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Effect of chaff on bulk flow properties of wheat

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Consistent and reliable flow of bulk wheat from hoppers and silos is vital in handling, processing, and storing wheat. The presence of impurities in bulk wheat might influence the discharge of wheat from hoppers and storage vessels. Chaff is one common impurity, amounting to about 2–7% (weight basis) in bulk wheat. This study focused on measuring the bulk and flow properties of bulk wheat in the presence of chaff at different moisture content levels. Bulk density, tapped density, and true density varied from 805.50 to 718.36 kg/m^3, 831.52 to 746.31 kg/m^3, and 1404.63 to 1367.13 kg/m^3, respectively, with varying chaff proportions and moisture contents. The stability of bulk wheat samples remained the same, indicating that sample properties did not change during repeated handling. Compressibility ranged from 4.84 to 7.99%. The unconfined yield strength (UYS) of chaff was approximately 3 times higher than clean wheat samples. High UYS values indicate that arching could occur during bin discharge of bulk wheat containing impurities.

1. Introduction

Wheat is one of the most consumed cereal grains in the world. In the grain processing industry, wheat grains are used largely as raw materials for a number of food applications, particularly the production of wheat flours (Landillon et al., 2008). Storage and handling of bulk wheat is an important aspect of the grain handling and processing industries. Bulk wheat is subjected to a series of static and dynamic loads during handling, transport, processing, and storage (Bargale et al., 1995). During these operations, the physical and flow properties intrinsically affect bulk behavior, such as flow from hoppers and silos (Knowlton et al., 1994; Wang et al., 1995). Bulk wheat is considered free-flowing, and the change in compressed bulk density is minimal compared with other solids or powders such as wheat flour (Schulze, 2008).

Wheat is classified into different grades based on the percentage of dockage in the bulk. Dockage is described as "weed seeds, weed stems, chaff, straw, or grain other than wheat" (Womach, 2005). Depending on the grade, dockage could comprise up to 20% of bulk wheat (Grain Inspection Handbook, 2013). Although wheat kernels are irregular in shape, they are easy-flowing solids; however, impurities such as chaff are highly irregular in shape and have a high tendency to interlock, which affects bulk flow (Peleg, 1978).

The flowability of bulk solids, which is defined as the capacity of a granular solid to flow under a specified set of conditions, is a complex characteristic that is highly dependent on the state of the materials and their application. Bulk density, true density, porosity, and angle of repose are some of the useful flow indicators. Angle of repose also relates to the interparticulate friction or resistance to movement between particles (Train, 1958) and provides a rough estimate of the cohesive behavior of bulk solids (Zhou et al., 2008). Bulk and tapped densities and derived indices such as the Compressibility index and Hausner ratio, as defined by Carr (1965) and Hausner (1967), measure the ability of a granular material to be compressed and reflect the relative degree of interparticulate interactions. Fedler and Gregory (1989) developed a relationship to predict the flow resistance of wheat, sorghum and corn as a function of material property. Although the flow indicators and prediction models mentioned above provide some insight into the behavior of bulk solids, they are single measures and therefore do not reflect the potentially complex behavior that any granular material exhibits during handling. Sensitivity and ability to capture diverse aspects of flow behavior, especially during flow, are limited.

Chang and Converse (1998) reported that moisture content did not have any significant influence on the flow of wheat through orifice. But, the effect of dockage or chaff, and its moisture content, on the bulk flow properties of wheat has not been studied. The design and modification of equipment, particularly storage silos and hoppers, for wheat with impurities will require a fundamental

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understanding of physical properties and their effects on flow behavior. Therefore, the objective of this study was to investigate the effects of chaff and moisture content on the bulk physical and flow characteristics of wheat.

2. Materials and methods

2.1. Samples

Hard red winter wheat kernels were obtained from the Farmers Cooperative Association, Manhattan, Kan., USA. Wheat chaff was gathered from the Kansas State University Hal Ross Flour Mill, Manhattan, Kan., USA. Moisture content of the wheat was measured using the American Society of Agricultural and Biological Engineers (ASABE) Standard S352.2 of drying 10 g of unground samples in an air oven at 130 °C for 19 h (ASABE, 2006). The moisture content of chaff was measured using the ASABE Standard S358.3 of drying 25-g samples cut to small pieces and dried at 103 °C for 24 h (ASABE, 2012). Initial moisture content of wheat and chaff were 11.7 and 10.4% wet basis (wb), respectively. Experiments were conducted within the moisture range of 10–14% (wb). Moisture content of chaff was also maintained at the same moisture content as wheat. Wheat kernels and chaff were rewetted to about 15% (wb) moisture content by adding calculated amount of distilled water. After rewetting, the samples were stored at 4 °C for 72 h for equilibration. Drying to desired moisture level (10, 12, 14% wb) was carried out in ambient conditions by spreading kernels and chaff in thin layers without any additional heat or airflow. The moisture content of wheat and chaff used in this study are given below in Table 1. MC1, MC2, and MC3 denote moisture contents of wheat and chaff of about 10, 12, and 14% (wb), respectively.

The sizes of wheat kernels were measured using a single kernel characterization system (SKCS 4100, Perten Instruments, Inc., Springfield, IL, USA). Chaff dimensions were measured using a Vernier caliper (General Tools, New York, NY, USA.). Wheat (W) and chaff (C) were mixed at specific proportions (W:C at 100:0%, 97.5:2.5%, 95:5%, 92.5:7.5%, and 0:100%) on a weight basis. The proportions were based on U.S. wheat grades with different levels of broken and foreign material (Grain Inspection Handbook, 2013). Foreign material consists of broken wheat, chaff, insect-damaged kernels, live insects, and frass, but for this study, only chaff was mixed with bulk wheat to simulate different U.S. wheat grades.

2.2. Physical properties and flow indicators

2.2.1. Bulk density

The bulk density of wheat, chaff, and the wheat-chaff mix was measured using a Winchester cup setup (Seedburo Equipment Company, Chicago, IL, USA.). A 1-pint (4.7318×10^{-4} m^3) cup was set under a funnel and the samples were poured through a funnel to maintain natural flow into the cup. Excess sample was scraped off using a scraper in a zig–zag motion, and the cup was weighed using a balance (sensitivity: 0.001 g; Mettler-Toledo, Heightstown, NJ, USA). The bulk density (ρ_B) was then calculated from the weight and volume of the samples.

Table 1
Moisture content of samples, % wb.

Moisture content	Wheat	Chaff
MC1	9.89	10.40
MC2	11.67	11.83
MC3	13.35	14.01

2.2.2. Tapped density

Tapped density, which measures compaction during handling, was measured using an autotap instrument (AT 6-1-110-60, Quantachrome Instruments, FL, USA) according to ASTM Standard B527-6 (ASTM, 2006). Samples were filled in volumetric cylinders (250 ml), and the cylinders were tapped 750 times. The number of taps was optimized by a preliminary experiment (results not reported) to produce change in volume during tapping. After tapping, the changes in sample volumes were measured, and tapped densities (ρ_T) were calculated from the volume of samples after tapping and weighing.

2.2.3. Compressibility index (CI) and Hausner ratio (HR)

The CI and HR indicate the cohesiveness and compaction mechanisms that occur during handling of particulate materials as a result of vibration or tapping. CI and HR were calculated from the bulk and tapped density using the following equations:

$$CI = 100 \times \left(\frac{(\rho_T - \rho_B)}{\rho_T}\right) \tag{1}$$

$$HR = \frac{\rho_T}{\rho_B} \tag{2}$$

where ρ_B is the bulk density (kg/m^3) and ρ_T is the tapped density (kg/m^3).

2.2.4. True density

True density of the samples was measured using a gas pycnometer (AccuPyc II 1340, Micromeritics, Norcross, GA, USA). Helium gas was used to fill the chamber containing samples to determine particle volume, and the true density was calculated from the weight and solid particle volume.

2.2.5. Porosity

Porosity was calculated using the relationship between bulk and true densities as follows:

$$\varepsilon = \left(1 - \frac{\rho_B}{\rho_{True}}\right) \times 100 \tag{3}$$

where ρ_B is the bulk density (kg/m^3) and ρ_{Ture} is the true density (kg/m^3).

2.2.6. Angle of repose

A fixed diameter (0.09-m) plate was set under a funnel held 0.1 m above the plate, and the samples were poured to maintain a natural flow on the plate. After pouring the samples, the height of the cone was measured and the angle of repose was calculated using the following relationship (Ozguven and Kubilay, 2004):

$$\theta = \arctan\left(\frac{2H}{D}\right) \tag{4}$$

where H and D are the height and average diameter of the pile, respectively.

2.3. Flow properties

The FT4 Powder Rheometer (FT4, Freeman Technologies, Gloucestershire, UK) was used to evaluate flow properties in terms of the energy required to make the solid flow. Detailed descriptions of this equipment and its use in flow characterization can be found in Lindberg et al. (2004), Freeman (2007) and Leturia et al. (2014). The FT4 powder rheometer system consists of a vertical glass sample