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Effect of the moisture content of straw on the internal friction angle of a granular biomass–coal system

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ABSTRACT

In this study, we investigated the effect of moisture content on the internal friction angle of a binary granular straw–coal system using a Freeman FT4 powder rheometer. The results show that, as the moisture content increases, the internal friction angle decreases at first and then increases to reach a minimum value at a moisture content ranging from 8% to 10%. This irregular trend, associated with the preferential adhesion of finely pulverized coal particles to certain regions of the straw, is more complicated than the conventional understanding that the internal friction angle increases with the moisture content. An empirical model is proposed to describe the quantitative relationship between the internal friction angle and the straw moisture content, and this model fits well with the experimental data.

1. Introduction

At present, research and development into biomass energy is attracting the attention of more and more researchers because of its economic and environmental benefits [1,2]. For example, Dai et al. [3] considered that co-firing biomass and coal had potential for the development of biomass-to-energy capacity with significant economic, environmental and social benefits. Also, the dry entrained-flow co-gasification of biomass and coal is an important large-scale, highly efficient method for the utilization of biomass energy that has a bright future [4,5]. The dense-phase pneumatic conveying of binary particle mixtures is a crucial technique in dry entrained-flow co-gasification. However, the flow of the biomass–coal blends is not easy to predict since the resulting powder mixtures can give rise to handling and feeding problems due to the occurrence of intermittent flow or blockage [6]. Zulfiqar et al. [7] studied on flow properties of typical Australian coal and biomass (sawdust and woodchips) as well as their blends. They found that the flow properties of the coal and biomass blends were dependent upon the form of biomass being used.

The internal friction angle of the biomass–coal blends is a crucial design parameter for powder storage devices and transporters in the entrained-flow biomass–coal blend co-gasification process [8]. The moisture content has a significant impact on the internal friction angle. Moreover, industrially, a large amount of energy is consumed in drying materials. Therefore, it is critical to study the effect of the moisture content on the internal friction angle of binary granular systems.

The study of granular shear properties has a long history that dates back to the eighteenth century [9]. Then, Coulomb's theory was the most widely accepted because of its simplicity and practicality. According to Coulomb's theory, there is a linear relationship between the shear stress and the normal stress within a certain range of pressures. The exact equation of Coulomb's theory is

$$\tau = c + \sigma \tan\phi \tag{1}$$

where τ represents the shear stress, σ is the normal stress, and ϕ is the internal friction angle. c represents the cohesion of the powder and is equal to the value of yield locus when the normal stress is zero. A powder with $c = 0$ is defined as a "simple Coulomb powder" [10]. Recently, Jenike [11] proposed a shear cell technique to measure powder flow behavior. The flow parameters such as the internal friction angle have been shown by Jenike to not only reflect the granular flow behavior but also provide a theoretical foundation for silo design. This makes the design of granular matter handling equipment more accurate and more suitable for real engineering situations.

To date, the effect of the granular moisture content on the flowability of granular matter has been extensively studied through a number of experimental studies, and most researchers consider that the flowability of granular matter decreases with increasing moisture

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content, which enhances the viscous force between particles [12–16]. Crouter et al. [17–20] found that, in a low humidity range, increasing moisture content had little effect on the flowability of granular matter. However, when the moisture content exceeds a critical point that depends on the properties of granular matter, the flowability of granular matter becomes poorer with increasing moisture content. Saandler et al. [21] have researched the effect of moisture on the flow properties of theophylline using a powder flow analyzer (FlowPro). The results showed that theophylline had its best flowability at a relative humidity of 63%, and the flowability of theophylline decreases slightly at relative humidities lower than 63% and decreases sharply with increasing relative humidity over 63%. Lesser amounts of water might have a positive effect on powder flow because it can eliminate particle micro-irregularities and electrostatic charges, which reduce the flowability at low humidities [22]. Faqih et al. [15] used gravitational displacement rheometry (GDR) to study the effect of moisture on the flow properties of cohesive granular matter, identifying the different effects of moisture on cohesive particles and on non-cohesive particles. In the case of lactose, as the moisture content increases in the powder bed, the flowability becomes poorer as moisture condenses on the particle surfaces and the cohesion increases. The celluloses show the opposite effect to that of lactose. Emery et al. [16] found that increasing the moisture content resulted in a non-linear decrease in the flowability of hydroxypropyl methylcellulose (HPMC) and a non-linear increase in the flowability of aspartame. Littlefield [14] demonstrated that the internal friction angle of pecan shells was not significantly affected by the moisture content. Kamath et al. [23] found that the internal friction angle of wheat flour increased with increasing moisture content. Bahram et al. [24] discussed the primary factors affecting the flowability of vermicompost by shear testing. The results show that the internal friction angle of vermicompost fluctuates with increasing moisture content at high consolidation stresses. Furthermore, it non-linearly increases as moisture increases at lower consolidation stresses. Dugar and Dave [25] studied the effect of relative humidity on flowability of dried granules at 22%, 52%, 75% RH at room temperature for 48 h, and found that intragranular moisture levels were affected by solvent used on exposure to different humidity conditions. Landi et al. [26] studied the flow properties of moisturized powders in a Couette fluidized bed rheometer where the humidity was kept between 0 and 70% at ambient temperature. Goula and Adamopoulos [27] investigated the effect of maltodextrin addition on the drying kinetics and the stickiness during spray drying of tomato pulp in dehumidified air. Teunou and Fitzpatrick [28] studied the influence of relative humidity and temperature on the flowability of the food powders including flour, tea and whey permeate. Landi et al. [29] studied the effect of air humidity on flow properties of two different cuts of fine glass beads by means of shear tests. In their experiments, the moisture content of powder samples was conditioned by humid air at relative humidities between 13% and 98% in a fluidization column. Experimental results showed that, in spite of the very low moisture contents in the powder (< 0.2%), a significant change in the powder cohesion was observed, while the effect on the angle of internal friction was limited.

Reports above are very valuable and provide good reference for this work. However, related reports about the influence of needle-shaped particle moisture on binary granular systems are scarce. This paper is focused on the impact of needle-shaped biomass particle moisture on the internal friction angle of the biomass–coal blend. Thus, it deserves further quantitative investigation.

In this paper, a series of experiments was carried out to investigate the effect of straw moisture on the flow behavior of the binary granular straw–coal system. The internal friction angles of the binary particles were measured by the shear module of the FT4 powder rheometer. An empirical model to describe the quantitative relationship between the internal friction angle and the straw moisture has been developed and compared with the experimental data.

Table 1
Material properties.

Material	Sample code	Sauter particle size (μm)	Average sphericity	Average aspect ratio
Straw	F	191.7	0.781	2.447
	M	241.9	0.669	4.272
	R	412.4	0.671	5.019
Coal	C	10.9	–	–

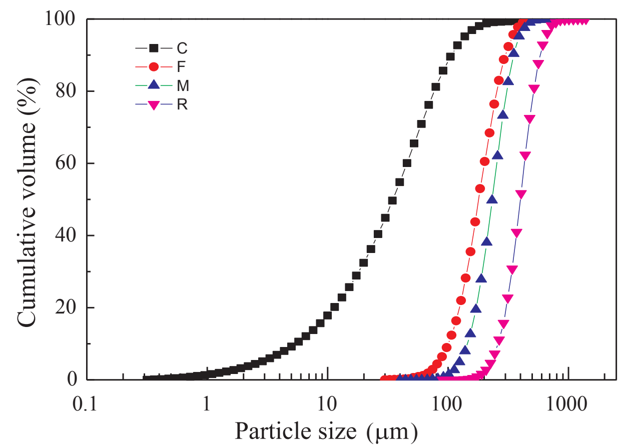

Fig. 1. The cumulative distribution functions of the experimental materials.

2. Materials and methods

2.1. Materials

To obtain a comprehensive relationship between the flowability and moisture content, three straw samples with different particle sizes were mixed with dry pulverized coal respectively. The moisture content (φ) of each kind of straw was set at four levels. The physical properties of the materials are shown in Table 1. Fig. 1 shows the cumulative particle size distribution functions of straws and coal, as measured by a particle size analyzer (Malvern Mastersizer 2000). The particle shape information was measured by a particle image analyzer (Baxter, BT-2900). The moisture content of pulverized coal is controlled to be less than 1.5% (wet basis (w.b.)), and the moisture content of the straw was controlled to be approximately 0%, 5%, 10%, and 15% (w.b.), all of which were measured by an infrared moisture meter (MA150).

2.2. Methods

The moisture content of the straw was controlled by two devices. A temperature humidity chamber (Binder) was used for humidification, and an electro-thermostatic blast oven (Jinghong) was used for drying. The straw particles were placed in glass culture dishes with 150 mm diameter at a straw layer thickness of less than 5 mm. The glass culture dishes containing the straw were placed into the two above devices successively to adjust the moisture content. To ensure accuracy and the uniformity, the straw moisture was measured randomly using a moisture meter (MA150) three times before mixing with the pulverized coal at mass fractions of straw particles of 5% and 10%. After mixing the moisturized straw with the pulverized coal, straw–coal blends were then kept in closed environment for time long enough to achieve the homogeneity of the moisture content. Since the straw–coal blends achieved the condition of water equilibrium, there was no further changes in the powder flow properties due to a further internal migration of the moisture from the straw to the coal.

FT4 powder rheometer was used to measure the internal friction angle of the samples [30]. The rotational shear cell module consists of a