Journal of Stored Products Research 63 (2015) 51–56

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Effects of insect-infested kernels on bulk flow properties of wheat

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A R T I C L E I N F O

Article history:
Received 28 January 2015
Received in revised form
24 June 2015
Accepted 25 June 2015
Available online 8 July 2015

Keywords:
Wheat
Insect infestation
Physical properties
Flow properties

A B S T R A C T

Insect damage to kernels during storage affects the processing quality of wheat and as well as bulk wheat properties, which in turn causes hopper flow problems such as funnel flow, ratholing, arching, or flushing. This study focused on kernel damage by *Rhyzopertha Dominica* F. (lesser grain borer), one of the most commonly found insects in wheat, and resulting changes in physical properties, such as bulk density, tapped density, true density, and angle of repose, and in flow properties, such as basic flowability energy, stability, aeration, compressibility, and permeability. Bulk and tapped densities of sound hard red winter wheat kernels and infested wheat kernels were about 720 kg/m^3 and 775 kg/m^3, respectively. Compressibility index (CI), Hausner ratio (HR), and angle of repose of infested wheat kernels were higher than for sound hard red winter wheat kernels, indicating decreased flowability. Grain dust and insect-infested kernels could form localized compacted areas within the grain bins, resulting in uneven flow during discharge. Results from this study indicate that the presence of insect-infested kernels could lead to arching and bridge formation in grain bins, thus affecting the flow characteristics of bulk wheat.

1. Introduction

Wheat quality standards presented by GIPSA (Grain Inspection, Packers and Stockyards Administration) regulate wheat grades with details on the contaminants that lower the wheat grade. As defined by GIPSA, damaged kernels are pieces of wheat kernels that are ground-damaged, weather-damaged, diseased, frost-damaged, germ-damaged, heat-damaged, insect-bored, mold-damaged, sprout-damaged, or otherwise materially damaged. Insect-damaged kernels are kernels bored or tunneled by insects (GIPSA, 2013). Although wheat kernels may visually appear to be sound or uninfested, insects may be present inside some kernels. The insects may eventually emerge and cause further damage to kernels by fragmenting them into flour. The presence of live or dead insects in wheat kernels lowers overall wheat quality (Maghirang et al., 2003).

Rhyzopertha dominica F.(lesser grain borer, LGB), is a primary pest in stored grain. The insect is injurious to cereals and breeds in wheat, corn, rice, and other substrates containing starch (Subramanyam et al., 2007). The optimum temperature for *R. dominica* infestation is 28 °C (Howe, 1950) at grain moisture contents between 12 and 14% (wet basis, wb). The grade of wheat is discounted based on the number of insect-damaged kernels (IDK) in the lot during grading. A wheat consignment containing more than 32 IDK per 100 g is designated as sample grade (GIPSA, 2013).

Adult feeding activities of *R. dominica* produce large amounts of frass, most of which consists of ovoid granules of apparently undigested endosperm mixed with a finer floury part (Breese, 1960). The frass contain larvae excreta, feces, fragments of immature insects, and other by-products, which could affect the end-use quality of the infested grain (Park et al., 2008). The presence of impurities affects the handling and processing of bulk wheat because of particle size differences and void spaces that become filled with frass or dust generated by insect activity. Bulk solids composed of larger particle size have better flow than bulk solids containing smaller particles (Hou and Sun, 2008). The smaller dust particles could occupy the external void spaces between wheat kernels and thus increase bulk cohesion, meaning the energy required to make the bulk wheat flow will be higher. The prediction of bulk flowability on the basis of particle size distribution is difficult and can sometimes be misleading, so an accurate and quantified characterization of bulk properties is essential to understand the flow (Schulze, 2007).

Failure to understand physical and flow characteristics could result in unreliable and inconsistent discharge and lead to loss of production time. Bulk solids characterization can be divided into quantitative parameters and qualitative parameters. Bulk density,

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http://dx.doi.org/10.1016/j.jspr.2015.06.002
0022-474X/

tapped density, true density, compressibility index (CI), Hausner ratio (HR), porosity, and angle of repose are described as qualitative flow indicators. Dynamic flow characteristics such as flow energy, shear tests, wall friction, etc. are commonly used quantitative flow indicators in bin and hopper design. In dynamic testing, the samples can be characterized in consolidated, conditioned, aerated, or even fluidized states to study solids flowability.

Insect infestation and improper moisture content could affect flowability. Arching of bulk wheat occurs during wheat storage as a result of improper flow through hoppers or from bins. Besides affecting bin capacity, arching is also a serious safety issue in U.S. grain handling facilities, so understanding the properties of wheat containing IDK could help predict flow and prevent accidents. Although the flow behavior of bulk wheat has been studied, the effects of insect damage and the influence of dust on the bulk flow of wheat have not been characterized. The objective of this research was to study the effects of moisture content and IDK proportion on the physical and flow properties of bulk wheat.

2. Materials and methods

2.1. Sample preparation

Hard red winter wheat kernels were obtained from the Farmers Cooperative Association, Manhattan, KS, USA. Moisture content of the wheat was measured using the American Society of Agricultural and Biological Engineers (ASABE) Standard S352.2 by drying 10 g wheat samples in an air oven at 130 °C for 19 h (ASABE, 2006). Initial moisture content of the wheat was 11.7% wb. Physical and flow experiments were conducted at the general storage moisture contents of approximately 12 and 14% (wb). Wheat kernels were conditioned to about 15% (wb) by adding a calculated amount of distilled water. After conditioning, the samples were stored at 4 °C for 72 h for moisture equilibration. Drying to the desired moisture level (12 and 14% wb) was carried out in ambient conditions by spreading kernels in a thin layer without any additional heat or airflow and decreasing the moisture content to target levels (Ileleji et al., 2003).

Moisture-conditioned wheat samples were used to prepare insect-infested kernels. *R. dominica* that have been in rearing, without insecticide exposure, since 1999 in the Department of Grain Science and Industry, Kansas State University were used. Insect-infested kernels were prepared by adding 200 *R. dominica* insects to 400 g sound wheat per jar in an 800 ml wide mouth ball jar. The wheat sample with insects was cultured in an incubator at 65 ± 5% relative humidity at 32 ± 1 °C for 42 days (Boina et al., 2012). About 7 kg of wheat samples were cultured to measure bulk physical and flow properties. The infested wheat samples contained sound kernels, *R. dominica*-infested kernels, dead *R. dominica*, and grain dust produced from the infestation. The final moisture contents of wheat and insect-infested kernels are given in Table 1. The particle size of wheat kernels was measured using a single kernel characterization system (SKCS 4100, Perten Instruments, Inc., Springfield, IL, USA). The particle size of grain dust was measured using a LECOTRAC LTS-150 Particle Size Analyzer (LECO Corporation, Tampa, FL, USA).

Table 1
Moisture content of wheat and insects infested kernels, % wet basis.

Moisture content	Wheat	Insect-infested kernels
MC1	11.67	11.83
MC2	13.35	14.01

*MC1, MC2 denote the conditioned moisture content of wheat and insect-infested kernels at approximately 12 and 14% (wb), respectively.

Wheat (W) and infested wheat kernels (I) were mixed at specific proportion (W:I at 100:0%, 97.5:2.5%, 95:5%, 92.5:7.5%, and 0:100%) on a weight basis. The proportion of mix was selected based on the U.S. grade of wheat with different broken and foreign material levels (Grain Inspection Handbook, 2013). To avoid segregation of dust and infested wheat kernels, before addition to sound wheat kernels, the cultured samples were mixed thoroughly and a Boerner divider was used to draw representative samples for each replicate measurement of physical and flow properties.

2.2. Physical properties and flow indicators

2.2.1. Bulk density

The bulk density of samples was measured using a Winchester cup setup (Seedburo Equipment Company, Chicago, IL, USA.). A cup with known volume (4.7318×10^{-4} m^3) was set under a funnel, and samples were poured through the funnel to maintain a natural flow into the cup. Excess sample was scraped off using a scraper in a zig-zag motion. The bulk density (ρ_B) was then calculated from the weight and volume of the samples.

2.2.2. Tapped density

Tapped density, which quantifies the density of solids after handling/compaction due to vibration, was measured using an autotap instrument (AT 6-1-110-60, Quantachrome Instruments, FL, USA). The tester taps the graduated cylinder according to the procedure outlined in ASTM Standard B527-6 (ASTM, 2006). The samples were placed into a volumetric cylinder (250 ml), and the cylinder was tapped 750 times. After tapping, the change in volume of sample was measured, and the tapped density (ρ_T) was then calculated from the volume of the sample after tapping (V_{Tapped}) and its weight.

2.2.3. Compressibility index and Hausner ratio

CI and HR indicate the cohesiveness and compaction mechanism that occurs during handling of particulate materials due to vibration or tapping. CI and HR were calculated from bulk and tapped densities using the following equations:

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

$$HR = \frac{\rho_T}{\rho_B} \quad (2)$$

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 the particle volume, and the true density was calculated from the weight and the solid particle volume.

2.2.5. Porosity

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

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

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