Effect of *Rhyzopertha dominica* (F.) infestations on the bulk wheat flowability

Bian, Q., Ambrose, K.*, Bhadriraju, S.#
Grain Science and Industry Department, Kansas State University, Manhattan, KS-66506, USA

*Corresponding author, Email: kingsly@ksu.edu
#Presenting author, Email: sbhadrir@ksu.edu

DOI: xx.xxxx/xxx.2014.xxx.xxx.xxx

Abstract

Insect damage of kernels during storage affects the processing quality of wheat and could impact hopper flow characteristics. Changes in bulk wheat properties may cause funnel flow, ratholing, arching, flushing, etc. during flow the lesser grain borer (*Rhyzopertha dominica* F.) is one of the most commonly found insects in wheat. This study focused on the effect of insects damaged kernels on the bulk flow properties of wheat. The change in physical properties such as bulk density, tapped density, and angle of repose; and the flow properties such as stability, compressibility, and internal anfle of friction were studied. Bulk and tapped density 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, Hausner Ratio and angle of repose of infested wheat kernels was higher than sound hard red winter wheat kernels, indicating decrease of flowability. The grain dust and insect damaged kernels could form localized compacted areas within the grain bins resulting in uneven flow during discharge. The results from this study indicate that presence of insect damaged kernels could lead to arching and bridge formation in grain bins affecting the flow characteristics of bulk wheat.

Keywords: wheat, physical properties, flow properties, compressibility, shear properties

1. Introduction

The lesser grain borer (LGB), *Rhyzopertha dominica* (F.), is a primary pest in stored grain. The insect is injurious to cereals; breeds in wheat, corn, rice and in other substrates containing starch (Subramanyam et al., 2007). The optimum temperature for LGB infestation is 28°C (Howe, 1950) at grain moisture contents between 12 and 14% (wet basis, w.b.) at 26 to 34°C (Birch, 1945). It is well known that 12 to 14% (w.b.) is the optimum wheat storage moisture content. 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 insect damaged kernels per 100 g is designated as sample grade (FGIS, 1997).

Adult feeding activities of LGB 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 (Sanchez-Marinez et al., 1997; Seitz and Ram, 2004; Park et al., 2008). The larvae and adult *R. dominica* feed on both the germ and endosperm and are capable of reducing wheat kernels to the pericarp (Chanbang et al., 2008).

With the presence of impurities, the handling and processing of bulk wheat will be affected by the differences in particle size and by the filling of void spaces with frass or dust generated by the insect activity. According to Peleg (1978), particles with irregular or fibrous shapes can mechanically interlock the particles during bulk flow. Characterization of bulk solid flowability is required for predicting flow through hoppers or from storage silos or bins (Pablo and Gustavo, 2010).

Understanding the physical and flow properties are important for their effect on particles' behavior in handling and processing operations, such as flow from hoppers and silos, transportation, mixing, compression and packaging (Knowlton et al., 1994). Failure to understand these characteristics could result in unreliable and inconsistent discharge leading to loss of production time. Bulk solids characterization can be divided into quantitative parameters and qualitative parameters. Bulk density, tapped density, compressibility index (CI), Hausner's ratio (HR), and angle of repose, are described as the qualitative flow indicators. Dynamic flow characters such as flow energy, shear tests, wall friction, etc are quantitative flow indicators that are commonly used for bin and hopper design. In dynamic testing, the samples can be characterized at consolidated, conditioned, aerated, or even fluidized states in order to study solids flowability.

Due to insect damages and improper moisture content could decrease the quality of wheat and most importantly could affect the flowability. Arching of bulk wheat, due to improper flow through hoppers or from bins happens during wheat storage. Other than affecting the capacity, arching is also a serious safety issue and a concern in grain handling facilities across U.S. So understanding the properties of the wheat containing IDK could help predict the bulk wheat flow and to prevent accidents originating from arching in bins. Though the flow behavior of bulk wheat is well studied, but the effect of insect damage and the influence of dust on the bulk flow of wheat has not been characterized. The objective of this research is to study the effect of moisture content and insect damaged kernels 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 Farm Coop, Manhattan, KS, 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 wheat samples in air oven at 130° for 19h (ASABE, 2006). Initial moisture content the wheat was 11.7% w. b. Physical and flow experiments were conducted at the general storage moisture contents of approximately12 and 14% (w. b.). Wheat kernels were conditioned to about 15% (w. b.) by adding calculated amount of distilled water. After conditioning, the samples were stored at 4°C for 72 h for moisture equilibration. Drying to desired moisture level (12 and 14% wet basis) was carried out in ambient conditions by spreading kernels in thin layer without any additional heat or airflow, decreasing the moisture content to target levels (Ileleji et al., 2003).

Moisture conditioned wheat samples were used for preparing insects infested kernels. Insect damaged kernels were prepared by adding 200 Lesser Grain Borer (LGB) insects to 400g sound wheat per 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 for measuring the bulk physical and flow properties. The infested wheat samples contained sound kernels, LGB damaged kernels, dead LGB, and grain dust produced from the infestation. The final moisture content of wheat and insects infested kernels are given in Table 1. In the cultured samples, the insects damaged kernel to sound kernel ratio was 18±3:100 and 25±5:100 at MC 1 and MC 2, respectively. The average dust generated by insect infestation was 1.43 and 2.31 % (by weight) at MC 1 and MC 2, 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 weight basis. The proportion of mix was selected based on the U.S. grade of wheat with different broken and foreign material level (Grain Inspection Handbook, 2013). To avoid segregation of dust and damaged wheat kernels, before adding with 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 one pint (4.7318×10^{-4} m^3) cup was set under a funnel, samples were poured through the funnel to maintain a natural flow into the cup. Excess sample was scraped off using a scrapper 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, that 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 filled in a volumetric cylinder (250 ml) and the cylinder was tapped for 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 sample after tapping (V_{Tapped}) and the weight.

2.2.3. Compressibility index and Hausner ratio

Compressibility Index (CI) and Hausner Ratio (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 the bulk and tapped density using the following equations (Kingsly et al., 2010):

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

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

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

2.2.4. Angle of repose

A fixed diameter (0.09 m) plate was set under a funnel which is held at a height (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):

$$\theta = \arctan\left(\frac{2H}{D} \right) \tag{3}$$

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 the flow properties of wheat, insects infested wheat kernels, and the mix samples.

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.

2.3.1. Stability index (SI)

SI was used to evaluate the flow properties of the granular material under free surface conditions. Eleven test cycles were performed to calculate. The flow energy is calculated from the anticlockwise motion of blade (23.5 mm diameter) through samples from the vessel top to the bottom. The first stage contains seven test cycles were performed at a blade tip speed of 100 mm/s to examine the effect of segregation on the bulk wheat during flow. For subsequent tests (test 8 to 11, second stage), the blade tip speed was gradually reduced from 100 mm/s to 70, 40 and 10 mm/s gradually to evaluate the sensitivity of the particles to different flow rates. From the 11 test cycle results, parameters were calculated.

SI is the factor evaluating flow energy changes during repeated testing and assesses how easily the particles are affected by being made to flow:

$$SI = \frac{\text{Flow energy at test 7}}{\text{Flow energy at test 1}} \tag{4}$$

2.3.2. Compressibility

Compressibility indicates the volume change under compaction, i.e., the decrease in volume of the packed bed of particles under normal stress (Turki and Fatah, 2008; 2010). Wheat and insects infested kernels samples were placed in a 50 ml cylindrical vessel and using a vented piston, normal stress from 0.5, to 15 kPa (0.5, 1, 2, 4, 6, 8, 10, 12, 15 kPa) was applied to consolidate the samples. Each normal stress was maintained for about 25 s to reach equilibrium at the target stress. The force applied on the sample and the compressibility percentage changes in volume were recorded.

2.3.3. Shear tests

The relationship between normal stress and shear stress are plotted to obtain experimental yield locus that represents the failure during shearing of the bulk solids (Fig. 3.1). In free flowing powders, the yield locus follows a straight line that passes through the origin (Peleg, 1978) and its slope defines the angle of internal friction, as calculated by Equation 9. For cohesive powders, however, the experimental yield locus is generally non-linear at different consolidation stresses (Thomson, 1997; de Jong et al., 1999). The shear test determines the following material characteristics as related to flow: the effective angle of internal friction (δ), and the angle of wall friction (ϕ_w).

2.4. Statistical analysis

All the tests were performed in triplicate and the mean values and standard deviations (mean ± standard deviation) are reported in this paper. Statistical analyses were conducted using SAS (SAS Institute Inc., Cary, NC, USA). The effect of moisture content, insects infested kernels proportion and their interactions on physical and flow properties were evaluated by subjecting the data to two-way analysis of variance (ANOVA) at α= 0.05, using PROC GLM. Ryan or Ryan-Einot-Gabriel-Welsch Q (REGWQ) multiple comparison tests were used to separate the differences ($P \leq 0.05$) between the effect of moisture content and impurities.Provide sufficient details of methodology and approach used. Established, published, or standard methods should be indicated by reference; only modification by authors should be described. Mention about commercial name of instrument to supply scientific details may be possible but sparingly and must not imply approval or endorsement of particular producer of the equipment.

3. Results and Discussion

3.1. Bulk physical properties

The average bulk density of dust generated from the insect infestation was 528.4 and 514.1 kg/m^3 at MC 1 and MC 2, respectively. The values were much lower than the density of sound wheat kernels (Table 1) that contributed to the decrease of bulk density with the increase in the insect damaged kernel proportion. Moisture content had also significant effect on the bulk density. Similar negative relationship of bulk density with moisture content was also observed for wheat (Karimi et al., 2009), gram (Dutta et al., 1988), sunflower seeds (Gupta and Das, 1997), and soybeans (Deshpande et al., 1993). Moisture content had similar effect on the tapped density of bulk wheat samples. At lower proportion of insect damaged kernels, the change in tapped density was not significant (Table 1). The tapped density of insect damaged kernels was higher than the other samples. The dust, insect damaged kernels, and sound kernels vary in average size and density. So, during tapped density measurement, the particles rearranged and compacted within the container volume due to vibration. So, handling bulk wheat with high insect infestation will be challenging. The compaction and rearrangement of particles could lead to arching and bridging of particles leading to poor flow.

Table 1 Bulk, tapped and true density of bulk wheat.

Sample	Bulk density, kg/m^3		Tapped density, kg/m^3	
	MC 1	MC 2	MC 1	MC 2
W 100%	801.54±0.51Aa	785.91±0.12Ab	825.33±0.57Aa	811.51±0.19Ab
W 97.5%-I 2.5%	799.55±0.10Ba	785.59±0.97Bb	824.40±0.52Aa	810.77±1.28Ab
W 95%-I 5%	798.48±0.34Ca	784.36±0.95Cb	823.21±1.07ABa	809.78±2.89ABb
W 92.5%-I 7.5%	796.52±0.61Da	780.86±1.06Db	822.26±0.81Ba	807.64±1.98Bb
I 100%	777.64±0.28Ea	769.60±1.93Eb	832.44±0.67Ca	831.31±1.34Cb

*Where W indicates wheat kernel, I indicates insects infested kernels and MC is the moisture content (% wet basis);
**Two-way ANOVA results: bulk density: MC: $P < 0.001$, I: $P < 0.001$, MC*I: $P < 0.001$; tapped density: MC: $P < 0.001$, I: $P < 0.001$, MC*I: $P < 0.001$.
***The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to insects infested kernels proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.

The derived flow indicators of Hausner's ratio (HR) and compressibility index (CI) of wheat samples are given in Table 2. The difference in HR and CI values for wheat with insect damaged kernels was not statistically significant. But, the increase in HR and CI values indicate that the increase in insect damaged kernel proportion in bulk wheat could make the flow little challenging. The two-way ANOVA results indicate that the moisture content did not affect the Hausner's ratio significantly, but did affect the compressibility index of bulk wheat samples.

Table 2 Flow indicators.

Sample	Hausner's ratio		Compressibility index	
	MC 1	MC 2	MC 1	MC 2
W 100%	1.03±0.0007Aa	1.03±0.0002Ab	2.88±0.07Aa	3.15±0.02Ab
W 97.5%-I 2.5%	1.03±0.0007Aa	1.03±0.0016Ab	3.01±0.06Aa	3.11±0.15Ab
W 95%-I 5%	1.03±0.0013Aa	1.03±0.0037Ab	3.00±0.13Aa	3.14±0.35Ab
W 92.5%-I 7.5%	1.03±0.0010Aa	1.03±0.0025Ab	3.13±0.10Aa	3.32±0.24Ab
I 100%	1.07±0.0009Ba	1.08±0.0017Bb	6.58±0.08Ba	7.42±0.15Bb

*Where W indicates wheat kernel, I indicates insects infested kernels and MC is the moisture content (% wet basis);
**Two-way ANOVA results: Hausner's ratio: MC: $P < 0.001$, I: $P < 0.001$, MC*C: $P = 0.0042$; compressibility index: $P = 0.0021$, I: $P < 0.001$, MC*I: $P = 0.0196$
***The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to insects infested kernels proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.

Angle of repose of bulk wheat, except for the insect damaged samples, ranged from 24.31 to 27.37º (Table 3). At lower proportion of insect damaged kernels, the difference in angle of repose was not statistically significant. The insect damaged samples had higher angle of repose due to the presence of dust that occupied the intergranular space and increase the angle of repose value. In addition, grain dust increases the contact area between particles. Carr (1965) suggested that angle of repose below 30° indicate good flowability, 30°-45° some cohesiveness, 45°-55° true cohesiveness, and >55° sluggish or very high cohesiveness with very limited flowability. Wheat samples with different proportion of insect damaged kernels could be categorized under solids with "good flowability" because the angle of repose was less than 30º.

Angle of repose is a qualitative and relative data that at best may help in finding differences between samples and angle of repose values are not applicable in design of handling and storage systems (Zhou et al., 2008). The angle of repose is a measure in uncompacted condition and differs from the conditions during storage or handling. As expected, with the increase in moisture content, angle of repose increased due to higher cohesion between particles.

Table 3 Porosity and angle of repose of samples.

Sample	Angle of repose,º	
	MC1	MC2
W 100%	24.31±0.61Aa	25.36±0.60Ab
W 97.5%-I 2.5%	24.84±0.53Aa	26.42±1.14Ab
W 95%-I 5%	25.50±0.84ABa	26.60±0.16ABb
W 92.5%-I 7.5%	26.79±1.37Ba	27.37±0.63Bb
I 100%	36.02±1.20Ca	40.30±0.30Cb

*Where W indicates wheat kernel, I indicates insects infested kernels and MC is the moisture content (% wet basis);
**Two-way ANOVA: MC: $P < 0.001$, C: $P < 0.001$, MC*C: $P = 0.0084$;
***The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to insects infested kernels proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.

3.2. Dynamic flow behavior

Stability index (SI) values of bulk wheat ranged between 0.9-1.1 (Table 4) that classifies the bulk wheat as 'stable' indicating no physical change occurs during handling of wheat with insect damaged kernels. With the difference in particle size between dust and wheat kernels, there could be potential segregation with dust settling at the bottom of conveying equipment and storage vessels.

Table 4 Stability index of bulk wheat samples.

Sample	Stability index (SI)	
	MC 1	MC 2
W 100%	1.01±0.02Aa	0.98±0.02Aa
W 97.5%-I 2.5%	0.99±0.01Aa	1.01±0.03Aa
W 95%-I 5%	1.05±0.01Aa	1.01±0.02Aa
W 92.5%-I 7.5%	1.02±0.04Aa	1.00±0.05Aa
I 100%	0.97±0.04Aa	1.01±0.05Aa

*Where W indicates wheat kernel, I indicates insects infested kernels and MC is the moisture content (% wet basis);
**Two-way ANOVA: Stability Index: MC: P =0.6988, I: P =0.3281, MC*I: P = 0.1381
***The same uppercase letter in the same column indicates no significant difference (P < 0.05) due to insects infested kernels proportion, the same lowercase letter in the same row indicates no significant difference (P < 0.05) due to moisture content.

3.3. Bulk flow properties

Proportion of insect damaged kernels in bulk wheat did not affect the bulk compressibility of wheat samples (Table 5). Presence of insect damaged kernels and moisture content increased the compressibility of wheat kernels. In addition, the compressibility of insect damaged kernels was significantly different than other tested samples. Rearrangement of finer dust particles and the breaking of wheat kernels with insect drilled holes might have resulted in a higher compressibility for insect damaged kernels. The compressibility result shows that if there is insect activity in a section of grain stored in a bin, the compressibility of that section of grain could increase the cohesive strength of the bulk grain. Localized increase in strength could lead to arching and caking of grains within grain bins.

3.4. Shear properties

During storage and processing, solids would be subjected to consolidation stresses, causing changes in density and mechanical inter-particulate forces. Shear properties measures the flowability of powder under consolidation. At a specific normal stress higher shear stress corresponds to higher angle of internal friction and wall friction angle indicating a shear stress is needed to make cohesive materials to flow. From Table 6 and 7, the decrease in trend can be observed for angle of internal friction and wall friction angle at different insects damaged kernel proportion. But the values are not statistically significant different. With increase in inter-particulate cohesion, arches might form in a grain bin. But with changes in angle of internal friction due to application of load, for e.g. a person stepping on the cohesive grain arch, the cohesively bonded grain would break leading to sudden change in flow. Grain entrapment accidents happens as grain arch breaks due to changes from static to dynamic conditions resulting from the lowered friction between the grain kernels. Tables 6 and 7 indicate that the shear properties are not significantly different and were not affected by moisture content and the proportion of insects infested kernels.

Knowledge of wall friction provides important information on whether the bulk solid will flow against the material with which it is in contact. It is the frictional resistance to bulk solids flow that exists between the bulk solids and hopper/silo wall material (Iqbal and Fitzpatrick, 2004). Similar to angle of internal friction, at MC 1 and MC 2 moisture contents, the results are not significantly different. The results indicate that increase in moisture content will lead to a higher wall friction influencing the bulk flow of wheat.

Table 5 Compressibility of samples.

Sample	Compressibility, %	
	MC 1	MC 2
W 100%	4.86±0,11Aa	5.58±0.17Ab
W 97.5%-I 2.5%	4.92±0.39Aa	5.59±0.12Ab
W 95%-I 5%	5.18±0.19Aa	5.64±0.05Ab
W 92.5%-I 7.5%	5.12±0.20Aa	5.64±0.21Ab
I 100%	5.44±0.10Ba	6.07±0.21Bb

*Where W indicates wheat kernel, I indicates insects infested kernels and MC is the moisture content (% wet basis);
** Two-way ANOVA results: porosity: compressibility: MC: $P < 0.001$, I: $P = 0.0011$, MC*I: $P = 0.7612$
*** The same uppercase letter in the same column indicates no significant difference ($P < 0.05$) due to insects infested kernels proportion, the same lowercase letter in the same row indicates no significant difference ($P < 0.05$) due to moisture content.

Table 6 Angle of internal friction at 15kPa of wheat mixed with insect damaged kernels.

Sample	Angle of Internal friction,°	
	MC 1	MC 2
W 100%	26.96±0.21ab	28.64±2.46a
W 97.5%-I 2.5%	26.06±0.12ab	26.07±0.80ab
W 95%-I 5%	24.63±0.28b	24.37±3.91ab
W 92.5%-I 7.5%	23.82±0.27b	23.35±1.76b
I 100%	23.37±0.23b	25.00±2.90ab

**Different letters indicates significant difference ($P < 0.005$).

Table 7 Wall friction angle at 15kPa of wheat mixed with insect damaged kernels.

Sample	Wall Friction Angle,°	
	MC 1	MC 2
W 100%	18.24±0.31Aa	20.33±0.63Ab
W 97.5%-I 2.5%	18.55±0.60Aa	18.89±1.42Ab
W 95%-I 5%	17.86±0.51Aa	18.76±0.13Ab
W 92.5%-I 7.5%	17.54±1.11Aa	18.04±0.05Ab
I 100%	15.64±0.83Ba	16.53±0.62Bb

**Capital letter indicates the analysis between impurity proportions in columns, lowercase represents the analysis between moisture contents in rows.

4. Conclusions

In this paper, physical and flow properties of hard red winter wheat, insects infested wheat kernels and their mixture were investigated as a function of moisture content. Knowledge on these characteristics is necessary for design of handling equipment and to understand the behavior of grain during storage and handling. Increase in moisture content significantly influenced most of the physical and flow properties. Compressibility increased with the increase in proportion of insect damaged kernels. Presence of insect damaged kernels and the dust from insect activity could increase the compressibility and lead to arching and caking of grains affecting their flowability.

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