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EFFECT OF MOISTURE CONTENT AND BROKEN KERNELS ON THE BULK DENSITY AND PACKING OF CORN

S. G. McNeill, S. A. Thompson, M. D. Montross

ABSTRACT. *Shelled yellow dent corn samples were conditioned to three moisture content levels (12%, 15%, and 18% w.b.) and mixed with a prescribed amount of broken corn particles of known size (geometric mean diameter of 1.0, 1.4, 2.0, 2.8, and 4.0 mm) and concentration (2.5%, 5.0%, and 7.5% by weight) levels. The initial bulk density and grain compaction under simulated overburden pressure tests were determined for each sample. Uniaxial compression tests were performed for seven vertical pressure levels (3.4, 6.9, 14, 28, 55, 110, and 165 kPa) with a minimum of three replications each. Tests were performed at two locations with identical apparatus, which was fully described by Thompson and Ross (1983). These devices used compressed air injected beneath a rubber diaphragm to apply vertical pressure uniaxially to a volume of granular material. Deflections of the grain mass were measured with a dial gauge and were used to calculate changes in bulk density and grain packing. Statistical models were tested for the initial bulk density and packing factor as a function of moisture content, broken corn particle size, and broken corn concentration level and their interactions. For clean corn, the initial bulk density was inversely affected by grain moisture while packing increased slightly with grain moisture. For corn mixed with fines, the initial bulk density decreased with grain moisture and the interaction of broken corn particle size and concentration but increased with the interaction of grain moisture and concentration of fines. Packing of corn mixed with fines increased slightly with grain moisture and broken corn concentration. For a given pressure, the predicted bulk density from the developed model was within 4% of the observed value, which was within the variation among test replications and may in fact represent observed differences in bulk density caused by bin loading methods that have been reported by other engineers. The results can improve predictions by WPACKING, the ASAE standard for estimating capacities of cylindrical grain storage structures.*

Keywords. *Packing factors, Corn, Storage capacity, Bulk density, Compressibility.*

Accurately estimating the inventory of bulk grain storage structures appears to be a relatively straightforward task. However, this task can become complicated because of variations in the physical and mechanical properties of bulk grain and their interaction with the structure. Grains are somewhat compressible when subjected to the cumulative weight exerted from the above material. This compression creates a packing effect that increases material bulk density, the structural requirements, and the capacity of the storage unit. Initial bulk density, grain depth, moisture content, the type and level of dockage, friction properties of the grain, shape of the storage structure, type of grain, method of filling, kernel dimensions, and kernel density are all thought to influence grain packing (*ASAE Standards*, 1999c). The influence of these physical variables on product compressibility must be clearly understood for adequate structural designs and accurate inventory estimates.

In an effort to simplify the procedures for estimating stored grain inventories, a computer model (WPACKING) was developed by Thompson et al. (1987). This program employs the differential form of Janssen's equation to estimate the pressure and in−bin bulk density for a given depth of grain in a bin, which in turn is used to calculate the bulk density at that depth. Janssen's (1895) equation is commonly used in the design of storage bins and utilizes the properties of the stored material and the geometry of the storage structure to estimate in−bin pressures. Janssen's equation assumes the properties of the stored material to be constant. However, in WPACKING the differential form of this same equation is used which assumes the properties of the stored materials to be mathematical functions, which vary with various grain parameters (i.e. moisture content, vertical pressure, etc.). By computing these values using the differential form of Janssen's equation for each depth in a bin, the capacity for that structure and the amount of packing can be estimated more accurately by taking into account the variation in grain properties. The computer program WPACKING was validated in a limited manner by Thompson et al. (1991) using data from full size bins and has become the current ASAE Standard for estimating the storage capacities of cylindrical grain structures (*ASAE Standards*, 1999c).

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BACKGROUND

BULK DENSITY

Previous research has reported the influence of moisture content on the test weight or uncompacted bulk density of grains. Brusewitz (1975) measured bulk densities of eight rewetted grains including clean shelled corn and cracked corn over a variation in moisture content ranging from 15% to 45% (all moisture contents are reported in wet basis). The test weight of these two products decreased with an increase in moisture content up to approximately 30%, and then increased with moisture content from 30% to 45%. Cracked corn samples produced lower bulk density values across all moisture levels but were not affected by moisture to the extent observed for shelled corn. The particle size distribution within the cracked corn sample was not reported.

Nelson (1980) developed a predictive equation for the bulk density of corn over a variation in moisture content ranging from 10% to 35%. Nelson also determined that the bulk density decreased as the moisture content increased, but to a lesser degree than the results reported by Brusewitz (1975).

The results of these two studies are given in ASAE Standard D241.4 (1999a) and can be used to estimate the uncompacted bulk density of shelled corn as a function of moisture content. It is noted in the Standard that variations in the initial bulk density of corn can be caused by differences in grain varieties and growing conditions. Similar bulk density values were predicted using either equation for moisture content levels between 15% and 18%.

Other factors have also been found to affect the test weight of shelled corn. Hall (1972) determined that the test weight of shelled corn varied with drying conditions, variety, and the amount of kernel damage. In another study, Hall and Hill (1974) harvested corn over a typical range of moisture levels and adjusted combine settings to create a range of damaged kernels. From this study a set of adjustment factors was developed to predict the final test weight based on the extent of kernel damage and moisture content at harvest. Results showed that the highest final test weight occurred as harvest moisture and damage levels decreased. Broken corn (BC) particle size was not identified in either study.

Other studies have been conducted to determine the effect of filling method on the in−bin bulk density of shelled corn. Stephens and Foster (1976) determined that grain spouted into a bin had an average bulk density 3.7% greater than the bulk density determined when using the Winchester cup. Chang et al. (1983) determined that when a spreader was used to fill a bin, the in−bin bulk density of corn was approximately 6% to 10% higher than when no spreader was used. Chang et al. (1986) investigated the effect of drop height and bin filling method (spout−flow and restricted flow) on the bulk density and distribution of fines for corn. They noted that neither drop height nor filling method affected bulk density but that filling method significantly influenced the distribution of fine material in the bin.

PACKING FACTORS

Many attempts have been made to develop a simple and convenient method for estimating the amount of packing in grain storage structures. Bates (1925) was among the first to describe such a method and suggested that the number of standard bushels of wheat (773 kg/m^3) in a storage unit was dependent on the test weight, depth of material, and dimension and shape of the structure. Through experiments he determined that the average amount of packing for wheat was 4.85% of the test weight. Bates inferred that different packing factors would probably exist for other grains.

The compressibility of corn meal, wheat, and other feed materials were measured by Clower et al. (1973) using a uniaxial compression tester at low pressures (0 to 27.6 kPa). The ratio of lateral to vertical pressures was also determined for these materials. Mathematical relationships were developed from the data to relate increases in vertical pressure to changes in bulk density. They found that bulk density varied in a parabolic manner with respect to vertical pressure.

A detailed method for estimating the packing factors of different grains was used by the Illinois Agricultural Auditing Association (1980). Their field manual contains packing factor tables for seven grains based on the initial test weight and cross−sectional storage capacity of the structure. These values are adjusted for variations in test weight for different grains, but no correction was given for grain height, bin wall material, and diameter greater than 10.5 m.

Malm and Backer (1985) attempted to determine the in−bin compaction of six whole grain products. Compaction factors were estimated by measuring the total settlement of stored material in bins at 7 to 14 days after filling and again at 23 to 40 days after filling. A statistical model was tested to correlate selected physical properties such as moisture content, percent dockage, test weight, crop depth, and dimensions of the structure to the packing factor, but only barley and oil sunflower were found to have a significant correlation to any of these properties.

Uniaxial compression tests were conducted using clean, whole grains by Thompson et al. (1987) to determine the variation in bulk density with respect to pressure and moisture content. Multiple varieties of six different grains were tested with an apparatus used by Thompson and Ross (1983) to determine changes in bulk density at different overburden pressures between 0 and 172 kPa and moisture contents between 10% and 16%. Mathematical expressions were developed which described the change in bulk density with respect to changes in pressure and moisture content. These expressions were incorporated into the WPACKING computer program to predict the amount of packing in bins of a given height and diameter. For example, the pack factor for corn in an 11.9−m diameter bin level filled to a height of 11.9 m was estimated to be 3.8% (*ASAE Standards*, 1999c).

Thompson et al. (1991) validated the ability of WPACKING to predict vertical pressures and packing factors using data from other studies, including an evaluation of shelled corn in a corrugated−wall bin. These results indicated that most of the variations in the predicted packing factors for a given type of grain were attributed to moisture content, friction properties of the stored material, grain depth, and bin diameter. Moreover, it was determined that grain height had a greater effect on packing than grain moisture or bin diameter. This test proved to be a useful validation of the bench−top compression test device used in the present study.

The objective of this study was to investigate three parameters [grain moisture, concentration of broken corn (BC), and BC particle size] that are believed to affect the bulk density, packing factor, and grain compaction of corn in storage structures.

EXPERIMENTAL PROCEDURE

Compression experiments were performed with yellow corn using an identical uniaxial test device at two locations to determine the variation in bulk density and grain packing when varying the moisture content, size of BC particles, and concentration of BC particles with respect to changes in vertical pressure. Because of the number of independent variables in this experiment a fractional−factorial experimental design known as TENNEFAC (Sanders, 1989) was employed to select a separate set of experimental conditions for each test location. Treatment selections for each location are shown in table 1 with those tests performed at Georgia or Kentucky identified by a G or K, respectively. Test assignments were based on the levels of moisture content, BC concentration, and particle size. Clean corn samples were tested initially for each moisture level at both locations to establish a reference for the material. Although a few other duplicate experiments were selected at both locations, the basic premise of this experimental design was that not all combinations of independent variables had to be tested to determine their influence on the dependent variables (initial bulk density and packing). An experimental efficiency of 80% was imposed in the selection of test combinations for each location.

All experiments were performed on the same lot of yellow corn, which was subdivided into two sub−samples for testing at Georgia and Kentucky. Approximately 250 kg (550 lb) of corn (Northrup−King PX−9540, Syngenta Seeds Inc., Golden Valley, Minn.) was collected from a Kentucky producer. The corn had been harvested the previous fall using a conventional combine, dried to approximately 15% with ambient air, and stored in an aerated metal grain bin throughout the winter. Following collection, the entire lot was cleaned by hand with a standard corn sieve (4.76−mm round hole) and sub−divided into one base sample for testing at each location. Base samples were further split into three sub−lots and conditioned to target moisture contents. Each sub−lot was then divided into five final samples to which BC was added as prescribed by the experimental design.

Table 1. Observed initial bulk density values[a] (kg/m^3) for clean corn and corn mixed with fines at each moisture content, broken corn (BC) concentration and particle size level at each test location.

Moisture Content (% w.b.)	BC (%)	Geometric Mean Diameter of BC (mm)				
		Clean Corn	4.0	2.8	2.0	1.4	1.0
12	0.0	733.0[b] 726.9[c]					
	2.5		742.4[b]	724.0[c]			748.5[b]
	5.0				729.1[c] 751.4[b]		742.8[c]
	7.5		719.5[c]	735.2[b]	738.6[c]	759.9[b]	
15	0.0	722.4[b] 716.6[c]					
	2.5		713.0[c]		724.8[c]	724.8[b]	
	5.0			733.3[b]		734.9[b] 729.3[c]	
	7.5			720.6[c]	737.6[b]	748.2[c]	756.4[b]
18	0.0	714.4[b] 702.4[c]					
	2.5		722.1[b] 690.4[c]	713.3[b]		687.2[c]	
	5.0			703.7[c]	721.0[b]		734.3[b] 705.9[c]
	7.5		712.6[b]				721.3[c]

[a] The least significant difference was 8.49 kg/m^3 ($\alpha = 0.01$).
[b] Test conducted at the University of Georgia.
[c] Test conducted at the University of Kentucky.

The nominal moisture content values chosen for these tests were 12%, 15%, and 18%. The first two moisture levels represent the recommended range of values for safe storage across the United States and Canada, while the upper level represents the intermediate moisture for low temperature and combination drying systems. Moisture samples were collected at the conclusion of each set of pressure applications and tested immediately with a Steinlite moisture meter. When the moisture content varied by more than ±0.5% of the target level the compression data was rejected, the moisture was adjusted and compression tests were repeated.

Five sizes of broken corn particles were used in these experiments using material collected from the cleaning operation of an elevator. This material was divided into five categories by mechanical sieving using a set of U.S. standard sieves (Numbers 6, 8, 12, 16, and 20, ASAE Standard S319.2, 1999b). Selection of these sieves were based on the results of a preliminary analysis of corn samples that were collected from the receiving station of three commercial grain elevators, which indicated that 90% of the BC was in this range (unpublished work by authors). A food blender was used to generate additional quantities of fine material for all tests. Samples within each moisture content category were mixed with the prescribed amount of BC of a particular geometric mean diameter, sealed in plastic bags, and placed in refrigerated storage (4°C) at least two weeks prior to testing to allow moisture equilibration of the sample.

Three different concentrations of broken corn were used during testing. Broken corn concentrations of 2.5%, 5.0%, and 7.5% by weight were chosen after informal discussions with grain farmers and commercial elevator operators. These concentrations represent U.S. grain grade levels 1, 4, and 5, respectively (USDA, 1999).

A standard method of filling the pressure chamber was used for all tests at both locations to minimize the loading effect on the initial bulk density and packing. The filling apparatus consisted of four compartments of equal volume with a hinged bottom door so that grain was emptied from each cell simultaneously when a spring loaded tripping mechanism was released (Thompson and Ross, 1983). By using this filling apparatus, the initial bulk density was within 0.4% of the test weight determined by the Winchester bushel test (USDA, 1999). After filling, corn in the pressure chamber was leveled even with the top of the pressure cell using a wooden stick with rounded edges, similar to the one used for the Winchester test.

Compression tests were performed using identical uniaxial compression devices at each location, which are described by Thompson and Ross (1983). Each compression device had a 30− × 30−cm chamber area with a 10−cm height that contained grain during testing. A removable metal steel plate was used to seal the test chamber. The base of the chamber contained a flexible rubber diaphragm. During testing, compressed air was injected beneath the rubber diaphragm to apply vertical pressure uniaxially to the volume of granular material. Deflections of the grain sample were measured using a dial gage. The dial gage was actuated using a metal rod, which was connected to the stem of the dial gage, inserted through a hole in the middle of the removable top plate, and rested on a thin metal plate, which sat on top of the rubber diaphragm. An initial dial reading was recorded prior to testing. Pressure was then applied to the apparatus and a dial reading recorded after a waiting period of 8 min. This process was repeated until all pressures in the sequence were applied. The material was then removed from the chamber, weighed, and sampled for moisture determinations.

Compression tests were performed at seven levels of vertical pressure (3.4, 6.9, 14, 28, 55, 110, and 165 kPa) with a minimum of three replications each. These pressure levels were chosen to simulate the stress conditions created by various depths of overbearing grain in the range typically expected in farm and commercial bins (Thompson et al., 1991). Application pressures were measured with a dial gauge accurate to 1.5 kPa before and after each compression test and liquid manometers were used to verify the accuracy of pressure gauges at both locations.

RESULTS AND DISCUSSION

INITIAL BULK DENSITY

Initial bulk density values (D_o) were computed for each replicate by using the mass of corn contained in the pressure chamber and its initial volume. Mean D_o values for each moisture content, BC concentration, and particle size level are shown in table 1. Initial bulk density values for clean corn decreased by 1.4% and 3.7% as the moisture content increased from 12% to 15% and from 15% to 18%, respectively. Within each test location and moisture level, observed mean values for initial bulk density were generally lower for clean corn. For example, for clean corn with 15% moisture content the mean initial bulk density for both test locations was 719.5 kg/m^3, yet when small corn pieces were added by a large amount (BC with a mean geometric diameter of 1.0 mm at 7.5%) the bulk density increased by 5.1% to a value of 756.4 kg/m^3.

A comparison of duplicate sample conditions between test locations indicated that the initial bulk density values were generally lower at the Kentucky location, while the standard deviation and coefficient of variation values were higher. Differences between mean D_o values for all tests common to both locations ranged from 0.8% to 4.5% and were attributed to slight variations in experimental procedures between locations such as the method used to load and level the test chamber even though identical equipment was used with the same filling procedure. Nevertheless, data from both locations were combined to develop mathematical relationships.

A STEPWISE regression procedure (SAS, 1991) yielded a straightforward linear model for the initial bulk density for clean−shelled corn as a function of moisture content (table 2). Values predicted by the model were 730.1, 719.3, and 708.6 kg/m^3, for 12%, 15%, and 18% moisture content corn, respectively. All of these values were about 4% lower but followed the same trend reported by Nelson (1980). Values found by Brusewitz (1975) were within 1.0% of the value reported by Nelson at 15% moisture and within 0.5% of the value found in this study at 18% moisture. The D_o values for all three studies decreased with an increase in grain moisture.

Observed initial bulk density (D_o) values for all samples with broken corn (BC) is plotted against mean particle size and compared to clean corn in figure 1. Values are coded by symbols to indicate sample moisture content and BC concentration. In general, D_o values for BC samples were above those samples observed for clean corn, especially when small to medium size BC particles (1 to 2.8 mm) were present in high concentrations. This increase in bulk density was thought to be the result of small broken particles occupying more of the void spaces between intact corn kernels and larger BC particles. Conversely, D_o values generally either decreased or stayed approximately the same as clean corn when large BC particles were added at low concentrations. As the size of the broken particles increase, they approximate the size of whole grain kernels and therefore have less impact on D_o values for clean corn lots.

The inverse relationship of moisture content and initial bulk density for corn containing broken kernels is quantified in table 1 and illustrated in figure 1. Comparing treatments common to both locations with clean corn and corn containing 5.0% BC, D_o increased by 1.4% with medium size particles (geometric diameter of 2.0 mm) at 12% moisture; by 1.8% with small pieces (geometric diameter of 1.4 mm) at 15% moisture; and by 1.7% with very small pieces (geometric diameter of 1.0 mm) at 18% moisture. With large pieces of broken corn (geometric diameter of 0.4 cm) D_o decreased by 1.0% as BC concentration increased from 0 to 7.5%.

A second STEPWISE regression procedure (SAS, 1991) was employed to further investigate the influence of BC concentration and particle size on the initial bulk density of corn. The best model selected by the MAXR option ($p > 0.01$) is also shown in table 2 with predicted values plotted against observed values in figure 2. Error bars on this graph represent the range of values within the least significant difference (8.49 kg/m^3) that was determined statistically for all data, while the solid line represents a reference for equal values. Most predicted values were within the least significant difference value except on the extreme ends of the range of observed values. Prediction errors ranged from 0.06% to 3%

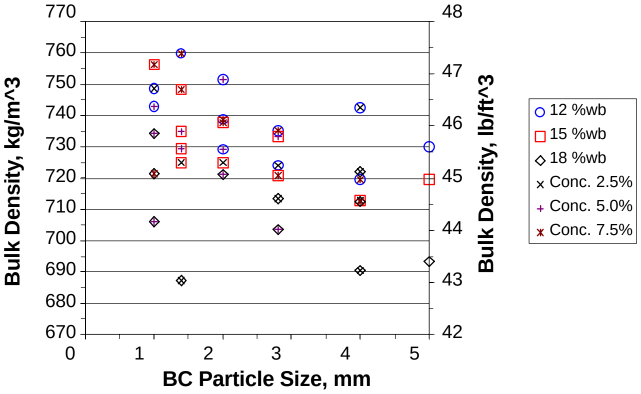

Figure 1. Observed initial bulk density for clean shelled corn (plotted at BC = 5) and corn mixed with fines as a function of broken corn (BC) particle size, moisture content, and concentration.

Table 2. Prediction equations for the initial bulk density (D_o) and slope of the compression curve (S) for clean corn and corn mixed with fines using data from both locations.

Sample	Test Variable	Equation	R^2	MSE
Clean corn	D_o	$773.07 - 3.583m$	0.813	0.10
	S	$1.123 + 6.830E{-}6m^4$	0.972	0.01
Corn mixed w/fines	D_o	$748.87 - m(0.00878 \times m^2 - 0.320c) - 30.27cp$	0.687	0.43
	S	$1.0392 + 0.0345c + 1.440E - 4m^3$	0.687	0.07

for all tests. Moisture content, percentage of broken corn, and particle size significantly affected initial bulk density values in the ranges selected in this study.

PACKING FACTOR

Bulk density values were computed as a function of simulated overburden pressure (D_p) from the deflection dial readings for each pressure level using the following equation:

$$D_p = D_o\left(\frac{h}{h - \Delta h_p}\right) \tag{1}$$

At the no load condition, $\Delta h_p = 0$ and $D_p = D_o$.

Packing factors were calculated for each pressure using the following equation:

$$PF_p = 100\left(\frac{D_p}{D_o} - 1\right) \tag{2}$$

The observed pressure−density relationship showed that packing increased with corn moisture content and simulated overburden pressure, as previously reported by Thompson and Ross (1983). For almost all test conditions, clean corn had smaller pack factor values than corn at a similar moisture content containing broken particles and fines. The shape of packing curves suggested that the amount of packing could be approximated for each condition by a power function. Thus, a non−linear statistical analysis (SAS, 1991) was performed using the following equation:

$$PF_p = S{*}P^n \tag{3}$$

Results of this analysis revealed that the value of n changed very little between tests and the overall mean value for the entire data set was 0.333. A transformed linear regression (SAS, 1991) was then performed using the cube root of pressure as the independent variable to determine the slope (S) for each test. Physically, S represents the change in bulk packing as pressure is applied during filling of a storage unit. Mathematically, S represents the slope of the regression line on packing factor plots. Larger S values indicate that the material is more compressible and has a large packing factor.

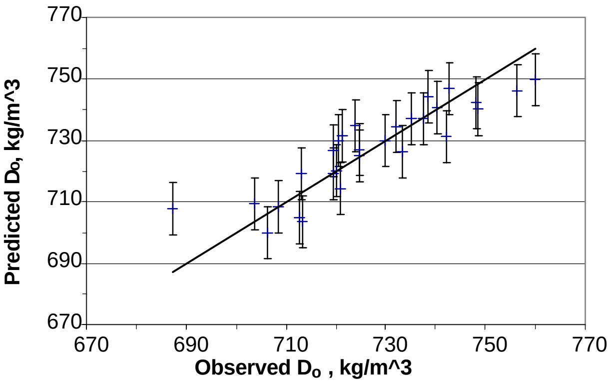

Figure 2. Comparison of predicted and observed initial bulk density (D_o) values for all tests with error bars to represent the least significant difference and a line to represent equal values.

Mean S values for clean corn increased with moisture indicating a greater amount of packing. The average measured value of S for clean corn was 1.27, 1.47, and 1.85 $kPa^{-1/3}$ at moisture contents of 12%, 15%, and 18%, respectively. The mean value for 18% moisture samples was significantly different than the two lower moisture samples. Additionally, at 12% moisture content, mean S values for clean corn were not significantly different ($\alpha = 0.01$) than those observed for samples containing broken corn.

The influence of vertical pressure on the packing factor for clean corn and corn mixed with 5% fines is shown in figure 3 for 12% and 18% moisture grain and in figure 4 for 15% moisture corn for common tests from both locations. For 12%, 15%, and 18% moisture tests, BC particle sizes were 2.0, 1.4, and 1.0 mm, respectively (table 1). Error bars are overlaid for the observed values to represent one standard deviation of the mean for all treatment replications. In most cases, the pack factor increased as the percentage of broken particles increased, as shown in these figures.

A final prediction equation was developed using the STEPWISE procedure with MAXR option (SAS, 1991) to correlate the variation in physical properties of bulk corn as affected by fines with results shown in table 2. In comparison to clean corn, S values increased slightly with moisture content and also with the concentration of fine material. Interestingly, BC particle size did not emerge as a significant term in the prediction equation.

To estimate D_p values for corn containing fines, equations 2 and 3 were set equal (with n = 1/3) and combined with the prediction equation from table 2. Bulk density values were computed at discrete overburden pressures and then compared with corresponding values in the original data set using the following prediction equation:

$$D_P = D_O\left(1 + \frac{S \times P^{1/3}}{100}\right) \tag{4}$$

Relative errors were computed to by comparing predicted estimates with the corresponding observed mean bulk

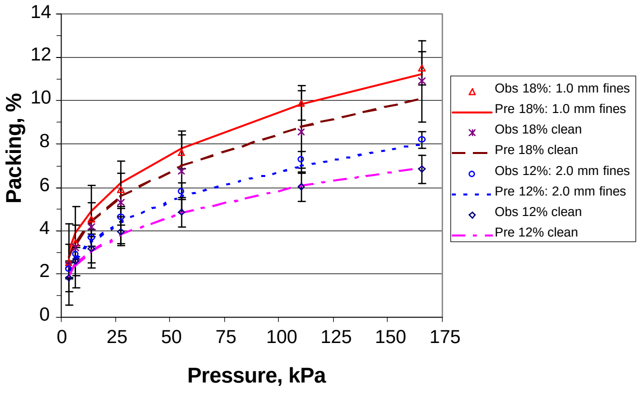

Figure 3. Observed and predicted packing factors (%) of clean corn and corn with 5% fines at 12% and 18% moisture content. (Error bars represent ± one standard deviation of the mean for all treatment replications from both locations.)

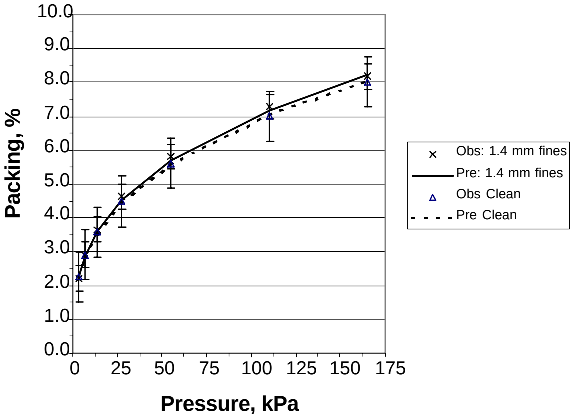

Figure 4. Observed and predicted packing for clean corn and corn with 5% fines at 15% moisture. (Error bars represent ± one standard deviation from the mean value for all treatment replications from both locations.)

density values for all pressures. It was determined that errors for the model shown were within 4%, which was generally less than the variations in observed values between replications.

This predictive equation can thus be incorporated into computer models to estimate the changes in bulk density and packing of corn as a function of overburden pressure assuming appropriate physical properties are known. The equation is considered to be an adequate predictor of corn packing due to variations in grain moisture content and the concentration and particle size of broken grain material.

CONCLUSIONS

The following conclusions are based on observations of initial bulk density and results of the compression tests and statistical analysis described in this study for clean corn and corn mixed with fines of known concentration and particle size:

- Bulk density of clean corn and corn mixed with fines is inversely affected by grain moisture.
- Bulk density of corn mixed with fines is positively correlated with the interaction of grain moisture and the concentration of fines and negatively correlated with grain moisture and the interaction of broken corn concentration and particle size.
- Packing of clean corn increases with grain moisture.
- Packing of corn mixed with fines is positively correlated to grain moisture and concentration of fines.
- The developed model predicted bulk density values for a given pressure within 4% of those observed which was within the variation found between replications.

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NOMENCLATURE

c = concentration of broken corn (%)
D_o = initial bulk density (kg/m^3)
D_p = bulk density for a given pressure (kg/m^3)
h = grain depth in chamber before pressure is applied (initial depth is 101.6 mm)
Δh_p = change in grain depth in chamber for a given pressure (mm)
m = moisture content (% w.b.)
n = regression coefficient for pack factor
p = geometric mean particle size (mm)
P = vertical pressure (kPa)
PF_p = packing factor at a given vertical pressure (%)
S = slope of compression curve (kPa)$^{-1/3}$