymers hydroxypropyl guar gum and xanthan gum. The stability of fly ash–water slurry can be increased by increasing the biopolymer concentration in a time period of ~72 h, which is confirmed by the elastic modulus value.\textsuperscript{22} In addition to the cationic surfactant and biopolymer, anionic surfactant SDS also exhibits an excellent stabilizing effect on microfly ash slurry, which inhibited spontaneous coal combustion.\textsuperscript{13,23}

From literature reviews, a conclusion that most of the additives or dispersants used in fly ash slurry stabilization are synthetic in nature and not eco-friendly can be drawn. Therefore, in the present investigation, an attempt has been made to utilize a natural dispersant from the plant, Sapindus mukorossi (S. laurifolia). It is saponin rich and typically in profusion in India. Saponin is a naturally occurring nonionic surfactant, which contains a hydrophilic component described as glyconic consisting of polysaccharides, such as rhamnose, pentose, galactose, and glucose, and a hydrophobic component described as aglyconic. An aglycon is made up of steroids and triterpenes, which are linked with a polysaccharide unit through oxygen and so on to form macromolecules.\textsuperscript{24} In this paper, we have reported the rheological behavior of fly ash slurry using the aqueous extract of S. laurifolia as a dispersant. Also, the agglomeration of fly ash particles after their transportation to the destination site is observed, which leads to minimization of air pollution.

\section*{RESULTS AND DISCUSSION}

\textbf{Optimization of S. laurifolia Concentration.} The dispersants are the molecules that experience steric hindrance and/or electrostatic repulsion while adsorbing on the fly ash surface.\textsuperscript{15,25} The mechanisms of stabilization of the slurry rely on the susceptibility of the dispersant to be attached on the fly ash surface. The presence of surfactants in solution reduces the surface tension or interfacial tension of the solution. Thus, surface tension of the solvent consistently decreases with a gradual increase in the dispersant concentration. From Figure 1, it is observed that the minimum surface tension is achieved at 0.017 g/cc, which is the critical micelle concentration (CMC) of the dispersant. A correlation can be established between van der Waals forces of attraction among the fly ash particle and the amount of dispersant adsorbed. It has been found that by adding more of the dispersant to the slurry, the magnitude of van der Waals forces of attraction among the fly ash particles can be minimized. From Figure 2, it is observed that by increasing the concentration of dispersants from 0.010 to 0.017 g/cc containing a 60% weight fraction of fly ash, the apparent viscosity of the fly ash slurry decreases from 1680 to 503 mPa. Upon further increasing the S. laurifolia concentration, there is no appreciable reduction of the apparent viscosity and plateau values are obtained, which may be due to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Plot of dispersant concentration versus surface tension.}
\end{figure}
the formation of micelles and no further adsorption of dispersants on the fly ash surface.26

Effect of Fly Ash Loading on Apparent Viscosity of Slurry. The apparent viscosity of the slurry can be altered by varying the concentration of fly ash in the slurry, which is very important in pipeline transportation. The viscosity of slurry is the resultant effects of van der Waals forces among fly ash particles. Thus, the viscosity increases with the rise in the amount of fly ash loading as they get agglomerated at higher concentration. The indispensable condition for better slurry transportation is during the transportation viscosity, which should be low and high at the destination end for better sedimentation.7,26 Figure 3 describes the deviation of the apparent viscosity of the slurry by adding different amounts of fly ash in the range of 50—64%.27,28 The slurry follows the equation of the Bingham plastic model

$$\tau = \tau_0 + \gamma \eta$$  \hspace{1cm} (1)

where \( \gamma \) and \( \tau \) indicate the applied shear rate and shear stress, respectively. \( \tau_0 \) is the yield stress, and \( \eta \) is defined as the Bingham viscosity. The initial threshold of shear stress and yield stress of slurry increases with the rise in the solid weight fraction of fly ash in the fly ash–water slurry, which may be attributed to the increase in particle–particle interactions due to greater packing of fly ash. It is confirmed from Figure 4a,b that the natural dispersant, saponin from \( S. \ laurifolia \), exhibits a similar type of flow characteristic to CTAB.

Effect of Temperature on Apparent Viscosity. There is a correlation between the viscosity of the fluid and ease of movement of molecules with respect to one another. With the increase in temperature, the apparent viscosity of the slurry decreases due to the decrease in cohesive force between the particles and the increase in dissolving capacity of the dispersant.14,29 Therefore, the yield stress decreases with the rise in the temperature. In our present investigation, Figure 5 describes an exponential decrease in viscosity with the increase in temperature. This may be due to the decrease in interparticle attraction as the kinetic energy of fly ash particle increases. Also, first, moving the suspended sugar chain of

Figure 2. Plot of dispersant concentration versus apparent viscosity.

Figure 3. Plot of fly ash concentration versus apparent viscosity.

Figure 4. (a) Plot of shear stress versus shear rate of fly ash slurry in the presence of a natural dispersant. (b) Plot of shear stress versus shear rate of fly ash slurry in the presence of commercial surfactant CTAB.
saponin at the fly ash–water interface increases the mobility of the fly ash particle. The Arrhenius expression (eq 2) describes the relation between viscosity and temperature that may be represented by a simple relation as
\[
\eta = A \exp\left(\frac{E}{RT}\right)
\]
On rearrangement, eq 2 yields eq 3
\[
\ln(\eta) = \frac{E}{RT} + \ln(A)
\]
The above equation represents the apparent viscosity at a particular shear rate where \(T\) is the temperature in kelvin of the slurry, \(E\) is the activation energy for the fluid flow, \(R\) is the universal gas constant, and \(A\) is the fitting parameter.

**Surface Activity of the Fly Ash Slurry.** Dispersants are surface active agents that reduce the interfacial tension between solid particles and the liquid in the slurry system by lowering the surface tension of a liquid, which improves the wettability of fly ash particles. The stabilization of the fly ash slurry primarily depends upon the binding tendency of the dispersant to the fly ash surface. The more the dispersant is at ease in the solution, the less is its tendency to be adsorbed onto the fly ash surface. Therefore, the study of solution behavior of the dispersant in the mixture is essential. The effect of surface tension by the dispersant depends on the replacement of solvent molecules at the surface of solution, that is, the air–water interface. With the increase in the exchange of solvent molecules by the surfactant at the interface, the surface tension decreases. The surface tension decreases with the increase in the dispersant molecules in the mixture and hence in the dispersant concentration in the mixture, which indicate the segregation of the interface that was inhibited beyond CMC. The gradual decrease in the surface tension with the increase in dispersant concentration in the slurry has been observed with 20% fly ash concentration, and the minimum surface tension value of 40 mN/m at a CMC of dispersant at 0.017 g/cc was attained and was immutable thereafter, as observed from Figure 6.

![Figure 5. Plot of apparent viscosity versus temperature.](Image)

**Stabilization Mechanism of Fly Ash Slurry.** In the preparation of stable high-concentration fly ash slurry, particles should not be agglomerated to each other, which can be achieved by creating a repulsive barrier between the fly ash particles. Stabilization of fly ash slurry depends upon the extent of stabilization of silica (SiO₂) and alumina (Al₂O₃) particles because of the major contribution up to 54.6 and 32.8%, respectively. The mechanism of stabilization can be explained either by a steric or electrostatic factor. In our present investigation, the zeta potential of slurry decreases from −29 to −13 mV at CMC of the dispersant, and the mechanism of stabilization may be due to steric repulsion instead of electrostatic repulsion. Due to a certain kind of specific interaction with silanol hydrogen, the hydrophobic part of the dispersant is attached to the fly ash surface and the hydrophilic sugar chain is hydrated, as shown in Figure 8a,b, respectively. This type of interaction creates a steric barrier around each particle and inhibits particle–particle association.

**Comparative Cost Analysis with Commercial Dispersant.** The cost of additive *S. laurifolia* fruits (Tables 1 and

![Figure 6. Plot of surface tension versus dispersant concentration.](Image)

![Figure 7. Plot of zeta potential versus dispersant concentration.](Image)
2) used in the viscosity reduction of fly ash–water slurry has been estimated by comparing its cost with well-known commercial dispersants CTAB and SDS. From Figure 9a, the lowest viscosity is observed at 0.325 × 10⁻³ g/cc CTAB concentration, and no significant change in viscosity is observed with a further increase in CTAB concentration. Similarly, from Figure 9b, the lowest viscosity is observed at 2.34 × 10⁻³ g/cc SDS concentration. Since the CMCs of CTAB and SDS concentrations are 0.9 mM (0.328 × 10⁻³ g/cc) and 8.2 mM (2.34 × 10⁻³ g/cc), respectively, the optimized concentration for pipeline transportation may be their CMC. From viscosity measurement and CMC results, the stabilizing effect of 1 kg of CTAB is equivalent to 51.82 kg of S. laurifolia fruits. Thus, the estimated overall cost of the dispersant CTAB is determined to be ∼3.6-fold in comparison to that of a S. laurifolia fruit. The cost of a S. laurifolia fruit is ∼0.72 U.S. dollars per kilogram in India, whereas the CTAB (Merck, India) costs ∼186 U.S. dollars (per kg). Similarly, by comparing with SDS, 7.26 kg of S. laurifolia fruits has an equal stabilizing effect on fly ash slurry with 1 kg of SDS.

### Table 1. Comparative Cost Analysis of S. laurifolia with CTAB

| Sl. no | surfactant     | amount of additive (kg) | CMC (g/cc) | price, (USD) |
|--------|----------------|-------------------------|------------|--------------|
| 1      | CTAB           | 1.0                     | 0.328 × 10⁻³ | 186          |
| 2      | S. laurifolia fruit | 51.829                  | 0.017      | 50.65        |

### Table 2. Comparative Cost Analysis of S. laurifolia with SDS

| Sl. no | surfactant     | amount of Additive (kg) | CMC (g/cc) | price (USD) |
|--------|----------------|-------------------------|------------|-------------|
| 1      | SDS            | 1.0                     | 2.34 × 10⁻³ | 355.27      |
| 2      | Sapindou s. laurifolia fruit | 7.264                  | 0.017      | 7.09        |

### CONCLUSIONS

The pipeline transportation of fly ash from the thermal power plant to its destination site such as an ash pond is an economical method with a minimum negative impact on the environment by utilizing an aqueous extract of S. laurifolia, wisely replacing well-known commercial dispersants CTAB and SDS. This natural dispersant stabilizes the fly ash slurry to the maximum extent at 0.017 g/cc, which is the CMC. Wettability of fly ash slurry is increased, which is confirmed from the reduction of the surface tension value from 70.6 to 40 mN/m. The decreased value of the zeta potential from −29 to −13 mV confirmed that the stabilization mechanism is of a steric type instead of electrostatic repulsion. The SEM image (Figure 10) of the air-dried slurry indicates that there may be agglomeration of fly ash particles in the presence of the dispersant S. laurifolia.

### MATERIALS AND METHODS

#### Procurement of Fly Ash Sample

The fly ash sample was procured from Jindal Steel, Chhattisgarh. The fly ash physical characteristic properties are given in Table 3, and the chemical assay is summarized in Table 4. The particle size distribution of the fly ash sample was measured by a particle size analyzer (Malvern, Pvt. Ltd.), and its peak pattern is presented in Figure 11. The surface topography of the fly ash sample was examined...
Preparation of Aqueous Extract of *S. laurifolia*. The additive *S. laurifolia* was collected from the Eastern sector forest of Odisha, India. Dry fruits of *S. laurifolia* (10 g) were taken, and the pericarp of the fruits was removed, dried, and powdered. The pericarp of *S. laurifolia* was changed to a powder form and then dissolved in a desired volume (100 mL) of water. The aliquot was subjected to agitation for a duration of 3 h using a magnetic stirrer. Then, the supernatant solution obtained was centrifuged (centrifuge, Eppendorf, Pvt. Ltd.) and filtered to extract the active component as saponin into the corresponding aqueous medium. This extract was utilized as the dispersant in the preparation of fly ash–water slurry.

Surface Activity of the Aqueous Extract of *S. laurifolia*. The surface tension of the aqueous extract was measured using a surface tensiometer (Kyowa-350, Japan). The varying trend of the surface tension of the aqueous phase is plotted with depressant concentration, and results are shown in Figure 1. The trend shows a quick drop of surface tension while increasing the depressant dose. The pure water surface tension is 72 mN/m and gets saturated until a minimum value of 40 mN/m, where the concentration of depressant reaches 0.017 g/cc (1.7 wt %).

Measurement of Surface Charge on Fly Ash Particles. The probe 24V (52–60 Hz) T3A attached to a microprocessor was used in measuring the zeta potential for the fly ash slurry sample. The condition of 10% S/L of fly ash with deionized water was maintained and then subjected to stirring at 400 rpm for 30 min at a temperature of 25 °C. Subsequently, 1 mL of the resulting sample was taken for zeta potential analysis. Similarly, the zeta potential of fly ash along with a dispersant was determined at varying doses at the same conditions. Most of the experiments were investigated in triplicate; furthermore, the mean values were considered and reported.

Measurement of Rheological Behavior. The rheology experimental study for fly ash slurry was examined using a HAAKE RheoStress 1(Thermo Scientific rheometer). For the test, the slurry was prepared by slowly adding fly ash ranging from 50 to 65% by weight in distilled water with continuous stirring of the mixture for 5 to 10 min. In this study, ~30 mL of the slurry sample was introduced into a cleaned rheology cup in which the temperature was maintained up to 30 °C. The experiment was tested twice, and the average output data was further analyzed. The relationship of shear stress and shear rate showed the best fit to the Bingham plastic model.

![Figure 10. SEM microphotograph of agglomeration of fly ash in the presence of dispersants.](image1)

![Figure 11. Particle size distribution of the fly ash sample (ref 36).](image2)

![Figure 12. SEM photomicrograph of the fly ash sample.](image3)
Author Contributions

Debadutta Das: 0000-0001-6983-1740

ORCID
Debadutta Das: 0000-0001-6983-1740

Author Contributions
All authors have equally contributed and given approval to the final version of the manuscript.

Funding
The authors have no financial support for this research.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

D.D. would like to acknowledge Dr. P. K. Senapati of CSIR-IMMT Bhubaneswar for his technical expertise and discussions. P.K.P. acknowledges KIGAM, South Korea, for awarding Visiting Scientist. R.K.M. is thankful to Prof. Trilochan Sahu, Principal, Government College of Engineering, Keonjhar, for providing necessary facilities. The co-authors of KIGAM thankfully acknowledge the National Research Council of Science and Technology (NST) and KIGAM, South Korea, with the support from the Ministry of Science, ICT, and Future Planning of Korea.

ABBREVIATIONS

CTAB: cetyl trimethyl ammonium bromide
SDS: sodium dodecyl sulfate
PSD: particle size distribution
CMC: critical micelle concentration
SEM: scanning electron microscope

REFERENCES

(1) He, W.; Frueh, J.; Hu, N.; Liu, L.; Gai, M.; He, Q. Guidable Thermophoretic Janus Micromotors Containing Gold Nanocolonifers for Infrared Laser Assisted Tissue Welding. Adv. Sci. 2016, 3, 1600206.
(2) Gai, M.; Frueh, J.; Hu, N.; Si, T.; Sukhorukov, G. B.; He, Q. Self-propelled two dimensional polymer multilayer plate micromotors. Phys. Chem. Chem. Phys. 2016, 18, 3397–3401.
(3) Mu, L.; Rutkowski, S.; Gai, M.; Frueh, J. Alginite Microparticle Arrays as Self-Polishing Bio-Fouling Release Coatings. J. Nanosci. Nanotechnol. 2019, 19, 8052–8062.
(4) Ahmaruzzaman, M. A Review on the utilization of fly ash. Prog. Energy Combust. Sci. 2010, 36, 327–365.
(5) Chandel, S.; Seshadri, V.; Singh, S. N. Transportation of high concentration coal ash slurries through pipelines. Inter. Appl. Sci. Technol. 2010, 1, 1–9.
(6) Seshadri, V.; Singh, S. N.; Jain, K. K.; Verma, A. K. Rheology of fly ash slurries at high concentrations and its application to the design of high concentration slurry disposal system (HCSD). In Proceedings of the International Conference on Fly Ash Utilization; Indian Journals: 2005, 1, 10.
(7) Senapati, P. K.; Mohapatra, R.; Pani, G. K.; Mishra, B. K. Studies on rheological and leaching characteristics of heavy metals through selective additive in high concentration ash slurry. J. Hazard. Mater. 2012, 229-230, 390–397.
(8) Frueh, J.; Gai, M.; Halstead, S.; He, Q. Chapter 2: Structure and Thermodynamics of Polyelectrolyte Complexes. In Polyelectrolyte: Thermodynamics and Rheology; Springer: 2014.
(9) Assefa, K. M.; Kaushal, D. R. Experimental study on the rheological behaviour of coal ash slurries. J. Hydrol. Hydromech. 2015, 63, 303–310.
(10) Vlasak, P.; Chara, Z.; Stern, P. Drag reduction of dense Fine-Grained slurries. J. Hydrol. Hydromech. 2010, 58, 261–270.
(11) Verma, A. K.; Singh, S. N.; Seshadri, V. Pressure drop for the flow of high concentration solid liquid mixture 90° horizontal conventional circular pipe bends. Indian J. Eng. Mater. Sci. 2006, 13, 477–483.
(12) Chandel, S.; Seshadri, V.; Singh, S. N. Effect of additive on pressure drop and rheological characteristics of fly ash slurry at high concentration. Part. Sci. Technol. 2009, 27, 271–284.
(13) Naik, H. K.; Mishra, M. K.; Rao Karanam, U. M.; Deb, D. Evaluation of the role of a cationic surfactant on the flow characteristics of fly ash slurry. J. Hazard. Mater. 2009, 169, 1134–1140.
(14) Naik, H. K.; Mishra, M. K.; Rao Karanam, U. M. The effect of drag-reducing additives on the rheological properties of fly ash-water suspensions at varying temperature environment. Coal Combust. Gasif. Prod. 2009, 1, 25–31.
(15) Naik, H. K.; Mishra, M. K.; Rao, K. U. M. Influence of chemical reagents on rheological properties of fly ash–water slurry at varying temperature environment. Coal Combust. Gasif. Prod. 2011, 3, 83–93.
(16) Naik, H. K.; Mishra, M. K.; Rao, K. U. M. Rheological characteristic of fly ash slurry at varying temperature environment with and without an additive; World of coal ash (WOCA) conference: 2009.
(17) Kunal, S.; Kundan, L. Effect of Cetylpyridinium chloride, Triton x-100 and Sodium Dodecyl Sulphate on rheology of fly ash slurry. Int. J. Sci. Res. Publ. 2012, 2, 1–5.
(18) Senapati, P. K.; Mishra, B. K.; Parida, A. Modeling of viscosity for power plant ash slurry at higher concentrations: Effect of solids volume fraction, particle size and hydrodynamic interactions. Powder Technol. 2010, 197, 1–8.
(19) Kumar, U.; Singh, S. N.; Seshadri, V. Experimental investigation on pressure drop characteristics of Bi-modal slurry flow in a straight horizontal pipe. Int. J. Sci. Eng. Res. 2015, 6, 153–158.
(20) Aguilar, G.; Gasićević, K.; Mattheys, E. F. Reduction of friction in fluid transport- experimental investigation. Rev. mex. fis. 2006, 52, 444–452.
(21) Elizabet, M. V.; Linda, C. P.; Richard, A. K.; Lethabo, C. M. Characterization of coal fly ash modified by sodium lauryl sulphate, World of Coal Ash Conf. (WOCA), Denver, USA: 2011.
(22) Shi, Q.; Qin, B.; Bi, Q.; Qu, B. Fly ash suspensions stabilized by hydroxypyropyl guar gum and xanthan gum for retarding spontaneous combustion of coal. Combust. Sci. Technol. 2018, 190, 2097–2110.
(23) Qin, B.; Jia, Y.; Lu, Y.; Li, Y.; Wang, D.; Chen, C. Micro-fly-ash particles stabilized Pickering foams and its combustion - retardant characteristics. Fuel 2015, 154, 174–180.
(24) Das, D.; Panigrahi, S.; Misra, P. K.; Nayak, A. Effect of Organized Assemblies. Part 4. Formulation of Highly Concentrated Coal-Water Slurry Using a Natural Surfactant. Energy Fuels 2008, 22, 1865–1872.
(25) Pani, G. K.; Rath, P.; Barik, R.; Senapati, P. K. The effect of selective additives on the Rheological behavior of power plant ash slurry. Part. Sci. Technol. 2015, 33, 418–422.
(26) Das, D.; Panigrahi, S.; Senapati, P. K.; Misra, P. K. Effect of Organized Assemblies. Part 5: Study on the Rheology and Stabilization of a Concentrated Coal-Water Slurry Using Saponin of the Acacia concinna Plant. Energy Fuels 2009, 23, 3217–3226.
(27) Skarvelakis, C.; Antonini, G. Rheological behaviour of multiphase slurries for combustion applications. Fuel 1996, 75, 1758–1760.
(28) Guo, D.-h.; Li, X.-c.; Yuan, J.-s.; Jiang, L. Rheological behaviour of oil-based heavy oil, coal and water multiphase slurries. Fuel 1998, 77, 209–210.
(29) Das, D.; Dash, U.; Meher, J.; Misra, P. K. Improving stability of concentrated coal–water slurry using mixture of a natural and synthetic surfactants. Fuel Process. Technol. 2013, 113, 41–51.
(30) Mishra, S. K.; Senapati, P. K.; Panda, D. Rheological behavior of Coal-water slurry. Energy Sources 2002, 24, 159–167.
(31) Rontu, N.; Vaida, V. Surface partitioning and stability of pure and mixed films of 8–2 fluorotelomer alcohol at the air–water interface. J. Phys. Chem. C 2007, 111, 11612–11618.

(32) Boger, D. V.; Leong, Y. K.; Christie, G. B.; Mainwaring, W. E. Flow behavior of high studies brown-coal-water suspensions as liquid fuel In. Proceedings of the Australasian Institute of Mining and Metallurgy Annual Conference on Coal Power; Australasian Institute of Mining and Metallurgy: New Castle, Australia, 1987.

(33) Misra, P. K.; Somasundaran, P. Organization of amphiphiles VI. A comparative study of the orientation of polyoxyethylated alkyl phenols at the air-water and the silica-water interface. J. Surfact Deterg. 2015, 7, 373–378.

(34) Misra, P. K.; Panigrahi, S.; Somasundaran, P. Organization of amphiphiles, Part VIII: Role of polyoxyethylated alkylphenols in optimizing the beneficiation of hydrophilic mineral. Int. J. Miner. Process. 2006, 80, 229–237.

(35) Misra, P. K.; Dash, U.; Somasundaran, P. Effect of Organized Assemblies, Part VII: Adsorption Behavior of Polyoxyethylated Nonyl Phenol at Silica–Cyclohexane Interface and Its Efficiency in Stabilizing the Silica–Cyclohexane Dispersion. Ind. Eng. Chem. Res. 2009, 48, 3403–3409.

(36) Pattanaik, S.; Parhi, P. K.; Das, D.; Samal, A. K. Acacia concina: A natural dispersant for stabilization and transportation of fly ash-water slurry. J. Taiwan Inst. Chem. Eng. 2019, 99, 193–200.

(37) Routray, A.; Senapati, P. K.; Padhy, M.; Das, D.; Mohapatra, R. K. Effect of mixture of a non-ionic and a cationic surfactant for preparation of stabilized high concentration coal water slurry. Int. J. Coal Prep. Util. 2019, 1.

(38) Das, D.; Routray, A.; Pattanaik, S.; Parhi, P. K.; Das, B. R.; Narayan, S. Effect of particle size distribution and selective alcohol additive for preparation of stabilized high concentration coal water slurry. Micro Nanosyst. 2019, DOI: 10.2174/1876402912666191010142942.

(39) Dash, U.; Misra, P. K. Organization of amphiphiles XII. Evidence in favor of formation of hydrophobic complexes in aqueous solution. J. Colloid Interface Sci. 2011, 357, 407–418.