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Flow behavior and hopper design for black soybean powders by particle size

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ABSTRACT

In this study, the flow properties of black soybean powders having different particle sizes (d_{90} = 1448.66, 1484.14, 1458.18, 1385.73, 1246.89, 740.06 μm) were measured, and the flow characteristics were applied to a hopper design. For a given black soybean powder, reducing the particle size tends to reduce flowability. At the smallest particle size (d_{90} = 740.06 μm), the flow function was located in the cohesive region and the ratio of change in the bulk density increased from 4.72% to 19.13% as the particle size decreased from d_{90} = 1448.66 μm to 740.06 μm. The results of the internal friction angle at different particle sizes were not exactly consistent with the results of the flow function, which could be a result of the different particle shapes in addition to the different sizes. Image processing of particles with different particle sizes revealed a difference of HSC (high sensitivity circularity), and particles with more circular shapes showed a lower internal friction angle. The black soybean powders with the smallest particle size showed poor flowability and required larger values of the hopper angle and a larger minimum size of the hopper opening.

1. Introduction

Soybeans are a major grain of the legume family and play an important role in nutritious diets because of their valuable components, such as protein, dietary fiber, and phytochemicals (Kashaninejad et al., 2008; Chen et al., 2010). Black soybeans (*Glycine max*) have black seed coats, which include a substantially higher degree of anti-oxidative activity than yellow soybeans. The greater anti-oxidative activity is related to the black soybeans' higher level of flavonoids, such as anthocyanins and isoflavones (Jeng et al., 2010). Because of such high nutritional value in the black soybean, it has been widely used as a health food and a medicinal ingredient in oriental medicine (Jeng et al., 2010; Kim et al., 2012).

Black soybean is a useful ingredient for many processed food products, such as black soybean paste, black soybean sauce, soymilk, yogurt and tofu (Bai et al., 2013; Ye et al., 2013; Shih et al., 2002), and the commercial application of black soybeans must be in the form of powder. Thus, grinding is a necessary process to use black soybeans as a food ingredient, and controlling the particle size from the grinding process is important for the subsequent processing that occurs in the manufacturing process. Smaller particles may aid other processes, such as expression, extraction, and leaching or may shorten heat treatment blanching or cooking (Barbosa-Ćanovas et al., 2005). However, smaller particle sizes in the powder form can be difficult to handle, especially when particles are flowing out of hoppers and feeders (Teunou et al., 1999; Fu et al., 2012). The bulk properties of food powders such as their bulk density and flowability are important characteristics that are highly dependent on the particle size, geometry, surface characteristics and moisture content of the individual particles (Fitzpatrick et al., 2004; Barbosa-Ćanovas et al., 2005).

Properties of food powders affect the behavior of powder during storage, handling and processing. Generally, when food powders flow through a hopper, the flow behavior is of two types: core flow and mass flow. Core flow occurs when the powder flows towards the outlet of a silo in a channel formed within the powder itself. In mass flow, all the powder in a silo is in motion whenever any of it is drawn from the outlet (Rhodes, 2008). In mass flow, stresses are generally low throughout the mass of solids and produce low compaction of the powder. There are no stagnant regions in the mass flow hopper. The particles in a mass flow hopper flow first-in-first-out, so residence times are short for material in the silo. However, arching occurs in the mass flow of powder from a hopper. An arch is a stable obstruction that forms over the point

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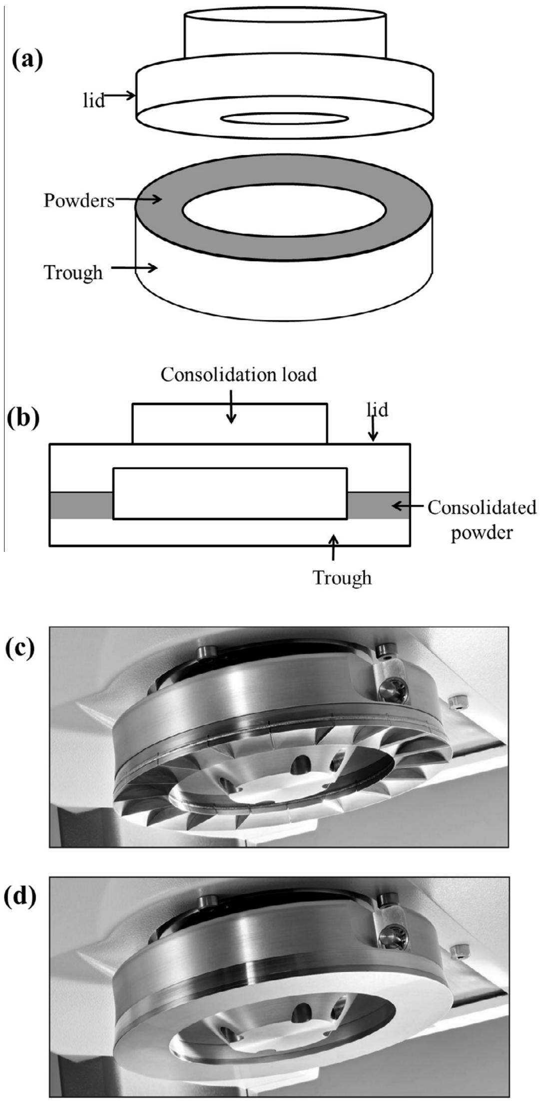

Fig. 1. Instrument for powder flow test: (a), (b) schematic of shear cell, (c) vane lid, (d) wall friction lid.

of the narrowest cross-section of the storage vessel (usually the discharge outlet) and can result from either mechanical interlocking or cohesive strength (Barbosa-Ćanovas et al., 2005; McGlinchey, 2008). In the case of fine powders, arching can also be described by the unconfined yield strength, which is caused by adhesion forces acting among the particles (cohesive arching). In the case of coarse bulk solids, arching is caused by the blocking or interlocking of single particles (interlocking arching) (Barbosa-Ćanovas et al., 2005).

Measurement of powder flow properties is required to design a hopper that does not have issues with arching during the flow of particles (Fitzpatrick et al., 2004). Shear cell techniques are generally used to measure powder flow properties, such as the effective angle of internal friction, angle of wall friction and flow function. The powder flow properties mainly characterize the flowability of powders and are applied for calculating the hopper angle and opening size. Studies on the flowability of food powders have been reported and showed that the particle size and moisture content of food powders significantly affect the flowability of food powders (Teunou et al., 1999; Fitzpatrick et al., 2004; Opaliński et al., 2012). However, very few results were related to designing the hopper.

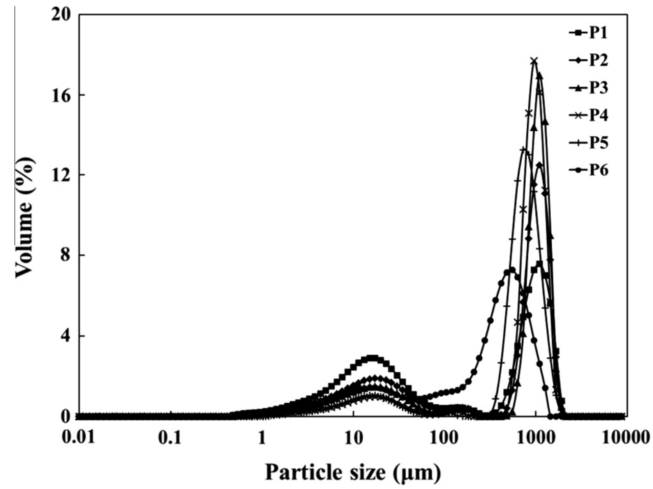

Fig. 2. Particle size distribution of black soybean powder.

Table 1
Particle size distribution and volume based mean diameter, $d_{[4,3]}$ and sieve diameter (d_s) of black soybean powder.

Sample	d_{10}	d_{50}	d_{90}	$d_{[4,3]}$ (μm)	d_s (mm)
P1	6.66	537.74	1448.66	593.30	1.40
P2	11.00	984.98	1484.14	828.69	1.18
P3	9.56	1007.63	1458.18	839.03	1.00
P4	23.35	972.90	1385.73	902.11	0.60
P5	22.10	768.44	1246.89	751.37	0.43
P6	10.83	306.39	740.06	336.94	0.25

Although few studies available for designing hopper dimensions, most of powders were prepared after applying processing on the natural products, such as spray drying from extracts or leaching. The particles obtained from grinding natural products, such as whole black soybeans, are certainly different from those from processed products because the seed coat and the endosperm parts have different structures. The different structures usually generate different shape of particles after grinding, especially when the particle size is not small enough. Flow properties of powder might be dependent on the particle shapes, so that the particle shape should be analyzed to understand the flow properties. In this

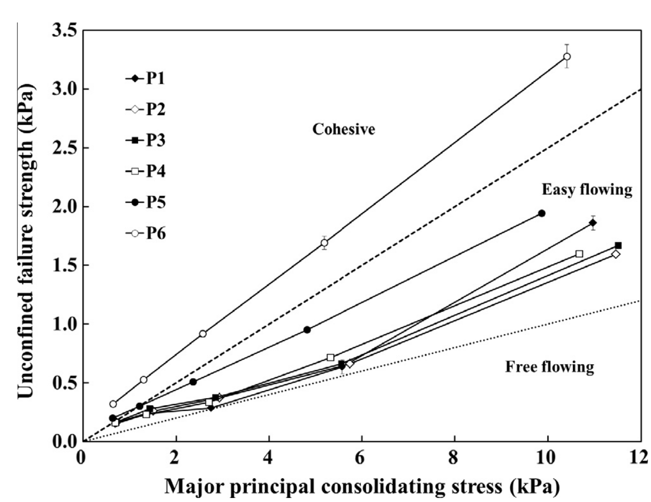

Fig. 3. Flow function by particle size (particle size: P1 > P2 > P3 > P4 > P5 > P6).