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Effect of Dropping Height on Segregation of Different Sized Particles in Stored Wheat Bulk

Vincent R. Parker, Digvir S. Jayas, Fuji Jian

Department of Biosystems Engineering, University of Manitoba, Winnipeg, MB, Canada, R3T 5V6

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Abstract

The segregation of materials during loading and unloading of grain leads to non-uniform distribution of dockage in the grain bulk. The effects of particle size and loading height on bulk density and dockage distribution were tested using wheat as the grain bulk and canola and soybean as dockage representatives. A mixture of canola (4.5% by mass), soybean (4.5%), and wheat (91%) was dropped into a square bin (1.0 ×1.0×0.1 m) from three heights (0.65, 1.30, and 1.95 m). The bin was separated into 100 finite elements to determine the bulk density distribution of the mixture and the distribution by mass of the individual components. The mass of each component was measured for each element. Comparisons were made between different elements when loaded from the same height as well as between the same positions when loaded from different heights.

It was found that loading height influences the distribution of both dockage components larger than and smaller than wheat in a grain bin loaded from a central spout. There was a significant difference in the distribution of spherical dockage that is smaller and lighter than wheat, horizontally across the bottom of a grain bin loaded from a central spout. Small, light, spherical dockage had higher values at the center elements when compared with other elements.

Keywords: Dockage, Distribution, Foreign material, Segregation, Loading height

INTRODUCTION

The quality of grain during storage is a function of the initial grain conditions and the subsequent grain storage environment. The initial grain conditions that affect grain preservation include: temperature, moisture content, amount of dockage, gaseous composition, and the amount of microorganism infection (Trisvyatskii, 1969). These factors are difficult to control at harvest time and therefore, measures must be taken to control these factors during grain storage if quality is to be maintained.

As temperature and moisture content increase the rate of grain spoilage also increases. Therefore, the first objective of a grain storage strategy is to quickly reduce the temperature and moisture content of the grain after harvest. In Western Canada this is usually achieved through aeration or near-ambient air drying in storage bins. These techniques rely on uniform airflow and their effectiveness is affected by the amount and distribution of dockage within the grain bulk (Navarro and Noyes, 2002).

The physical properties of a grain bulk such as porosity, flowability, moisture distribution and heat transfer characteristics are all influenced by the presence of dockage (Boumans 1985, Muir et al. 2001, Pabis et al. 1998, Trisvyatskii 1969). Because dockage has different physical characteristics than the grain bulk, it tends to naturally segregate during the loading of grain into bins. As a result, areas or columns are formed within the grain bulk that are distinctly different from each other (Trisvyatskii, 1969). These sections can significantly affect the effectiveness of grain preservation techniques that may be used.

It has been proven that dockage plays an important role in the storage of grain (Trisvyatskii, 1969). Determining how dockage distributes within a grain bulk may lead to more effective storage strategies. Natural segregation of dockage during loading of a grain bin may be governed by the characteristics of the grain, the dockage, or a combination of both. If a relationship between these characteristics can be established then predicting dockage distribution may be achieved and grain storage techniques improved.

This study was undertaken to determine the effect of drop height on the distribution of spherical dockage of two different sizes in wheat. The objectives of this study were to determine the effect of:

1. Drop height on bulk density distribution in grain bins filled from a central spout.
2. Drop height on dockage distribution patterns in a grain bin filled centrally.
3. Dockage size on dockage distribution patterns in a grain bin filled centrally.

MATERIALS AND METHODS

Grain mixture

The mixture used for testing consisted of, 91% hard red spring wheat, 4.5% soybean, and 4.5% canola by mass. In this mixture the soybean and canola were used to simulate spherical dockage of different sizes within a wheat bulk. The moisture contents of the wheat, soybean, and canola were determined at the beginning and the end of the experiment using a standard oven-drying method (ASAE, 2002). The mixture was stored in sealed plastic bags between trials to prevent moisture loss.

Sieves
Two different sized hand sieves were used to separate the mixture into individual components. A No. 5 U.S.A. standard test sieve (ASTM E-ll specification manufactured by W.S. Tyler Inc., Gastonia, North Carolina), was used to separate out the soybean. This sieve removes all particles with a diameter of more than 4 mm. A second sieve was constructed to separate the canola from the wheat. This sieve was a 25 x 10 cm rectangle with aluminum sides and a mesh bottom perforated with 2 mm diameter holes.

Hopper bottom bin
The hopper bottom bin was constructed of polyvinyl chloride (PVC) and had a maximum capacity of 0.30 m^3 (Fig 1).

Figure 1. Hopper bottom bin and holding stand with auger and leveling equipment.

At least 0.28 m^3 of mixture was loaded per trial to ensure that the hopper would not require reloading during the trial. This was important because reloading during a test would affect the repeatability of the experiment. The hopper had a 10 cm diameter opening at the bottom. To simulate a change in drop height, different lengths of 10 cm diameter black PVC pipe was added or removed from the hopper bottom bin. At the lowest end of PVC pipe a sliding mechanism was attached which allowed for flow control. When the hopper was loaded the sliding mechanism was completely closed allowing no flow. Once all of the grain mixture was loaded and at rest, the sliding mechanism was opened completely, to allow for maximum flow. The three drop heights of 65, 130, and 195 cm represent the distance from sliding mechanism to the floor of the grain chamber.

Holding stand

The hopper was mounted on a metal holding stand. The stand maintained the height of the bottom opening of the hopper bin at 2.0 m above the floor of the grain chamber. As well the stand had wheels to allow for easy positioning.

Grain chamber

Centered below the hopper bin opening was the grain chamber (Fig. 1). The grain chamber consisted of two parts, the main bin, and the side riser. The main bin was a 1.0 x 1.0 m square with 10 cm high sides and constructed of wood with the inside bottom lined with a 5 mm layer of compression foam. The foam was added to help dampen the impact of the grain particles on the wood and prevent grain breakage. The side riser was a 1.0 x 1.0 m square with 10 cm high sides and was constructed of wood but had no bottom. This piece was added to the grain chamber during loading to allow the grain chamber to fill completely with grain during testing. The side riser was fastened to the grain chamber using metal clips that were easily unfastened after loading. A metal divider was constructed out of aluminum welded together to divide the grain chamber into 100 equal sections each with a volume of $0.001 m^3$.

Experimental procedure

The grain mixture consisted of 200 kg wheat, 10 kg soybean, and 10 kg canola mixed together by parts in a rotating drum to obtain a uniform mixture. Prior to every trial, the mixture was loaded into the hopper bin using a 10 cm standard pitch auger. The mixture was manually stirred in the hopper bin during loading to help prevent natural segregation from occurring and maintain a uniform mixture. After the hopper was loaded a plum line was dropped from the center of the unloading pipe to align the pipe with the center of the grain chamber. A bubble level was used to ensure the unloading pipe was vertical and that the grain chamber was horizontal. This procedure helped to minimize variations in test results and increase experimental repeatability. After alignment was complete the sliding mechanism was opened fully and the grain was allowed to flow until the hopper was empty. This allowed the grain to completely fill the grain chamber. Then the side riser was removed by unfastening the metal clips and lifting it directly upward allowing excess grain to flow onto the floor where a plastic tarp had been placed to collect excess material. At this point a 1.5 m length of 2 x 7 cm rectangular piece of aluminum was used to level the grain to the top of the grain chamber. The metal bar was placed diagonally across opposite corners of the grain chamber and then pulled in a perpendicular path to the edge. This process was repeated eight times with the bar switching diagonals with each pull until the grain mixture was level with the top of the grain chamber.

The grain chamber was then divided into 100 equal sections each with a volume of $0.001 m^3$ by forcing the metal divider into the mixture from the above. The contents of each section were then vacuumed out into glass jars which were sealed with lids. The mixture from each jar was separated by hand using the No. 5 hand sieve first to separate the soybean out of the mixture. Then the 2 mm sieve was used to separate the canola from the wheat. Each sieve was given 50 shakes before being emptied into measuring containers for weighing.
The experiment was conducted at room temperature and consisted of dropping the mixture from heights of 65, 130, and 195 cm. The same grain was used for three replications of the same drop height.

Data Collection and Analysis

The mass of wheat, soybean, and canola recovered from each of the 100 elements was measured and recorded. The mixture bulk density was calculated using the measured masses and the sample volume.

Each sample section of the grain chamber was numbered 1-100 (Fig. 2).

1	2	3	4	5	6	7	8	9	10
11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30
31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50
51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70
71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90
91	92	93	94	95	96	97	98	99	100

Figure 2. Numbering order of finite elements.

This numbering arrangement allowed for easy calculation of distance of each sample from the center of the grain chamber.

To simplify the statistical analysis, not all 100 elements were compared. Instead samples from each replication were chosen to represent the four following areas: center, half the distance to the wall, wall, and corner. The four elements selected to represent each area are listed in Table 1.

Table 1. Elements used as representative sample locations.

Center	1/2 wall [a]	wall [a]	corner
45	48+58	5+6	1
46	25+26	40+50	10
55	43+53	41+51	91
56	75+76	95+96	100

[a] **value divided by two to obtain average of the two elements.**

With three replications for each height, it follows that there was a total of 12 individual measurements for each representative section at a given height. For statistical comparison these 12 values were averaged.

The distribution of the mixture components between different loading conditions was analyzed using statistical methods and SAS program (SAS Institute Inc. 1988). Within each trial the Turkey procedure was used to test for significant differences in the distribution of bulk density and mass of individual components among the four different positions of center, half wall, wall, and corner. Then each position was compared for significant differences between drop heights. As well, the four data values obtained for each of the representative areas within the three replications at each height were compared for significant differences.

RESULTS

Bulk density distribution

The bulk density of the mixture showed significant differences between the center and the wall at all three drop heights (Table 2). The bulk density was always higher at the center and decreased as the distance from the center increased.

Comparing bulk density measurements from the same positions loaded from different drop heights showed that at all locations except the corner there was no significant difference in bulk density between drops height 65 cm and 130 cm (Table 3). It was also found that the drop of 195 cm gave the lowest bulk density values at all locations. At all locations there was a significant difference in bulk density between drop heights of 65 cm and 130 cm.

Table 2. Statistical comparison of bulk density (kg/m^3) at four locations in the grain chamber loaded from three different drop heights.[d]

	Drop height (cm)		
Location	65	130	195
Center	816.7 [a]	836.3 [a]	809.7 [a]
1/2 Wall	798.3 [a,b]	810.6 [b]	793.7 [a,b]
Corner	783.1 [b,c]	754.5 [c]	734.4 [c]
Wall	766.1 [c]	760.1 [c]	750.8 [b,c]

[d] Values for a given height (column) followed by same letter are not significantly different ($P< 0.05$).

Table 3. Statistical comparison of bulk density (kg/m^3) at each location loaded from three different drop heights.[d]

	Location			
Drop height (cm)	Center	1/2 Wall	Wall	Corner
65	816.7 [a,b]	798.4 [a,b]	766.1 [a]	783.1[a]
130	836.3 [a]	810.7 [a]	760.2 [a,b]	754.5[b]
195	809.7 [b]	793.7 [b]	750.8 [b]	734.4[c]

[d] Values for a given height (column) followed by same letter are not significantly different ($P< 0.05$).

Soybean distribution

A comparison of the mass distribution of soybean within each height showed that at 2 of the 3 drop heights the mass in the center was significantly lower than the mass at the wall (Table 4).

A comparison of the mass distribution at the same position loaded from different drop heights showed that at all positions except the corner, drop height of 195 cm had the highest values (Table 5). In the corner it was drop height of 65 cm that had the highest value. At the wall and corner positions, drop height of 130 cm gave significantly different masses than the drop heights of 65 and 195 cm. However, drop heights of 65 and 195 cm did not give significantly different values at these positions.

Table 4. Statistical comparison of soybean mass (g) at four locations in the grain chamber loaded from three different drop heights.[d]

	Drop height (cm)		
Location	65	130	195
Center	41.6 ^{a}	42.1 ^{a}	45.9 ^{a}
1/2 Wall	41.9 ^{a}	42.3 ^{a}	55.7 ^{b}
Wall	50.4 ^{b}	45.1 ^{a}	50.9 ^{a,b}
Corner	52.2 ^{b}	45.0 ^{a}	51.8 ^{a,b}

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

Table 5. Statistical comparison of soybean mass (g) at each location loaded from three different drop heights.[d]

	Location			
Drop height (cm)	Center	1/2 Wall	Wall	Corner
65	41.6 ^{a}	41.9 ^{a}	50.4 ^{a}	52.1 ^{a}
130	42.1 ^{a,b}	42.3 ^{a}	45.1 ^{b}	45.0 ^{b}
195	45.9 ^{b}	55.7 ^{c}	50.9 ^{a}	51.8 ^{a}

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

Canola distribution

A comparison of the mass distribution of canola within each drop height showed that at all three heights there was a significant difference between the center and wall positions (Table 6). For drop heights 130 and 195 cm, the center value was significantly different from all other positions.

A comparison of the mass distribution at the same position loaded from different drop heights showed that at all positions the values for 65 cm were significantly different than the values for drop height 195 cm (Table 7). There were significant differences between the three drop heights at the half wall location. As well there were no significant differences in canola masses between drop heights 130 and 195 cm except at the half wall location.

Table 6. Statistical comparison of canola mass (g) at four locations in the grain chamber loaded from three different drop heights.[d]

	Drop height (cm)		
Location	65	130	195
Center	44.4 [a]	46.4 [a]	50.3 [a]
1/2 Wall	43.3 [a]	36.2 [b,c]	31.9 [b]
Wall	26.9 [b]	33.2 [b]	37.4 [b,c]
Corner	24.3 [b]	40.8 [c]	41.6 [c]

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

Table 7. Statistical comparison of canola mass (g) at each location loaded from three different drop heights.[d]

	Location			
Drop height (cm)	Center	1/2 Wall	Wall	Corner
65	44.4 [a]	43.3 [a]	26.9 [a]	24.3 [a]
130	46.4 [a,b]	36.2 [b]	33.2 [b]	40.8 [b]
195	50.3 [b]	31.9 [c]	37.4 [b]	41.6 [b]

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

Wheat distribution

A comparison of the mass distribution of wheat within each drop height showed that at all three drop heights there was no significant difference between values at the center and half wall locations (Table 8). At all drop heights the center location was significantly different than the corner and wall positions.

A comparison of the mass distribution by position loaded from different heights showed that at all locations the drop height of 195 cm had the lowest value (Table 9). As well, the mass of wheat for the drop height of 195 cm was significantly different from drop height 130 cm at all locations.

Table 8. Statistical comparison of wheat mass (g) at four locations in the grain chamber loaded from three different drop heights.[d]

	Drop height (cm)		
Location	65	130	195
Center	730.8 [a]	747.9 [a]	713.5 [a]
1/2 Wall	713.2 [a,b]	732.2 [a]	706.1 [a]
Wall	688.8 [c]	681.9 [b]	662.5 [b]
Corner	706.6 [b,c]	668.7 [b]	641.0 [c]

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

Table 9. Statistical comparison of wheat mass (g) at each location loaded from three different drop heights.[d]

Drop height (cm)	Location			
	Center	1/2 Wall	Wall	Corner
65	730.8 [a,b]	713.2 [a]	688.8 [a]	706.6 [a]
130	747.9 [a]	732.2 [b]	681.9 [a]	668.7 [b]
195	713.5 [b]	706.1 [a]	662.5 [b]	641.0 [c]

[d] Values for a given height (column) followed by same letter are not significantly different (P< 0.05).

DISCUSSION

Bulk density distribution

As a grain bin loads the center section is subjected to greater amounts of force than other sections due to the impact of the falling grain. As well, once the grain has stopped falling the cone formed from filling causes the center area to be subjected to a greater weight of grain than the outer edges. Therefore, this area would be expected to have a higher bulk density than other areas within the bin. The data from this experiment agreed with this expectation, with bulk density being highest at the center and lowest at the wall for all three drop heights.

As drop height increases the momentum of the grain particles also increases, until terminal velocity is reached. Therefore, at higher drop heights the center sections would be subjected to more force and the bulk density would be expected to be higher for this position. However, for the drop heights studied, the largest drop height of 195 cm gave the lowest bulk density values at all positions.

This was an unexpected result and is not explainable at this time. More studies are required to confirm if further increases in drop height will maintain this trend. If this trend is continued or bulk density does not increase further, it implies that bulk density increases with increased drop height initially and then becomes reduced and constant.

Dockage distribution by size

The mass of soybean in the center was less than all other locations for all three drop heights. However, the difference between the center and the wall was not statistically significant for drop height of 130 cm. At all heights the mass of canola was higher in the center than at the wall and this difference was statistically significant for all three heights. This confirms the expected results that particles smaller than the average particle size will stay near the center and larger particles will move toward the wall as observed by Jayas et al. (1987) while studying distribution of foreign material in full size bins with canola containing dockage from a field harvest. Soybean and canola are both spherical particles with soybean being larger in size. During testing it was observed that the larger soybean particles appeared to roll down the edge of the cone of grain during filling. This result agrees with Boumans (1985) statement about the behavior of heavy grain particles during loading. This effect was not observed for the smaller canola particles. This difference may be related to the size of the particle relative to the intergranular space between wheat kernels. The canola may be more readily trapped in the intergranular space and therefore, cannot roll from the top of the filling cone to the outer edge. However, further experimentation is required to determine if this effect is due to particle shape or the difference in particle mass.

Effect of drop height on grain particle distribution

The comparison of mass values by location for different loading heights produced mixed results. Soybean had the highest mass values at all locations except the corner when loaded from drop height of 195 cm. Whereas canola had the highest values at all positions except the half wall position when loaded from drop height 195 cm. In all cases, the difference between the highest value and the lowest value was statistically significant.

One explanation for the canola distribution may be linked to mass. It was observed during testing that as loading height increased more canola particles bounced out of the grain chamber. With increased loading height the particles striking the center of the grain cone would have greater momentum and therefore a greater number of particles would penetrate the grain surface and be trapped. Those that did not penetrate the grain surface could reflect outward towards the wall. This would cause many of the canola particles to jump over the half wall position and either end up near the wall or out of the grain chamber.

A similar effect may explain the soybean distribution. Soybean is too large to fit into the intergranular space between the wheat kernels and may have a tendency to roll down the outside of the grain cone. However, as their momentum increases with increased loading height a greater number of particles may hit and penetrate into the grain surface enough to prevent rolling from occurring. This would lead to higher mass values of soybean toward the center location at higher drop heights.

Wheat was found to have the lowest values at all locations when released from drop height of 195 cm. This is an unexpected result that is not explainable at this time and requires further experimentation.

SOURCES OF ERROR

Non-uniform grain chamber loading

During the experimental design it was believed that as the grain loaded into the grain chamber it would form a small cone that would grow uniformly toward the wall. However, it was found that this was not true during the first few seconds of loading. After the sliding mechanism opened the first grain particles fell toward the grain chamber and when they hit the chamber they produced a ring of material (Fig. 3).

Figure 3. Ring formed due to grain impact with grain chamber bottom.

This ring created an artificial boundary within the grain chamber that affected the flow characteristics of the material until a cone of sufficient size was produced to overflow this initial grain ring. This may not have a significant effect in a bin with a large area. Due to the small size of the experimental grain chamber and the fact that only the bottom 10 cm of grain bulk was being analyzed, the ring formed may have had a significant effect on the experimental results.

Non-uniform loading of hopper bottom bin

Natural segregation during the loading of the hopper by an auger may have affected the uniformity of the mixture in the hopper bottom bin. The original mixture was composed of 9 % simulated dockage in the form of soybean and canola. However, it was observed that the canola was not transported through the auger as easily as wheat and soybean. Although the material in the hopper was mixed by hand during loading natural segregation in the auger may have led to a higher percentage of canola near the top of the hopper bottom bin. According to Trisvyatskii (1969) the top section is one of the first areas to unload out of a hopper. Therefore, the first section of the grain chamber loaded into the grain chamber may have had a higher percentage of canola than other sections due to hopper loading and not because of actual distribution characteristics.

Breakage of grain particles

Breakage of grain particles through repeated trials may have also presented a source of error when comparing later trials to earlier trials. Due to the amount of mixture required for the experiment it was not feasible to make a fresh mixture for each experiment. Therefore, the same mixture was used for all trials. This may have introduced error due to mechanical breakage of the grain particles as the experiment progressed. Broken kernels have different flow properties than the original kernels and may have affected experimental results.

Loss of moisture content

Loss of moisture content may influence the comparisons made between drop heights of 65 and 195 cm. The moisture content of the mixture components was measured at the beginning and end of the experiment, but not before each individual trial. Even though steps were taken to prevent moisture loss some moisture content changes did occur (Table 10).

Table 10. Measured moisture content (% wb) of mixture components at beginning and end of experiment.

Grain	Initial	Final	Change
wheat	12.5	11.1	-1.4
soybean	6.7	8.7	2
canola	5.4	6.7	1.3

The change in mass of each grain was calculated based on the initial and final moisture content to determine if the change in bulk density between drop heights 65 and 195 cm was due to a change in moisture content. The adjusted bulk density (kg/m^3) values obtained for drop height 195 cm are: center 819.4, 1/2 wall 803.4, wall 759.8, and corner 743.1. These values are all greater than the unadjusted values obtained however, only the center and 1/2 wall values are greater than those obtained from the drop height 65 cm. Therefore, the change in moisture content does not completely explain the unexpected bulk density results.

CONCLUSIONS

In a grain bin loaded from a central spout:

1. Bulk density is greatest near the center and decreases as distance from the center increases.
2. Loading height influences bulk density.
3. There are significant differences in the distribution of spherical dockage that is smaller and lighter than wheat, horizontally across the bottom of bin. Small, light, spherical dockage has higher values at the center sections.
4. Loading height influence the distribution of both dockage components larger or smaller than wheat.

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