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Effect of granular shape on angle of internal friction of binary granular system

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HIGHLIGHTS

- Three regions have been divided based on the magnitude of granular aspect ratio.
- The effect of factors on angle of internal friction has been studied in detail.
- An integrated model has been proposed which agrees well with the measured results.

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ABSTRACT

The study of angle of internal friction (Φ_I) is widely prevalent due to its importance in science and engineering, and yet the quantitative description concerning the effect of granular shape on the Φ_I is few. In our study, the influence of granular shape on the Φ_I of various binary granular systems was investigated theoretically and experimentally with a Freeman FT4 Powder Rheometer. The results show that the variation amplitude of tangent Φ_I ($\Delta\tan\Phi_I$) exhibits a linear relation with the related particle physical properties. Our findings show that three regions have been divided for various binary granular systems based on their magnitude of aspect ratio, and there exists a powder function between $\Delta\tan\Phi_I$ and granular shape factors. On this basis, an integrated model has been proposed to describe the quantitative relationship between angle of internal friction and granular shape factor, which agrees well with the experimental data.

1. Introduction

Angle of internal friction (Φ_I) is one of the key factors in characterizing the flow characteristics behavior of granular materials, which describes the failure properties of particle assemblage under normal stress. In particular, its contribution is usually in such applications as the design of conventional silos and the processing of powders, chemicals and food products [1–3]. Due to the economic and environmental benefits of co-utilizations of biomass and coal, all kinds of these technologies attract more and more researchers' continuing attention [4,5]. The characterization of the shear properties of biomass–coal blends is especially important for the design of reliable transportation container and composition of the product gas during co-gasification process [6,7]. The surface convexity and aspect ratio on Φ_I granular flow is a subject that attracted little attention in the previous reports. Therefore, it is essential to investigate the Φ_I of binary granular system, such as biomass–coal blends.

The study of granular shear properties has a long history which could date back to the eighteenth century [8]. Due to the simplicity and practicality, the most widely accepted theory is proposed by Coulomb. Based on the well-known Coulomb's theory, the shear strength is a linear relationship of the normal stress within a certain range of pressure. The function are listed below:

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

where τ is the shear stress, σ is the normal stress and Φ_I is the angle of internal friction. c is the cohesion of the powder and its value corresponds to the intercept of the yield locus on the shear stress axis, which is often composed of the resistance from mutual biting of granules and the united effect of condense and colloid [9]. In recent decades, a pioneering work [10] developed by Jenike that exhibited an application of shear cell techniques for measuring powder flow

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Nomenclature

c	the cohesion of powder, kPa
A_h	average aspect ratio of host particle
C	granular surface convexity
C_g	granular surface of guest particle
k	the slope of the model
l	the length of particles, mm
S	the projected area of particles, mm^2
A	aspect ratio of particles
A_g	average aspect ratio of guest particle
C_h	surface convexity of host particle
n	powder exponential
C_1	a constant number
b	the width of particles, mm
S_r	the area of bounding rectangle, mm^2

Greek letters

Φ_b	angle of internal friction of blends, °
Φ_g	angle of internal of guest particles, °
τ	shear stress, kPa
$\Delta\sigma$	variation of normal stress, kPa
δ	efficient angle of friction angle, °
Φ_h	angle of internal friction of host particle, °
w	biomass particles mass fraction, %
σ	normal stress, kPa
$\Delta\tau$	variation of shear stress, kPa

behaviors and provided a theoretical foundation for the design of silo.

Up to present, the effect of granular shape on the flowability of granular materials has been extensively studied through a number of experimental studies [11–13] which have been found that the flow performance highly depends on granular shape, such as aspect ratio, roundness and surface convexity. However, general reviews concerning the influence cannot be drawn. Schulze [14] held the view that the flowability of smooth, spherical particles is better than rough, non-spherical particles for coarse particles. While for cohesive granules with the complex inter-particle adhesive forces, the rough particles may possess a more favorable flow behavior. A comprehensive work [15] presented two correlations to propose a quantitative expression about the constant volume friction angle and particle shape coefficient, which gives a visual understanding of the influence of particle shape on granular flow behavior. Kunio et al. [16] measured the effect of particle shape on the Φ_I of powders with triaxial compression test which indicated that Φ_I increases with increasing angularity of particles and decreasing initial porosity of the granular system due to the increased interlocking effect. Podczeck and Miah [2] used shear test data to establish a nonlinear relationship between the flow parameters and particle shape with statistical correlations to determine the optimal lubricant concentration for the pharmaceutical excipients. In the simple shear flows, Cleary [17] demonstrated that particle shape sharply increases the shear strength of the material and turns the materials into stronger and harder to shear. The effect of nanoscale variations of surface convexity on granular flow characteristics has been conducted by Pohlman, et al. [18]. The results indicate that the angle of repose, directly related to the coefficient of friction of the particles, increased monotonically with increasing concentration of rough particles for binary granular system. In view of the importance of the particle shape and particle size distribution for the utilization of biomass, Guo et al. [19] have researched the related physical characteristics quantitatively by images analysis for four kinds of biomass material. The results showed that biomass particles have large aspect ratio after smashed, and which increases with the increase of particle size. Some researchers [20–22] have investigated the shear properties of biomass and biomass–coal blends. Both of them held the view that, for needle shaped particles, a large value for the aspect ratio was always accompanied by a particularly high angle of internal friction due mainly to the high presence of overlong particles governing the mechanical interlocking forces. However, mostly reports still drift outside the fundamental mechanics of angle of internal friction which remain poorly understood. Thus, it deserves further quantitative investigation.

Consequently, a series of experiments concerning the effect of particle shape on flow behavior by the Φ_I of binary particles were carried out with a FT4 Powder Rheometer. An improved model to describe the quantitative relationship between angle of internal friction and granular shape factor has been developed, above all, which could applied to more binary mixed powders including host particle and guest particle. It should be noted that the main component is named host particle and the other is defined as guest particle. In addition, we believe that the work would be helpful to investigate the binary granular system flow behavior and to provide the essential data for the success of biomass–coal blends in dense phase pneumatic conveying system.

2. Materials and methods

2.1. Materials

To obtain the comprehensive relation between the flowability and shape factor, 12 kinds of granular materials were employed, and whose physical properties are shown in Table 1. Fig. 1(a) shows the cumulative particle size distribution functions of regular granules, which is measured by a particle size analyzer of Malvern Mastersizer 2000. The cumulative particle size distribution function of needle particles is illustrated in Fig. 1(b) with a particle image analyzer of BT-2900. Since the moisture content is a key factor to the flow properties of powder [23], materials are dried at 105 °C for 2 h in an oven. The moisture content of experimental material is measured and controlled below 2% by an infrared moisture meter MA150. In order to corresponding to previous studies and the role of host particle and guest particle, it should be noted that mass fraction of guest particles (w) is 5%, 10%, 15%, 20% and 25% (see Tables 2 and 3).

2.2. Methods

Angle of internal friction of powder (Φ_I), reflecting the friction behavior between particles, is an important parameter on the design of hopper. The shear properties will provide significant information as to whether the powder will flow through the process or whether bridging, blockages and stoppages are likely. The influence of granular shape on the flowability can be shown visually by the Φ_I. The rotational shear cell module, a component of FT4 Powder Rheometer, is used to measure angle of internal friction of the samples [24]. During the shear test, the maximum normal stress is 20 kPa. The rotational shear cell module consists of a vessel containing the powder sample and a shear head to induce vertical and rotational stresses. A powder yield loci obtained from