EFFECTS OF PRESSURE AND MOISTURE CONTENT ON BULK DENSITY OF TRITICALE GRAIN UNDER COMPACTION

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HIGHLIGHTS

- Compaction of triticale grain with three moisture contents (8%, 12%, and 16% wet basis) was measured at five applied pressures (0, 7, 14, 34, and 55 kPa).
- Bulk density increased with increasing pressure for all moisture contents and was significantly ($p < 0.0001$) dependent on both moisture content and applied pressure.
- A Verhulst logistic equation was found to model the changes in bulk density of triticale grain with R^2 of 0.986.
- The model showed similar behavior to that of wheat and rye, indicating that the results of this study can be used with the methods of ASABE Standard S413 to predict the quantity of triticale grain stored in bins.

ABSTRACT. *The objective of this study was to determine the combined effects of moisture content (MC) and pressure on the changes in bulk density of triticale grain under compaction at conditions typical of those seen in storage structures and to develop mathematical models to describe the compression behavior. Triticale compaction was measured at three MCs (8%, 12%, and 16% wet basis) and four compaction pressures (7, 14, 34, and 55 kPa) using a square metal box based on the design used in an earlier study by Thompson and Ross. Data from the compaction tests were used to calculate bulk densities for the three MCs and four pressures. Bulk densities were found to be significantly ($p < 0.0001$) dependent on both MC and pressure. Bulk densities varied with increasing MC, as has been observed in similar studies for other agricultural grains such as rye and wheat. These results provide guidance for estimating the bulk density of triticale in bins and other storage structures. The Verhulst logistic equation was found to best describe the changes in bulk density of triticale caused by rearrangement of the grain kernels at lower pressures for the three MCs. At higher pressures, the grain was observed to be more compliant, and Hooke's law was used to accurately describe the observed changes. Data from the compaction tests were used to estimate the model parameters, with a correlation coefficient (R^2) of 0.986. The model was then used in WPACKING to compare the results of this study to pack factor predictions for triticale and wheat. WPACKING is a computer program that is the basis for ASABE Standard S413. The results of this comparison showed that this method can be used with the methods of ASABE Standard S413 to predict the quantity of triticale grain stored in bins.*

Keywords. *Bulk density, Interaction, Moisture content, Pressure, Triticale, Verhulst logistic equation.*

Triticale (*Triticale hexaploide* Lart.) (fig. 1) is a cross between wheat (*Triticum*) and rye (*Secale*) and was first produced in 1875 (Wilson, 1876). In the U.S., triticale is primarily produced in western states as a feed grain and forage crop for livestock. Triticale is higher in protein and essential amino acids than corn, with 50% higher lysine content (Myer and Barnett, 2000). Current varieties of triticale are lower in gluten than the parent crop wheat and do not have the baking characteristics needed to compete with wheat for use in bakery goods and pasta.

The USDA (2004) provides a procedure using the Winchester bushel test (WBT) to measure the loose bulk densities of agricultural grains. However, when grain is placed in storage, the weight of the material above individual grain kernels causes the shapes and positions of the kernels to change slightly as the grain compacts. Therefore, the actual bulk densities in bins are greater than the loose bulk densities measured using the WBT and must be corrected for the effects of the surrounding grain pressure. Accurate values of

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Figure 1. Triticale grain after cleaning.

grain bulk density are required to predict pressures (ASABE, 2020a) in bulk grain and to estimate the quantity of grain in storage structures (ASABE, 2020b; Bhadra et al., 2015, 2016, 2017, 2018; Thompson et al., 1990; Turner et al., 2016a, 2016b, 2017).

Many researchers have developed models to predict bulk density that take into account the effects of moisture content (MC) and applied pressure. Altuntas and Demirtola (2007) developed linear models for the bulk density and porosity of selected grain legume seeds that account for the effect of MC. Brusewitz (1975) developed second-degree polynomial functions to model the effect of MC on the bulk density of selected cereal grains including wheat and rye. Chiputula et al. (2021) developed regression models to predict the effects of pressure on the bulk density of rye grain. Faborode and O'Callaghan (1986) developed a model for the dependence between load and density of fibrous agricultural materials. Ferrero et al. (1991) described the density-pressure relationship with an exponential function for the compaction of fibrous plant materials (wheat, burley, and rice straw). Milani et al. (2000) used the Burger model to describe bulk density as a function of pressure. Thompson and Ross (1983) developed a best-fit curve model for wheat in bulk as a function of pressure and MC using the RSQUARE procedure in SAS (ver. 9.4, SAS Institute, Cary, N.C.).

The objective of this study was to determine the combined effects of MC and pressure on the changes in bulk density for triticale grain under compaction at conditions typical of those seen in storage structures and to develop mathematical models that describe the compression behavior. This study observed the behavior of bulk triticale in laboratory compression tests and then developed a semi-empirical model of the observed behavior that can be used to predict the compaction behavior of bulk triticale grain in storage.

AGRICULTURAL GRAIN COMPACTION

When varying overburden pressures are applied to bulk agricultural grain, the grain goes through three apparent loading phases in which the grain kernels first rearrange slightly in the void space of the bulk grain, followed by deformations of the individual kernels, and finally breakage of the kernels at very high pressures. Thompson and Ross (1983) observed that the largest change in the bulk density of wheat per unit pressure increase occurred at pressures below 14 kPa. They attributed much of this change to rearrangement of the grain kernels as pressure was applied, resulting in an overall decrease of the void space between the kernels. As pressure increases, stresses produced by contacts between the kernels cause deformation of the kernels, which adds to the increase in bulk density. Thompson and Ross (1983) proposed that much of the change in bulk density between 34 to 172 kPa was caused by elastic particle deformation. At higher pressures, plasticity comes into play, and further increases in pressure produce breakage of the kernels (Nelson, 1980; Petingco et al., 2018).

The elasticity of grain kernels is also affected by MC. Thompson and Ross (1983) reported that 33% to 40% of the total bulk density change for wheat at 8% and 12% MC and at pressures between 0 and 7 kPa was caused by rearrangement of the kernels. At higher pressures, the increase in bulk density caused by particle elasticity of the kernels is much greater at high MCs than at low MCs. At higher pressures, less of the increase in bulk density is believed to be caused by rearrangement of the kernels, and much more of the increase is believed to be caused by grain deformation. Plastic deformation and kernel breakage are undesirable. However, in most postharvest handling and storage operations for agricultural grains, the overburden pressures are low enough that only kernel rearrangement and elastic behavior between kernels occur.

The effects of MC and applied pressure on the bulk densities of agricultural grains have been modeled by many researchers. The approach of most of these researchers has been to model the relationship between the changes in bulk density with either the MC of the grain or the pressure applied to the grain (Altuntas and Demirtola, 2007; Brusewitz, 1975; Chiputula et al., 2021; Faborode and O'Callaghan, 1986; Ferrero et al., 1991; Milani et al., 2000). Thompson and Ross (1983) developed a best-fit curve model for the bulk density of wheat as a function of both MC and applied pressure. In this study, the effects of MC and applied pressure on the changes in bulk density of triticale grain were simultaneously modeled based on two compaction parameters: kernel rearrangement to fill the void space, and kernel elasticity.

COMPACTION MODEL

A compaction model was developed that took into account two different effects that occur during compaction of bulk grain: the rearrangement of kernels to fill the void space, and the elastic behavior of the kernels. The changes in bulk density were modeled as a function of MC and applied pressure. These two variables were thought to have an interaction effect on the change in bulk density of triticale grain. Therefore, an interaction variable (y) for MC and applied pressure was used to model the changes in bulk density (eq. 1):

$$y = Mp \tag{1}$$

where M is the wet basis (w.b.) MC of the grain (decimal), and p is the applied pressure (kPa).

The Verhulst logistic equation (Bacaër, 2011) was used to describe the changes in bulk density caused by kernel rearrangement. The Verhulst logistic equation was chosen based on the shape of grain compaction curves observed in the literature. Thompson and Ross (1983) fitted a curve using only an RSQUARE procedure; however, they proposed that large changes in bulk density occurred at low pressures, which were believed to be caused by rearrangement of the kernels. As the overburden pressure increased, they proposed that the changes in bulk density were increasingly caused by kernel-to-kernel interaction. At high pressures, the change in bulk density slowed.

In the Verhulst logistic equation, three stages of growth occur. In the initial stage, growth is exponential. As growth continues, it slows to a linear increase, ending in a no-growth period. The Verhulst logistic equation appears to be an appropriate model to describe the changes in the bulk density of grain. While the bulk density of grain never reaches a constant state as the overburden pressure increases, the changes in bulk density are very small at high pressures. The basic form of the Verhulst logistic equation is shown in equations 2 and 3:

$$\frac{d\rho_r}{dy} = \alpha\rho_r\left(\frac{\rho_m - \rho_r}{\rho_m}\right) \tag{2}$$

$$= \alpha\left(1 - \frac{\rho_r}{\rho_m}\right)\rho_r \tag{3}$$

where

$\frac{d\rho_r}{dy}$ = change in bulk density with respect to y

$\left(\frac{\rho_m - \rho_r}{\rho_m}\right)$ = proportion of void space in bulk grain

ρ_m = asymptotic value of bulk density (kg m^{-3}) for a given compaction test (i.e., the maximum bulk density attainable for a given compaction test)

ρ_r = bulk density after compaction (kg m^{-3}).

Equation 4 is a solution for differential equation 3:

$$\rho_r = \left(\frac{\rho_m\rho_0}{(\rho_m - \rho_0)e^{-ay} + \rho_0}\right) \tag{4}$$

where

α = intrinsic increase in bulk density with respect to y (kPa^{-1})

ρ_0 = loose bulk density (kg m^{-3}) when $y = 0$ ($p = 0$) at a specified MC of grain.

Rearranging equation 4 and introducing parameter β yields equation 5:

$$\rho_r = \left(\frac{1+\beta}{1+\beta e^{-ay}}\right)\rho_0 \tag{5}$$

where β is the maximum increase in bulk density ($y \to \infty$) and is given by equation 6:

$$\beta = \frac{\rho_m - \rho_0}{\rho_0} \tag{6}$$

Additional contribution of the elastic behavior of grain to the changes in bulk density were modeled using a term analogous to Hooke's law (eq. 7):

$$\rho_e = ky \tag{7}$$

where ρ_e is the contribution of elastic grain behavior to changes in bulk density, and k is a constant (s^2 m^{-2}).

To describe the changes in bulk density of triticale grain, equation 8 was used. This equation consists of two parts. The first part is the logistic equation, which was used to model much of the exponential changes in bulk density that were believed to be caused predominately by the kernel rearrangement that occurs at low pressures. While the logistic equation also models other parts of the change in bulk density, the second part of the equation helps in describing the latter changes in bulk density when kernel-to-kernel interactions are predominant:

$$\rho_b = \left(\frac{1+\beta}{1+\beta e^{-\alpha y}}\right)\rho_0 + ky \tag{8}$$

Substituting Mp for y into equation 8 gives equation 9:

$$\rho_b = \left(\frac{1+\beta}{1+\beta e^{-\alpha Mp}}\right)\rho_0 + kMp \tag{9}$$

Equation 9 was used to describe the overall change in bulk density (ρ_b, kg m^{-3}) of triticale grain under compaction as a function of both applied pressure and MC.

COMPACTION PROCEDURE

The triticale grain (Trical 342) used for this experiment was mechanically harvested at the North Florida Research and Education Center (NFREC) in Quincy, Florida. The grain was harvested, threshed, and cleaned at the NFREC and then stored in a cold room at 5°C. The grain used in these tests was randomly taken from the NFREC's stock of seed, and the initial MC was determined by the oven method (ASABE, 2020c). Three MCs were tested (8%, 12%, and 16% w.b.) to represent low, average, and high values for stored grain. The grain was dried at 55°C to produce 8% and 12% MC grain. The 16% MC grain was produced by adding distilled water to the grain. The amount of distilled water to be added was determined using equation 10:

$$W_w = Wg\left(\frac{MC_f - MC_i}{100 - MC_f}\right) \tag{10}$$

where W_w is the mass of water added, W_g is the mass of grain at the initial MC, MC_i is the initial MC (% w.b.), and MC_f is the final MC (% w.b.).

After the appropriate amount of distilled water was added, the grain was left in a 5°C cold room for four days to obtain uniform MC. The initial bulk densities of the grain at the three MCs were determined by WBT. The porosity ratios of the bulk grain were measured based on tests with a Beckman model 930 air comparison pycnometer, and the mean values (standard deviations in parentheses) were determined to be 0.57 (0.003), 0.54 (0.013), and 0.60 (0.003) for 8%, 12%, and 16% MC, respectively. All tests were conducted in a thermostatically controlled laboratory at 20.5°C and relative humidity of 49%.

A square metal box, based on the design developed by Thompson and Ross (1983), was used to obtain compaction data. The box had inside dimensions of 30.5 cm × 30.5 cm and a wall height of 10.2 cm. The box was constructed from 2.6 cm thick aluminum plates and had a 1.3 cm hole in the center of the bottom plate, which was connected to a pressure system (fig. 2a). A flexible neoprene pressure diaphragm covered the base of the box and was sealed to the base to which the pressure system was connected. The pressure system consisted of a flexible pipe connected to the compressed air system of the laboratory.

The displacement of the diaphragm was measured by the movement of a 4.8 mm diameter, 475 mm long brass rod that rested on a thin metal plate placed on the top of the diaphragm. The top cover of the box had a hole for the rod to slip through that was directly above the center of the diaphragm. The box was filled with grain from a container mounted directly above the box. The process for filling the box was intended to produce uniform initial conditions in the box that were approximately equivalent to the conditions produced in the measuring cup of the WBT. The grain in the box was leveled before installing the box cover using a leveling technique similar to that used in the WBT.

A pressure regulator connected to the box was used to apply pressure to the triticale grain in the box by inflating the diaphragm to the desired air pressure. This simulated the overburden pressures that might occur in a grain bin. A digital gauge in contact with the top end of the brass rod was used to measure the grain displacement (fig. 2c). Deformations of the triticale were measured at pressures of 7, 14, 34, and 55 kPa and were manually recorded from the digital gauge 45 min after pressure was applied. Four replications of each combination of pressure and MC were conducted.

Bulk densities at different pressures were calculated from the vertical displacements of the compacted bulk grain using equation 11 (Thompson and Ross, 1983):

$$\rho = \rho_0 \left(\frac{H}{H - \Delta h} \right) \tag{11}$$

where

ρ = bulk density (kg m^{-3})

ρ_0 = loose bulk density (WBT, kg m^{-3})

H = initial height of bulk grain (10.2 cm)

Δh = vertical displacement of compacted grain (cm).

This study used a 3 × 5 factorial experimental design with three MCs (8%, 12%, and 16%), five pressure levels (0, 7, 14, 34, and 55 kPa), and four replications. An analysis of variance of the data was conducted using PROC ANOVA in SAS to test for significant differences in mean bulk densities for the three MCs and five pressures and to test potential MC-pressure interaction effects. Solver (Excel 2013) was used to determine the parameters of the model by minimizing the sum of squared errors (SSE) between the measured bulk densities of triticale grain and the predicted values (eq. 12):

$$\text{SSE} = \sum_{n_{i=1}} \left(y_i - y_f \right)^2 \tag{12}$$

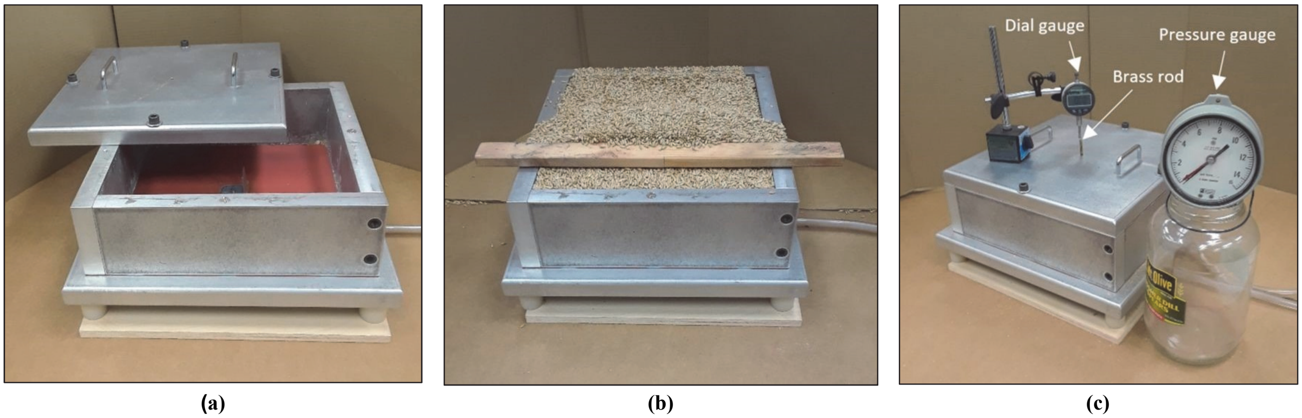
where y_i is the observed value, and y_f is the model value.

RESULTS AND DISCUSSION

EFFECTS OF MC AND PRESSURE ON BULK DENSITY OF COMPACTED TRITICALE

The mean bulk densities at the five pressures for the three MCs are given in table 1. Loose bulk densities, determined with the WBT, are shown at 0 kPa pressure. These values decreased from a maximum of 665.7 kg m^{-3} at 8% MC to 627.2 kg m^{-3} at 16% MC.

PROC ANOVA in SAS at $\alpha = 0.05$ indicated significant differences in mean bulk density with MC, pressure, and MC-pressure interaction (all with $p < 0.0001$). This result indicates that the change in bulk density was caused by both the MC of the grain and the pressure applied to the grain. Mean bulk densities for the three MCs had significant differences at 0 and 7 kPa, but this was not the case at higher



(a) (b) (c)

Figure 2. (a) Empty compaction box, (b) leveling grain, and (c) box compaction with dial gauge and pressure gauge.

Table 1. Mean comparison for bulk density (kg m^{-3}) of triticale grain at different pressures for each moisture content (MC).[a]

MC	Pressure (kPa)				
(%)	0[b]	7	14	34	55
8	665.7 a	689.2 d	698.9 g	716.3 i	726.2 k
12	658.2 b	685.9 e	697.8 g	715.7 i	724.9 k
16	627.2 c	661.5 f	674.3 h	694.4 j	705.7 l

[a] In each column, means followed by the same letter are not significantly different.

[b] Loose bulk density determined with Winchester bushel test (WBT).

Table 2. Parameters of bulk density model for triticale grain.

Parameter	Value	Units
β	0.0604	-
k	4.60	kg J^{-1}
α	1.20	kPa^{-1}

pressures for the 8% and 12% MC grain. At 16% MC, mean bulk densities were significantly different at higher pressures (table 1). This indicates that the grain at 8% and 12% MC behaved differently from the 16% MC grain as the pressure increased. Triticale was more compliant at 16% MC and therefore showed greater changes in bulk density than at 8% and 12% MC at high pressures. Similar behavior was observed by Thompson and Ross (1983) in wheat compaction tests and by Chiputula et al. (2021) for rye.

Means comparisons for pressures at each MC indicated significant differences for all pressures. Model parameters β, *k*, and α for the three MCs are given in table 2. Data from the compaction tests were used to estimate the model parameters with a correlation coefficient (R^2) of 0.986.

The observed and predicted bulk densities as a function of pressure for the three MCs are shown in figure 3. The effects of MC on bulk density were observed both in the WBT values for grain samples and in the compacted grain samples. The WBT values decreased as grain MC increased from 8% to 16%. At low pressures, the changes in bulk density were believed to be largely due to rearrangement of the grain kernels for all three MCs.

At lower pressures, the Verhulst logistic terms of the model dominated the modeling of grain compaction. At higher pressures, the changes in bulk density were largely caused by kernel-to-kernel interactions and kernel elasticity. After much of the void space in the grain bulk was filled, fewer changes in bulk density were caused by kernel rearrangement, and the Verhulst logistic portion of the model reached an asymptotic value (at pressure >34 kPa). As the pressure increased, kernel-to-kernel interactions contributed more to the changes in bulk density. Thompson and Ross (1983) and Chiputula et al. (2021) observed similar results in their studies with wheat and rye, respectively. The changes in bulk density caused by kernel-to-kernel interaction were modeled by the interaction term for MC and pressure in the model.

WPACKING MODEL APPLIED TO TRITICALE

ASABE Standard S413 (ASABE, 2020b) uses the computer model WPACKING, developed by Thompson et al. (1990), to determine grain packing factors. WPACKING uses the differential form of Janssen's equation (Janssen, 1895) to estimate the pressure and in-bin bulk density for a given depth of grain in a bin. Janssen's equation is commonly used in the design of grain bins and uses the properties of the stored material and the geometry of the storage structure to estimate in-bin pressures. The original solution of Janssen's equation assumes that the properties of the stored material are constant, i.e., the coefficient of friction (μ), ratio of lateral to vertical pressure (*k*), and bulk density. However, using the differential form of Janssen's equation, the μ, *k*, and bulk density of the stored material can vary with relevant parameters (i.e., MC and vertical pressure). The differential form of Janssen's equation can be solved numerically and is used to compute vertical and lateral pressures with varying grain depth in a bin (Ross et al., 1979). WPACKING has been validated using data from full-size bins and flat storage structures and has become the ASABE

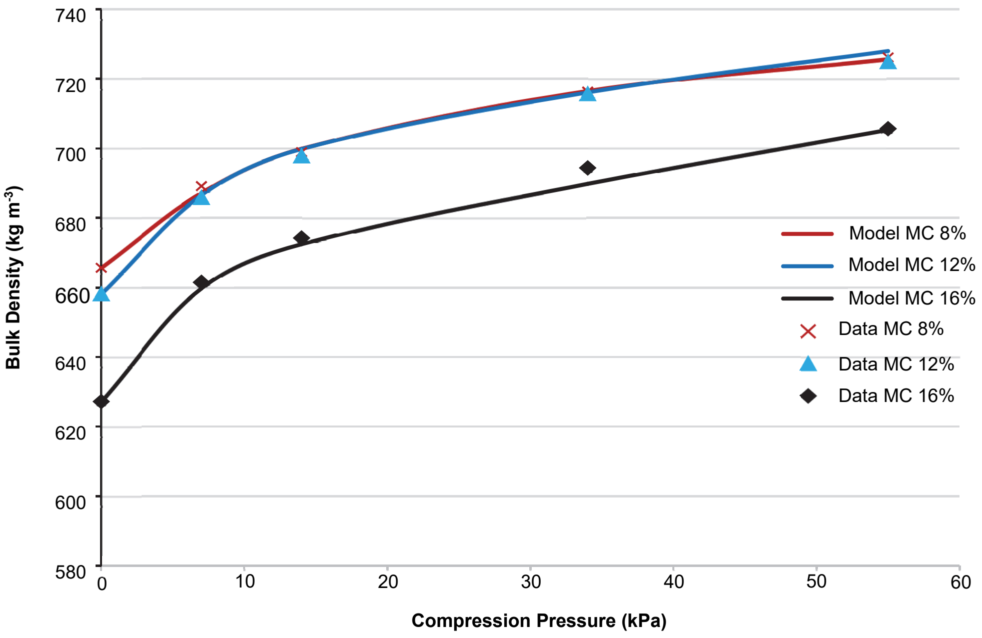


Figure 3. Bulk density versus pressure from the test data and from the model for triticale grain at 8%, 12%, and 16% MC.

standard for estimating the storage capacities of cylindrical grain bins (ASABE, 2020b).

Wheat

Bulk densities for two different types of wheat, hard red winter wheat (HRWW) and soft red winter wheat (SRWW), were measured as a function of pressure using a compaction box very similar to the box described in this article (Thompson and Ross, 1983). Each variety of grain had between 8% and 16% (w.b.) MC and was compacted at a range of overburden pressures between 0 and 138 kPa. The measured bulk density values were then compared to values predicted using a model with the same format as equation 9.

The experiments on wheat were performed at MCs very close to those of triticale but over a wider range of pressures. Initially, the same values of β, k, and α shown in table 2 were used in equation 9 and then compared to the experimental values for wheat. However, as the pressure increased, the difference between the predicted and experimental values increased, primarily due to the kMp term in equation 9. Using the same form of equation 9 but reducing the value of β from 4.6 to 1.2 resulted in closer agreement between the observed and predicted values over the range of pressures. This shows that while the form of the equation appears to work for other types of grain, the value of β appears to be grain-specific.

Triticale

Equation 9 was inserted into WPACKING to predict the RMA pack factor, in-bin bulk density, and standard volume of grain in a bin. Calculations were made for a flat-bottomed grain bin that was 18.3 m in diameter, 18.3 m tall, and made of corrugated steel. The percent packing, RMA pack factor, and standard volume of grain predicted by WPACKING are shown in table 3 for triticale, hard red winter (HRWW), and soft red winter wheat (SRWW). The percent packing is the ratio of the average in-bin bulk density and the loose or uncompressed bulk density (from the WBT). The percent packing and the standard volume were predicted for MCs of 10%, 12%, and 14% for each type grain. Initial bulk densities of 579 and 644 kg m^{-3} were used for triticale, which are typical values reported in the literature. For a bin this size, the percent packing was between 9% and 11% for both bulk densities.

Packing values for soft red winter wheat (SRWW) and hard red winter wheat (HRWW) for these same MCs using bulk densities of 708 and 772 kg m^{-3}, which are typical values reported in the literature, are also shown in table 3. For these wheat varieties, the pack factors ranged from 4.7% to 7.9% for the same storage conditions. Triticale has a lower initial bulk density than SRWW and HRWW and is much softer, with a much larger predicted increase in bulk density during storage than either of the two wheat varieties. This difference resulted in the larger pack factors for triticale than those observed for SRWW and HRWW.

Table 3. Percent packing, USDA Risk Management Agency (RMA) pack factor, and standard volume calculated for triticale, soft red winter wheat (SRWW), and hard red winter wheat (HRWW).

Grain	Moisture Content (% w.b.)	Initial Bulk Density (kg m^{-3})	In-Bin Bulk Density (kg m^{-3})	Percent Packing (%)	RMA Pack Factor	Standard Volume (m^3)
Triticale	10	579	632	9.1	1.023	4915
	12	579	637	10.0	1.031	4952
	14	579	642	10.8	1.039	4989
	10	644	703	9.2	1.137	5464
	12	644	708	10.0	1.146	5505
	14	644	713	10.8	1.154	5545
SRWW	10	708	758	7.1	0.982	5897
	12	708	761	7.5	0.985	5917
	14	708	763	7.9	0.989	5937
	10	772	824	6.7	1.067	6407
	12	772	826	7.1	1.071	6428
	14	772	830	7.4	1.074	6450
HRWW	10	708	744	5.0	0.963	5780
	12	708	748	5.6	0.968	5812
	14	708	752	6.2	0.974	5847
	10	772	808	4.7	1.047	6286
	12	772	814	5.3	1.053	6321
	14	772	817	5.9	1.059	6357

SUMMARY AND CONCLUSIONS

The objective of this study was to determine the combined effects of MC and pressure on the changes in bulk density for triticale grain under compaction at conditions typical of those in storage structures and to develop a mathematical model to describe the compression behavior. Triticale compaction was measured with grain at three MCs (8%, 12%, and 16% w.b.) with four applied pressures (7, 14, 34, and 55 kPa) using a square metal box based on the design used by Thompson and Ross (1983). Data from the compaction tests were used to calculate the bulk densities for the three MCs and four pressures. The bulk density was found to be significantly ($p < 0.0001$) dependent both on the grain MC and the simulated overburden pressure. The bulk density varied with increasing MC, as has been observed in similar studies for other agricultural grains such as rye and wheat. These results provide guidance for estimating the bulk density of triticale in grain bins and other storage structures.

The model given by equation 9, comprised of a Verhulst logistic function and a term analogous to Hooke's law, was developed to predict the bulk density of triticale grain as a function of both MC and pressure. The Verhulst logistic function was used to model the rearrangement of kernels to fill the void space in the bulk grain, which dominates the changes in bulk density at low pressures. The Hooke's law term modeled the elastic behavior of kernels, which dominated the increase in bulk density at high pressures. The model had a correlation coefficient (R^2) of 0.986, indicating a good fit to the observed behavior of grain for the conditions tested. The model given by equation 9 was used to compare the results of this study to predictions for wheat and showed similar behavior for wheat, indicating that the results of this study can be used with WPACKING (Thompson et al., 1990) and the methods of ASABE Standard S413 (ASABE 2020b) to predict the quantity of triticale grain stored in bins.

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