International Journal of Mining Science and Technology 26 (2016) 947–953

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Characteristics of coal sludge slurry prepared by a wet-grinding process

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 30 January 2016
Accepted 1 March 2016
Available online 7 June 2016

Keywords:
Coal sludge slurry
Municipal sludge
Wet-grinding process
Fixed-viscosity concentration
Hydrophilic groups

ABSTRACT

Coal sludge slurry (CSS) is an alternative fuel and a potential competitive method for sludge reduction. Based on the researches of coal water slurry, we studied CSSs by using a wet-grinding process with different types of regional municipal sludge (sludge) in an orthogonal experiment. The sludge type, sludge mixing proportion, dosage of dispersant, and grinding time were tested in this study. The results show that water content and its occurrence characteristics in the sludge have primary hindering influences on slurry ability. The range of fixed-viscosity concentrations with raw wet sludge is from 50.78% to 44.40% (by weight), while the range is from 53.35% to 51.51% (by weight) with dry sludge. All of the CSSs exhibit shear-thinning behaviors with different variation trends, especially the CSSs with more than 15% (by weight) raw wet sludge in it. Adding the same proportion of raw wet sludge increases the thixotropic properties of CSSs and the highest area of thixotropy loop is 3065 Pa/s, while the highest value of dry sludge is 1798 Pa/s. Hydrophilic group plays an important role in adsorbing water and building three-dimension networks with other particles, which is the main reason for CSS properties. Therefore, the mechanism can be used to find the way for making high quality CSS.

1. Introduction

Municipal sludge is generated during municipal wastewater treatment. The complex components vary by the city and the processes of wastewater treatment use. Municipal sludge (or sludge) is essentially an aggregate of high water content, organic matter, inorganic particles, microorganism zooglea, heavy metals and other hazardous substances. The traditional methods to dispose of sludge are recycling in agriculture and landfilling, and because of its combustible material content, it can also be utilized as an energy sources. To reduce the cost of operation and avoid secondary pollution, coal sludge slurry (CSS) has been developed, which is a sludge processing and utilization approach based on the coal water slurry (CWS) method for safe recycling.

In previous laboratory studies, CSSs were usually processed by a four-step dry grinding method [1–8]. First, the coal is crushed and comminuted to meet the particle size distribution (PSD) requirement. Next, the pulverized coal and raw sludge is mixed and a solution with deionized water and dispersant is also mixed. The mixed solution is then steadily added into the solid mixture in a beaker and stirred by a mechanical agitator. Finally, the slurry is collected, and the apparent viscosity η and shear stress τ can be measured by a viscometer. The problem of the above procedures is that the sludge is not crushed and comminuted together with the coal but rather it was only stirred by an agitator, thereby failing to consider the effects of forces in the wet-grinding process on the sludge.

Most of the wet-grinding process studies have been conducted in the CWS and cement industries. In the wet-grinding process, the ball mill comminutes solid and liquid materials together at a certain time to meet the requirement of the PSD. The PSD directly affects the main characteristics of slurry according to the studies, and it is significantly influenced by the loading and grinding time of the ball mill and the properties of the materials [9–11]. If we adopt the same process to measure the solid concentration as using the dry grinding process, different solid concentrations of slurry made by the same composition of materials have different total loadings and will influence the ball mill's efficiency in achieving the desired PSD, so these influencing factors should be avoided [12]. Another potential factor is the slurry solid concentration, which influences the PSD by controlling the stickiness of the slurry

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http://dx.doi.org/10.1016/j.ijmst.2016.05.036
2095-2686/

to the balls [13]. Bazin and Chapleau explained the complex mechanisms associated with measuring slurry rheological properties and linking them to grinding mill performance; elucidated the relationship between the solid concentration and grinding index through laboratory grinding tests; and showed that there was an optimum solid concentration related to the performance of a ball mill, even though the mineral samples and particle finenesses were different [14].

Previous studies analyzed the influence of bound water on slurrying by comparing the slurry ability of raw wet sludge with modified sludge, but there is no test that can measure the influence of the total water content (including bound water and free water). Sanin et al. developed a novel way to study real sludge by using non-living components to resemble activated sludge components [15,16]. In the study by Nick Hankins et al., a synthetic sludge which is simple non-biological and non-complex surrogate was prepared for studying the physical and chemical properties of biological activated sludge [17]. Differences between the surrogate and real sludge with respect to certain properties can be confirmed. Inspired by these previous studies, dry sludge was adopted to study the influence of the total water content compared to that of raw wet sludge. To obtain analogous sludge samples-having nearly the same solid composition but different water contents and water occurrence microenvironments, raw wet sludge was processed into dry sludge [18,19]. Two different types of regional sludge were chosen and dried.

In this investigation, coal and two types of regional municipal sludge were blended to prepare CSSs using a wet-grinding process. An orthogonal experiment was adopted to test four parameters: sludge type, sludge mixing proportion, dosage of dispersant and wet-grinding time. In order to show the slurrying mechanism of CSS, the effects of sludge in system are studied. Additionally, complex factors of differences in rheological and thixotropic behaviors, in comparison with those obtained using the dry grinding process, are analyzed.

2. Experimental

2.1. Materials

The two types of municipal sludge applied in the experiments were collected from two cities' waste water treatment plants, Foshan and Xuzhou. The distance between the two cities is nearly 1600 km, from the south to north in China, so the two types of sludge can be treated as typical regional sludges. Each of the sludges was separated into two parts, one maintained in raw wet state and the other heated at 105 °C for 24 h to dry [20]. The water content of the raw wet sludge of Foshan (WF) was 77.62% (by weight) and that of the raw wet sludge of Xuzhou (WX) was 78.77% (by weight). The two types of dry sludge are abbreviated as "DF" and "DX" for Foshan and Xuzhou, respectively. In this investigation, a modified way of observing the micromorphology of the sludge was used. First, the sludge was wrapped in filter paper and placed in a castable vacuum system (Cast N' Vac 1000, Buehler, USA) with a pressure of −88 kPa for 48 h. Then, the vacuumed sludge sample can be tested by SEM (Quanta TM 250, FEI, USA) in a low-vacuum model. In this way, the coexistence of the different components in the sludge can be maintained in its original state as much as possible.

Coal from Daliuta Mine in Shannxi, China was used for two reasons. First, it has low ash content, so the influence of its mineral particles on the slurry formation can be minimized. Second, it has become an important type of coal that is widely used in coal blending technology in CWS factories to increase the caloric value. The results of the proximate and ultimate analyses of the coal and two types of sludge are present in Table 1.

With the development of CWS technology, highly efficient dispersants have been studied and produced [21–23]. One successful commercial dispersant SAF (synthesized from acetone, formaldehyde and anhydrous sodium sulfite through a condensation reaction) is widely used in factories. The dispersant has a significant dispersion effect on different coals and good stability performance. SAF was chosen as a kind of dispersant with the dosage variation from 0.8% to 1.4% (by weight) on a dry coal basis.

2.2. Methods

2.2.1. Coal sludge slurry preparation

For the wet-grinding process, at first, the solid concentration of the CSS was estimated, and all of the materials were calculated and weighed, including the coal, sludge, deionized water, and dispersant. The water content of the raw wet sludge was calculated in terms of added water. Then, all of the materials were ground in a ball mill for a certain time. At last, the properties of the slurry were tested, especially η. A laboratory ball mill (Φ0.2 m × 0.18 m, 80 r/min) was adopted in this investigation.

Based on single-factor experiments, the sludge type (T) (including raw wet sludge and dry sludge), sludge mixing proportion (P), dosage of dispersant (D), and grinding time (G) were all tested in this study and the evaluating indicator was fixed-viscosity (at 1000 mPa s) concentration (C_{FV}). Each factor contained four levels: T: WF, DF, WX, DX; P: 5%, 10%, 15%, 20% (by weight) (on a dry coal basis); D: 0.8%, 1.0%, 1.2%, 1.4% (by weight) (on a dry coal basis); and G: 12, 14, 16, 18 min. As there were four experimental factors and four levels for each factor, an L_{16} (4^5) orthogonal table was used to organize the experiments to investigate the operating parameters (Table 2).

Orthogonal experimental matrix is for 5 factors with 4 levels, in which one column is blank (B). The last column is the C_{FV} (%, by weight) of the slurries.

2.2.2. Determination of fixed-viscosity concentration

The η of the CSS was determined by using a rotational concentric cylinder viscometer (Model NXS-4S, Chengdu Instrument Factory, China). When the grinding time was over, the slurry was collected immediately through the outlet with no stirring and shaking and poured into the testing container. The testing temperature was controlled at 20 °C by a thermostated water bath. The shear rate γ value automatically increased from 10, 20, 40, 60, 80 to 100 r/s and decreased in the same gaps to 10 r/s again. The data were recorded at each γ one time, except 100 r/s, because the data were recorded six times and the mean value was defined as the characteristic viscosity η_c at a 100 r/s shear rate. According to the CWS industrial standard, η_c should be lower than 1200 mPa s. In practical application, the value must be in a range from 800 to 1200 mPa s. The approximate value of η_c was measured directly and accepted if it was between 1000 and 1100 mPa s at a 100 r/s shear rate. The actual solid concentration of the accepted slurry was measured under the standard measurement of CWS and treated as the approximate value of the C_{FV} of this specific material compound. The differences in slurry ability of the materials could be obtained by comparing the values of C_{FV}, with a higher value of C_{FV} meaning a better slurry ability.

2.2.3. Rheological and thixotropic properties

The relationship between η and γ was established during the measurements of η. The rheological properties of CSS are influenced by the coal, PSD, dispersants and solid concentration of the slurry. The rheological properties of the slurry are very important in application. A thixotropy loop is usually applied to describe