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Measurement of bulk modulus of elasticity of dense pastes and its effects on flow rate in long pipeline

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ABSTRACT

The amount of dense pastes, such as dewatered coal washing tailing, red mud, calcium carbide sludge and sewage sludge, is enormous and continues to grow rapidly. More engineering long pipelines with large diameter are employed to meet the urgent needs of their disposition, which results to serious reversed flow and strong vibration to the pipeline system. Both the problems have close relationship with the elastic parameters of the delivered paste. This paper presents a test undertaken for finding the bulk modulus of elasticity of the coal tailing. The test was undertaken on a long engineering pipeline for transporting coal slime paste based on the wave velocity method. By selecting suitable feature points in the pressure curves, the pressure wave propagation velocity in the coal slime was tested accurately. By the relationship between the elastic modulus of the paste and the wave velocity, the composite modulus of the coal slime and pipeline, and the true bulk modulus of the paste were both calculated. By resulting in serious reversed flow and reducing the effective piston stroke of the pump, the elastic recovery of the coal slime has an important effect on the actual flow rate. The variation characteristics of the pressure curves have proved that the measurement is an easy and practical method for finding the elastic modulus of dense pastes.

1. Introduction

Paste and thickened tailings technology is widely used for surface and underground disposal of mining particulate solid wastes in Australia, South Africa, and Canada, etc., as satisfies the environmental and legislative requirements of minimizing water consumption and tailings dump safety (Jewell, 2000; Paterson, 2004; Belem and Benzaazoua, 2004). As the concentration of thickened tailings increases, the tailings are classified into three categories, slurry, paste and cake, to describe how they will perform when transported and deposited (Jewell et al., 2002). Other fine particle suspensions/slurries coming from several industrial processes are also in the paste form, such as coal tailing from coal preparation, red mud from aluminum industry, calcium carbide sludge from acetylene production, and sewage sludge from municipal wastewater treatment. These high-density suspensions are even more viscous than those mineral tailings, due to their finer grain sizes and more solids volume fraction. Here, we call them ‘dense pastes’.

The annual outputs of dense pastes are enormous. Taking the figures of the year 2006 in China for example, coal slime (the coal washing tailing) is about 75 million tons in China (Hao et al., 2009); red mud and sewage sludge is about 30 million tons and 20 million tons, respectively (Wu et al., 2010); and calcium carbide sludge is approximate 12 million tons (Hao et al., 2012). Economical disposal and utilization as a resource for dense pastes are of big interest throughout the world, such as land application or incineration of sewage sludge (Wang, 1997; Fytili and Zabaniotou, 2008), utilization as a raw material for calcium carbide sludge (Zhang et al., 2012), and burning coal slime to generate electricity. In China, approximately 200 coal slime pipelines had transported nearly 63.9 million tons of coal slime to CFB boilers as a partial substitution of coal fuel in 2002 to 2008, and produced an economic benefit of about 10.1 billion RMB (Wu and Hao, 2010).

As solid concentration increases, slurry physical characteristics change greatly. The traditional pipe transport theory of dilute slurry is no longer applicable. Consequently, the study on pipe transport of pastes has been the research highlight for many years. It mainly deals with their rheological characteristics and flow behaviors for paste-like slurries such as mineral tailings, fresh concrete and the dense pastes. Pastes behave as the non-Newtonian fluids in pipe. The rheological characteristics of fresh concrete, such as plastic viscosity, thixotropy, shear thickening and workability, were mainly studied by Chidiac and Mahmoodzadeh (2009); Roussel (2006), Feys et al. (2009) and Li (2007), respectively. Viscosity, yield stress and slump have strong dependence on the

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solid concentration of pastes (Claytona et al., 2003; Hernandez et al., 2005; Kwak et al., 2005; Zhao et al., 2006; Wang et al. 2008). The transportation resistance of coal slime (Zhao, 2005; Gong, 2010), red mud (Chen, 2007), and calcium carbide sludge (Hao et al., 2012) show differences due to size distribution, mineralogy and chemical composition. Stratification in paste flow was found by MRI tomography (Pullum et al., 2006). Wall slip and liquid phase migration are the curious phenomena for pastes (Lu and Zhang, 2005; Wilson and Rough, 2006). From the references listed above, it shows that little literature has described the elastic compressibility and its effects on the transportation for dense pastes.

With rapid increasing amount of dense pastes, more engineering applications adopt long pipelines with large diameter to transport them. Such pipelines often have lengths of near or exceeding 1000 m and diameters up to 300 mm. The maximum pumping pressure is up to 20 MPa. In contrast, pipelines for delivering mineral tailings are of smaller diameters, 100–200 mm, and lower pumping pressures less than 8 MPa. However, two serious problems emerge with the increasing pipeline length and pumping pressure. First, reversed flow reduces the actual flow rate greatly. Second, strong vibration damages the transport equipment during the transportation. Both the problems arise from the compression and decompression of dense pastes. Therefore, they have close relationship with the elastic parameters of dense pastes. However, research on the elastic parameters of dense pastes can seldom be referred in the above literature. This paper presents a testing method for finding the elastic parameters of dense pastes on an engineering pipeline of coal slime paste. It also discusses the effects of the elasticity of the paste on the transportation performance.

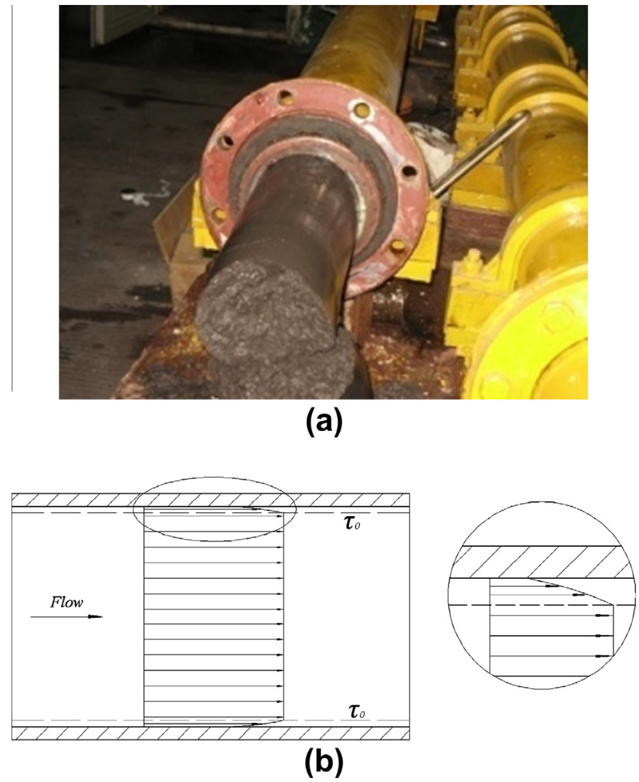

Fig. 1. Flow photo (a) and flow profile (b) of coal slime (75 wt%).

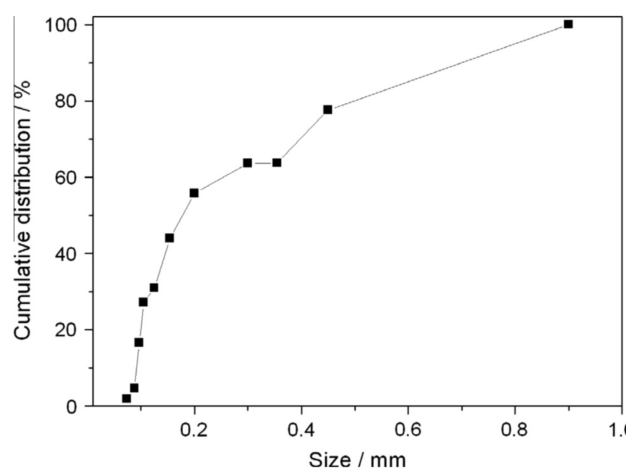

Fig. 2. Size distribution of coal slime.

2. Material and methods

2.1. Coal slime properties

Coal slime, the tailing of coal preparation, is a thickened solid–liquid slurry. Its solid component mainly consists of gangue and coal particles, with most of particle size less than 0.5 mm in general. After dewatering by filters, the solid concentration of coal slime ranges from 56% to 77% w/w due to different size grades and mineralogy, and its apparent viscosity ranges from tens to hundreds of Pa s accordingly. It behaves as a plug flow in pipes, as shown in Fig. 1, with only a thin dilute slurry layer close to the pipe wall interface having shear rate.

The solid concentration of the coal slime discussed in this paper is 59 wt%, at which it has a yield stress of 64.9 Pa tested by a vane rheometer. The size distribution of the coal slime measured by sieving is somewhat coarse, as shown in Fig. 2. The density of the coal slime is 1.50 g/cm^3.

2.2. Principal of measurement

As we know, the sound or pressure wave propagation velocity in a fluid full-filled pipeline can be calculated by Eq. (1) (Legius et al., 1997):

$$c = \sqrt{\frac{K}{\rho}} \tag{1}$$

where c is the velocity, K is the bulk modulus of elasticity of the fluid, and ρ is the fluid density.

The pipe is rigid by default in Eq. (1). In contrast, the actual pipe is flexible, which will affect the pressure wave velocity. Supposing K_c represents the composite modulus of the fluid and the pipe, the modified velocity is calculated by the following equation:

$$c = \sqrt{\frac{K_c}{\rho}} = \sqrt{\frac{K}{\rho}\cdot\frac{1}{1+\frac{D}{\delta}\frac{K}{E}}} \tag{2}$$

where D, δ and E is the diameter, the wall thickness, and the elastic modulus of the pipe, respectively.

$$c = \frac{\Delta l}{\Delta t} \tag{3}$$

The velocity can be calculated by Eq. (3), if the distance between two pressure sensors in the pipeline, $\triangle l$, and the time difference of the pressure variations for both the sensors, $\triangle t$, are known in advance. This method is called 'the wave velocity method'. Pressure variations can be made by external excitation such as the ultrasonic methodology (Martin et al., 2000; Pavic, 2006). Accounting