



# Characteristics of foam sol clay for controlling coal dust

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## ABSTRACT

A foam sol clay (FSC) mixture, mainly composed of fly ash (FA), surfactant (*n*-amylamine) and polyethylene oxide (PEO), was proposed for coal dust control. The FA surface, modified by a FSC solution, stability and foamability were investigated. It was found that the FA surface in alkaline solution was deprotonated to form a negative charge, which could be adsorbed by the polar head group of *n*-amylamine via electrostatic interactions. As a result, with increasing surfactant, the particles gradually converted from hydrophilic to hydrophobic and attached at gas-liquid interfaces so that the contact angle, zeta potential, froth stability and foamability increased. At a surfactant concentration ( $c_s$ ) of 35 g/L, a monolayer three-dimensional network was formed and the maximum foamability and half-life were obtained. Upon further increasing  $c_s$ , a bilayer and particle clusters were formed by surfactant chain-chain interaction, resulting in particles becoming hydrophilic again, and the FSC solution having stronger mechanical resistance against flowing, so that the viscosity rapidly increased and the diffusion of free surfactant molecules was hindered at the froth surfaces. Thus, the contact angle, froth stability and foamability decreased. PEO could bond sodium dodecyl sulfate and water to form a dual adsorption layer and hydrogen, respectively, which enhanced the wettability of the FSC on coal dust surfaces. PEO could adsorb and curl FA particles to form a thin layer of armor after froth air-drying. It was concluded that the froth generated by the FSC solution, including 200 g/L FA, 35 g/L  $c_s$  and 1 g/L PEO, could control coal dust with a long-term effect.

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## 1. Introduction

Coal dust is one of the major hazards in coal storage. When airborne coal dust is raised by wind or mechanical disturbance, it causes economical loss and it can damage the surrounding environment and risk the health of residents [1]. This kind of dust is harmful to the health of coal workers and nearby inhabitants. Long-term exposure of the human respiratory system to coal dust containing free silica suspended in the atmosphere can cause pneumoconiosis [2]. Moreover, coal handling equipment can be damaged due to dust intrusion [3].

To control or prevent coal dust, various technologies have been used, including spraying water, injecting dust suppressant, aqueous foam and so on. Water spray is the most traditional method for dust control [4–6]. However, it is effective for short periods of time only due to water easily being evaporated. This means that regular reapplication is required. The size, velocity, distribution, pattern and pressure of the spraying water droplets can all affect coal dust control efficiency [5–7]. In addition, coal dust commonly features obvious hydrophobicity.

Many studies of longer term and more efficient approaches for dust suppression have been conducted. In 1996, Guy et al. [8] studied the wetting behavior of chloroform, cyclohexane, diiodomethane,

dichloromethane, hexane, hexan-1-ol, o-xylene, oleic acid and toluene on coal surfaces, but the fundamental defects of these organic liquids were volatility, low toxicity and insolubility in water or flammability. In 1999, Gillies et al. [9] discovered that a polymer emulsion, a biocatalyst stabilizer, nonhazardous crude-oil-containing materials and a petroleum emulsion with polymer were a good long-term and efficient approach for suppressing the PM10 emission from unpaved roads, but these dust suppressants could adhere to vehicle tires and cause environmental and health concerns. In 2006 and 2016, Norman et al. [10] and Amato et al. [11] showed that a calcium magnesium acetate solution could control road dust emission, but it was ineffective for controlling airborne dust. In 2007, Wu et al. [12] illustrated that complex wetting agents comprised of 0.6 wt% sodium dodecyl sulfonic salt (SDS) and 6 wt% water glasses had good dust control properties, but their effect was only for short-time periods due to easy air-drying. In 2008, Aldrin et al. [13] obtained an MgCl<sub>2</sub> solution that could control road dust emission, but it posed environmental hazards. Copeland et al. [14] achieved dust control using #2 fuel oil, which was more effective than acetylenic glycol and distilled water, but its flammability and environmental hazards were significant issues. In 2012, Medeirosa et al. [15] and Yan et al. [16] obtained glycerin that could suppress dust, but its application was generally lacking. Tanthapanichakoon et al. [17] studied a wetted wire screen for capturing fugitive dust, but its drawback was the decrease in collection efficiency with increasing dust concentration or air velocity.

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Currently, aqueous foam is a popular method for dust control [18]. In 1949, Brady [4] first studied the formation theory of aqueous foam. Jacobi et al. [19] was the first to report foam technology for firefighting. In 1972, Schwendeman et al. [20] reported aqueous foam technology for dust control for the first time. Afterwards, with the development of surface and interfacial chemistry, the application of aqueous foam to control dust has received more and more attention. However, it is effective for capturing dynamic dust, not effective for static dust control. The main reason for this is that the suppressed static dust can be raised again, after the aqueous foam is air-dried, meaning reapplication is required [21].

Foam sol clay (FSC) technology, as an efficient approach for dust control, is studied in this work. It is mainly composed of fly ash (FA) and foaming solution (FS, including surfactant and sol solution). The froth formed by the FSC solution has excellent stability. After the froth liquid film ruptures or is air-dried, it can form a thin layer of armor by holding the coal dust together on the surface of the coal pile for suppressant longevity.

## 2. Materials and methods

### 2.1. Materials

FA was collected from Huaneng Yang Liuqing Thermal Power Co., Ltd., Tianjin. Its composition was determined using an atomic absorption spectrophotometer (Perkin Elmer 3030 model) and its mass fraction (wt%) was: SiO<sub>2</sub>, 56.0; Al<sub>2</sub>O<sub>3</sub>, 25.8; CaO, 7.7; Fe<sub>2</sub>O<sub>3</sub>, 6.3; TiO<sub>2</sub>, 1.1; MgO, 1.8; K<sub>2</sub>O, 0.6; Na<sub>2</sub>O, 0.5. The used particle size was <1 μm.

The surfactant was mainly composed of a short-chain amphiphile (*n*-amylamine; Aladdin, 99%) and a small amount of sodium dodecyl sulfate (SDS; Aladdin, 99%). The sol solution was mainly composed of distilled water and 1 g/L industrial-grade polyethylene oxide (PEO, Letai chemical). PEO has good properties for coal dust control, due to it having the ability to develop a hydrogen bonding affinity with water, utilizing its numerous ether-oxygen units and forming association complexes with coal. Once a hydrophobic coal surface adsorbs a PEO-water solution, its hydrophobicity will be converted into hydrophilicity [22].

The FSC solution was prepared by adding 200 g/L FA into the sol solution with even stirring to form a sol-clay solution. The surfactant was then added into the sol solution at concentrations of 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65 and 70 g/L.

### 2.2. Methods

The contact angle between FA and FS was measured by a drop shape analyzer (DSA100, KRÜSS), with a measuring range of 0–180°. Every 30 mm diameter cylinder piece was formed using ~200 mg of FA particles under 20 MPa pressure. The FA piece was placed into the test platform and the FS titrated via syringe. The contact angle was obtained once it attained equilibrium via rapid image processing technology.

The zeta potential of the FSC solutions was measured using a Malvern Zetasizer (Nano ZS90). Each sample of the two kinds of dispersible solution was sonicated for 10 min and then transferred into a testing cell to measure the zeta potential. The cell was allowed to stand at 25 °C for 120 s. Each sample was measured at least twice and averaged. The zeta potential values were automatically calculated by the Zetasizer according to the Smoluchowski equation. Simultaneously, the viscosity of FSC solution was measured using an interface rheometer (TRACKER).

The froth stability experiment was performed by a dynamic foam analyzer (DFA100, KRÜSS). Bubbles were produced in a glass column with a 40 mm inner diameter, 250 mm height and a porous filter plate at the bottom by sparging compressed air, which passed through the filter plate with a 16–40 μm pore size. The gas flow rate was set for 0.3 L/min and the foaming time was set for 18 s. A volume of 30 mL of each FSC solution sample was taken to be measured. The experimental

data were obtained by a connected computer, and the half-life and structural morphology of froth were obtained from the foam analyzer.

The surface morphology of the coal piles with a particle size below 38.5 μm covered by FSC was analyzed using scanning electron microscopy (SU3500) after air-drying.

## 3. Results and discussion

### 3.1. Fly ash particle surface modified by surfactant

Fig. 1 shows the contact angle ( $\theta$ ) of FS on the FA surface. The contact angle is ~5° without surfactant. Thus, the FA particles are hydrophilic and easily wetted, so that it is ineffective to keep the foam stability [23]. With increasing surfactant, the contact angle increases accordingly. However, at the surfactant concentration ( $c_a$ ) of 45 g/L, the contact angle on the FA particles surface reaches ~95°. It shows that the FA particles exhibit hydrophobic properties. When  $c_a$  is beyond 50 g/L, the contact angle on the FA surface is <90° and the FA particles exhibit hydrophilic properties again. The contact angle of FS on the FA surface has a dramatic result with increasing surfactant. As seen in Fig. 1, there is a change of the FA surface properties from hydrophilic to hydrophobic, then to hydrophilic again.

Partially hydrophobic particles can be attached at the gas-liquid interfaces to form stable froth, such as surface-modified CaCO<sub>3</sub> and hydrophobic silica nanoparticles [24,25]. Fig. 2 shows a schematic of the approach to modify the FA particles to attach at gas-liquid interfaces. When the surfactant is added into the sol-clay solution, the hydrophilic particles can be suspended, as shown in Fig. 2(a). With increasing surfactant, the hydrophilic particles are gradually transformed into hydrophobic properties and attach at gas-liquid interfaces, as shown in Fig. 2(b) and (c). For a spherical particle evenly attached at the gas-liquid interfaces, ignoring the gravity of the particle, the energy ( $E$ ) required to move the particle into the gas or liquid can be, respectively, expressed as follows:

$$E_G = \pi r^2 \gamma_{LG} \cdot (1 + \cos\theta)^2 \quad (1)$$

$$E_L = \pi r^2 \gamma_{LG} \cdot (1 - \cos\theta)^2 \quad (2)$$

where  $r$  is the radius of the particle and  $\gamma_{LG}$  is the liquid-gas interfacial tension.

From the above equations,  $E_G$  and  $E_L$  are equal to  $\pi r^2 \gamma_{LG}$  at  $\theta = 90^\circ$ . Thus, it is the most favorable state for the particle stabled at the gas-liquid interfaces.

Fig. 3 shows the schematic of foam liquid film embedded by particles. For the system, when FA particles are embedded at the froth film, the theoretical capillary pressure ( $P_c$ ) can be calculated. Denkov et al. [26] first considered such a system and Kaptay [27] derived the equation of  $P_c$  for a single layer of particles between two bubbles:

$$P_c = 2p \gamma_{LG} \cdot \cos\theta/r \quad (3)$$

where  $p$  is a theoretical packing parameter associated with the effect between the concentration and packing of particles on the  $P_c$ .

For  $\theta = 90^\circ$ ,  $P_c$  is zero and the meniscus will be displaced by the flat profiles. Due to the occurrence of drainage, the meniscus of the liquid film can be formed around the particles (sphere radius for  $R$ ). With drainage progressing,  $R$  decreases, the meniscus continues to curve, the width of the liquid film decreases, resulting in  $\theta$  decreasing and  $P_c$  increasing, accordingly. When the  $P_c$  reaches the maximum value or the liquid film decreases to zero, the froth coalescence or rupture.

According to Eq. (3), the  $P_c$  is inversely proportional to  $r$  and  $\theta$ . Therefore, smaller particles and a contact angle close to zero are more effective 'blockers' for froth stabilization. Pickering [28] previously reported that the particles in finely divided powders could efficiently stabilize the froths. Hunter et al. [29] indicated that the larger the

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