LABORATORY ASSESSMENT OF BUNKER SILO DENSITY PART II: WHOLE-PLANT CORN

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ABSTRACT. *To better understand and predict silage density in bunker silos, chopped whole-plant corn was placed in layers of 0.15, 0.30, 0.45, and 0.60 m in a 482- × 584-mm rectangular container simulating the footprint of a tractor tire. Pressure between 20 and 80 kPa was applied to the forage by a platen. The total time of compaction varied between 1 and 10 s. A total of 25 tests were conducted with crop dry matter (DM) content ranging between 33% and 44%. The pre-compressed density of the first layer (0.30 m high) averaged 95 kg DM/m^3. The highest compressed density ranged between 169 and 261 kg DM/m^3 with an average of 216 kg DM/m^3. After releasing pressure, the relaxed density of the first layer ranged between 117 and 153 kg DM/m^3 with an average of 131 kg DM/m^3. After six layers, the average relaxed density became 185 kg DM/m^3, a density 14% lower than the average highest compressed density. A logarithmic model fit the data very well ($R^2 \geq 0.93$ in 24 out of 25 tests), indicating that density increased continually as the number of layers increased. Model parameters were significantly affected by pressure, layer thickness, and crop processing while time of compaction had a small effect. DM content was not significant. A model based on extrapolation of laboratory results is proposed to predict density for deep bunker silos, but field data are required to validate the model under such conditions.*

Keywords. *Silage, Corn, Density, Bunker, Packing.*

Corn silage has become one of the most important forage crops for ruminants because of its relatively low cost of production and balanced feed value in terms of energy and fiber (Johnson et al., 1999). For reasons of economy and efficiency, corn silage is largely stored in bunker silos (Bodman and Holmes, 1997).

The amount of dry matter (DM) stored in a bunker silo can be estimated accurately by sampling for moisture and by weighing all forage wagons or trucks prior to unloading. However, this procedure is not common farm practice because of the time, equipment, and cost associated with such monitoring. Another approach is to predict mathematically the amount of DM from the density and volume of silage in a bunker. Appendix A presents several models that have been proposed in the past to predict DM density in bunker silos.

The mass of corn silage stored in a given volume of a bunker silo depends on factors such as packing tractor mass, time of compaction, crop moisture, layer thickness, silage height, and chop length (Muck and Holmes, 2000). Previous prediction models have accounted for one or more of these factors. However, most of these models cannot be used to extrapolate beyond the crop species and range of experimental values specific to each set of data.

The objective of this research was to develop a more general relationship between bunker silo density and various factors. Using a laboratory apparatus to simulate bunker silo compaction, the current article presents data obtained with chopped whole-plant corn as a function of pressure, time of compaction, and layer thickness. It discusses mathematical relationships that might be applied to predict DM density in bunker silos.

METHODOLOGY

APPLICATION OF PRESSURE

A detailed description of the experimental apparatus is given by Muck et al. (2004). A platen press, 0.584 m long × 0.483 m wide, was set up to compress successive layers of chopped forage in a rectangular container. Four pressures were applied by the platen to the forage: 19.4, 38.7, 58.1, and 77.4 kPa (250, 500, 750, and 1000 psi) applied by a 64-mm (2.5-in.) diameter hydraulic cylinder and measured by a gauge with a resolution of 170 kPa (25 psi), i.e. a resolution of 1.9 kPa (0.28 psi) when transferred by the 0.282-m^2 (437-in.^{2}) platen to the forage surface. In addition, the mass of the platen and cylinder (34 kg) represented a static pressure of 1.2 kPa against the forage. The total hydraulic and static pressures were therefore 20.6, 39.9, 59.3, and 78.6 kPa, respectively. Total pressures were rounded to 20, 40, 60, and 80 kPa, respectively, for purposes of treatment identification in tables and figures.

OTHER EXPERIMENTAL VARIABLES

Besides pressure, two other variables were controlled: layer thickness and time of compaction. Other variables such as moisture content and processing at harvest were not controlled but quantified.

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Layers of chopped forage were laid in non-compacted thicknesses of 0.15, 0.30, 0.45, and 0.60 m (6, 12, 18, or 24 in.). After each layer was placed in the container, the platen was lowered at the designated pressure for times varying between 1 and 10 s. After compaction, the forage was left to relax about 1 min before the next non-compacted layer was placed. The compressed and relaxed heights as well as height after adding a new layer were measured to estimate the compressed, relaxed, and pre-compression densities, respectively.

On a given day, a series of compaction runs were performed by varying one of the controlled variables: pressure, layer thickness, or time of compaction. The standard conditions were 40 kPa, 0.30-m layer thickness, and 5-s hold time. All the forage for a given day was chopped with a commercial forage harvester, set to 9.5-mm (3/8-in.) theoretical length of cut, and blown in the back of a pickup truck for transport to the press. In two cases, the chopped corn was also processed in the field with a commercial crop processor. Ten to twelve samples of chopped whole-plant corn were taken to estimate the average dry matter [oven-drying for 24 h at 103°C according to ASAE (2001) standard method S358.2]. Individual samples taken throughout the day were not associated with a single test. Therefore, the same average DM value was assigned to all tests on a given day.

Experimental Design and Statistical Analysis

Whole-plant corn was harvested between 11 September and 4 October 2001. Seven experiments were carried out to evaluate the effect of pressure, layer thickness, and time of compaction on density. Table 1 lists the seven experiments, 25 tests, and specific experimental conditions.

A logarithmic model, found to fit alfalfa and grass data very well by Muck et al. (2004), was also used to fit the whole-plant corn data. The relaxed density was estimated as a function of the number (N) of 0.30-m layers (or equivalent to 0.30 m) deposited. The general model was:

$$\rho = a + b \ln N \qquad (1)$$

where ρ is the relaxed dry matter density (kg DM/m^3), "a" is a parameter reflecting the relaxed density of the first or uppermost compacted layer, and "b" is a parameter reflecting the increase in relaxed density with an increasing number of layers. For each test, parameter a was obtained as the measured density for the first 0.30-m layer (N = 1). Parameter b was estimated by fitting equation 1 by the least squares method with density data from all other layers while parameter a was fixed at its measured value. Multiple linear

Table 1. Experimental conditions for compaction of chopped whole-plant corn destined for silage (CS) that was occasionally processed (/proc) by a processor on the harvester.

Date	Crop	Mass per Layer (kg)	Layer Thickness (m)	No. of Layers	Time of Compaction (s)	Pressure (kPa)	DM (% w.b.)
Experiment 1							
2001-09-11a	CS/proc	25.0	0.30	6	5	40	33.8
2001-09-11b	CS/proc	25.0	0.30	6	2	40	33.8
2001-09-11c	CS/proc	25.0	0.30	6	10	40	33.8
Experiment 2							
2001-09-18a	CS	25.0	0.30	6	5	40	32.6
2001-09-18b	CS	25.0	0.30	6	5	60	32.6
2001-09-18c	CS	25.0	0.30	6	5	20	32.6
2001-09-18d	CS	25.0	0.30	6	5	80	32.6
Experiment 3							
2001-09-20a	CS/proc	27.3	0.30	6	5	40	33.8
2001-09-20b	CS/proc	40.9	0.45	4	5	40	33.8
2001-09-20c	CS/proc	13.6	0.15	12	5	40	33.8
2001-09-20d	CS/proc	54.5	0.60	3	5	40	33.8
Experiment 4							
2001-09-25a	CS	20.5	0.30	6	6	40	44.3
2001-09-25b	CS	20.5	0.30	6	2 * 3 s	40	44.3
2001-09-25c	CS	20.5	0.30	6	3 * 2 s	40	44.3
Experiment 5							
2001-09-27a	CS	25.0	0.30	6	5	40	35.7
2001-09-27b	CS	12.5	0.15	12	5	40	35.7
2001-09-27c	CS	37.5	0.45	4	5	40	35.7
Experiment 6							
2001-10-02a	CS	22.7	0.30	6	5	40	36.7
2001-10-02b	CS	22.7	0.30	6	5	80	36.7
2001-10-02c	CS	22.7	0.30	6	5	60	36.7
2001-10-02d	CS	22.7	0.30	6	5	20	36.7
Experiment 7							
2001-10-04a	CS	20.5	0.30	6	5	500	38.4
2001-10-04b	CS	20.5	0.30	6	10	500	38.4
2001-10-04c	CS	20.5	0.30	6	2	500	38.4
2001-10-04d	CS	20.5	0.30	6	1	500	38.4

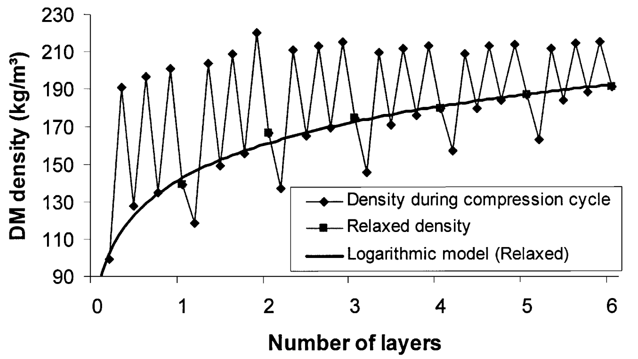

Figure 1. Example of the sequence of density after layer addition, compaction and relaxation (three 2-s compressions for each layer, in this case) before addition of a new layer and so forth. Based on the 25c September test with chopped whole-plant corn at 44% DM applied in 0.30-m layers and compressed under 40-kPa pressure.

regression analysis was carried out to determine the effect of pressure, layer thickness, time of compaction, processing, and DM on parameters a and b.

Results and Discussion

Densities Measured in the Laboratory

Figure 1 shows an example of the densities measured in the laboratory starting with deposition (the initial uncompressed density), followed by three successive short compaction times (the compressed density) and relaxation (the relaxed density). When a new layer was added, the cycle of deposition, compression, and relaxation was repeated; new densities were calculated as the average of cumulative layers. A succession of short compaction times as the one illustrated in figure 1 was done experimentally only twice (Experiment 4, 25 September, tests b and c in table 1); all other tests had a single compaction time between layers.

A logarithmic curve in figure 1 fits relatively well the relaxed density data at the end of the compaction cycle for each layer. For this specific example (25c Sept.), measured parameter a was 140 kg DM/m^3 and estimated parameter b was 29.5 kg DM/m^3 with a coefficient of determination of 0.875 (table 2). For whole-plant corn, the coefficient of determination to estimate parameter b in the logarithmic model was generally very good, with $R^2 \geq 0.93$ in 24 out of 25 tests.

Table 2. Lowest density of pre-compressed layers, highest compressed density, measured and estimated parameters of the logarithmic model for the relaxed density of chopped whole-plant corn. The number of 0.30-m layers required to equal the highest compressed density (HCD) is estimated from the parameter values and the logarithmic model.

Date	Controlled Variable[a]	Lowest Initial Density (kg DM/m^3)	Highest Compression Density (kg DM/m^3)	Parameter a (Measured) (kg DM/m^3)	Parameter b (Estimated) (kg DM/m^3)	R^2 in Model	Number of Layers to Equal HCD
Experiment 1							
2001-09-11a	5 s	91	214	126	33.7	0.984	14
2001-09-11b	2 s	93	212	128	29.5	0.927	17
2001-09-11c	10 s	92	220	141	27.2	0.970	18
Experiment 2							
2001-09-18a	40 kPa	91	219	127	32.7	0.972	17
2001-09-18b	60 kPa	90	228	129	33.8	0.937	19
2001-09-18c	20 kPa	93	179	119	22.9	0.995	13
2001-09-18d	80 kPa	91	250	133	35.9	0.986	26
Experiment 3							
2001-09-20a	0.30 m	103	222	140	29.1	0.980	17
2001-09-20b	0.45 m	109	217	140	27.0	0.943	17
2001-09-20c	0.15 m	94	230	140	30.3	0.982	19
2001-09-20d	0.60 m	106	206	140	21.8	0.946	20
Experiment 4							
2001-09-25a	6 s	100	215	127	34.4	0.966	13
2001-09-25b	2 * 3 s	99	221	136	32.2	0.989	14
2001-09-25c	3 * 2 s	99	215	140	29.5	0.875	13
Experiment 5							
2001-09-27a	0.30 m	97	212	128	32.6	0.928	13
2001-09-27b	0.15 m	90	211	128	35.3	0.931	10
2001-09-27c	0.45 m	100	197	128	26.4	0.956	14
Experiment 6							
2001-10-02a	40 kPa	92	240	153	19.7	0.935	81
2001-10-02b	80 kPa	94	261	141	32.7	0.987	39
2001-10-02c	60 kPa	91	233	129	34.8	0.981	20
2001-10-02d	20 kPa	91	169	119	18.7	0.987	14
Experiment 7							
2001-10-04a	5 s	85	215	117	36.1	0.973	15
2001-10-04b	10 s	88	218	124	36.3	0.976	13
2001-10-04c	2 s	92	207	125	30.2	0.998	15
2001-10-04d	1 s	92	199	120	28.1	0.975	16

[a] Controlled variables were either pressure (kPa), time of compaction (s) or layer thickness (m).

Table 2 also reports the lowest initial densities. These minimum values always occurred in the first uncompressed layer. The uncompressed density of 0.30-m layers of whole-plant corn ranged from 85 to 109 kg DM/m^3, and averaged 95 kg DM/m^3. There was a trend for thicker layers to be denser initially, e.g. the 0.45-m thick layer on 20 September (CS-b) had the highest initial density of 109 kg DM/m^3, but data were insufficient to develop a relationship between layer thickness and initial uncompressed density.

The highest compressed density in each of the 25 tests varied between 169 and 261, and averaged 216 kg DM/m^3 (table 2). Out of 25 tests, the highest compressed density was observed four times in the first layer, nine times in intermediate layers, and 12 times in the last layer.

After releasing pressure, the relaxed density of the first layer was equivalent to parameter a in equation 1. Values of parameter a ranged between 117 and 153 kg DM/m^3 with an average of 131 kg DM/m^3 (table 2). On average, relaxation caused a 39% reduction in the density of the first layer compared to the maximum compressed density. However as the number of layers increased, the effect of relaxation on the average density of all layers decreased. The average value of parameter b for all tests was 30.0 kg DM/m^3. After six layers, the average relaxed density was 185 kg DM/m^3, a reduction of 14% compared to the average highest compressed density. If the logarithmic curve is extrapolated, the average relaxed density after 17 layers actually becomes equal to or greater than the average highest compressed density observed experimentally (216 kg DM/m^3). For each individual test, the theoretical number of layers required to reach the highest compressed density was calculated from equation 1 and parameters a and b. Values reported in table 2 show this theoretical number (N) of 0.30-m layers varied between 10 and 81. This means the average relaxed density in a deep bunker silo could be greater than the highest compressed density observed in six layers of the experimental silo. This result might be realistic considering the effect of the weight of cumulative layers in addition to the tractor mass on compacting silage as height increases. Validation of the logarithmic model to predict density will require observations in field-scale bunker silos with a large number of layers.

EFFECT OF PRESSURE, TIME, AND LAYER THICKNESS ON DENSITY

Figure 2 reports the relaxed densities of three tests during experiment 1 for times of compaction between 2 and 10 s. The density with 10 s of compaction time was initially about 14 kg DM/m^3 higher than densities after 2 and 5 s of compaction (parameter a was 128, 126, and 141 kg DM/m^3 for 2, 5, and 10 s, respectively, in table 2). The difference declined after six layers because parameter b was actually lowest for the 10 s treatment (27.2 kg DM/m^3).

Figure 3 shows the relaxed densities in experiment 2 as a function of pressure in the range of 20 to 80 kPa. Relaxed density resulting from a pressure of 20 kPa was clearly lower than densities at the three other pressures. Parameter a was 119, 127, 124, and 133 kg DM/m^3 for 20, 40, 60, and 80 kPa, respectively. Parameter b also increased with pressure (22.9, 32.7, 33.8, and 35.9 kg DM/m^3, respectively). The increase of both parameters a and b with higher pressure indicated a higher initial density and a widening gap as the number of layers increased.

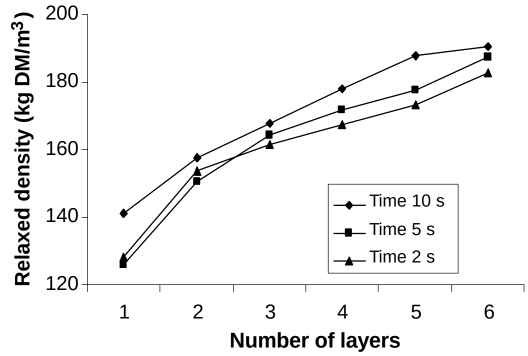

Figure 2. Relaxed density observed in experiment 1 (11 Sept.) as a function of the time of compaction applied at 40-kPa pressure on 0.30-m layers of chopped and processed whole-plant corn with DM averaging 34%.

Figure 4 illustrates the relaxed densities in experiment 3 as a function of layer thicknesses between 0.15 and 0.60 m. A common x-axis was based on 0.30-m equivalent layers: 12 layers of 0.15 m being equivalent to six layers of 0.30-m layers, four layers of 0.45 m, and three layers of 0.60 m. A uniform value of parameter a was used for all four tests in experiment 3 because experimental measurements in three tests out of four did reproduce the initial 0.30-m layer. The measured parameter a after compression-relaxation of a single 0.30-m layer was 140 kg DM/m^3. Estimated parameter b was 30.3, 29.1, 27.0, and 21.8 kg DM/m^3 for 0.15-, 0.30-, 0.45-, and 0.60-m thickness, respectively. The decrease in parameter b was consistent as the layer thickness increased.

Figure 5 shows the relaxed densities of experiment 4 where three patterns of time of compaction were applied. After six layers, the densities for the three treatments (once for 6 s, twice 3 s, three times 2 s) converged to a similar density. The way the compaction time is applied appears to have less importance than total time of compaction. In practice, these results suggest that a slow moving compaction tractor and a fast moving compaction tractor should result in similar relaxed densities if they are used for the same amount of time to compress the same mass of forage.

Figure 6 reports the relaxed densities of experiment 5 for three layer thicknesses. The trend is similar to experiment 3 (fig. 4). Parameter b decreased as layer thickness increased. Thin layers resulted in higher density than thick layers.

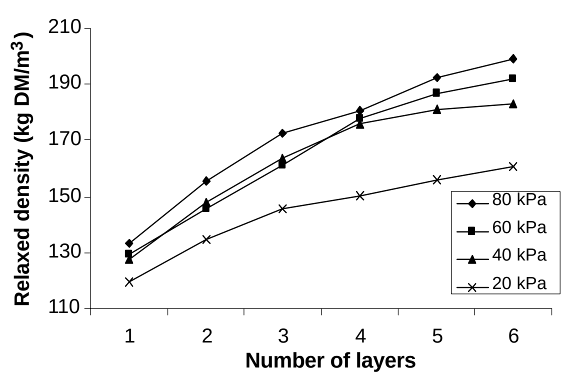

Figure 3. Relaxed density observed in experiment 2 (18 Sept.) as a function of pressure applied for 5 s per layer on 0.30-m layers of chopped whole-plant corn with DM averaging 33%.

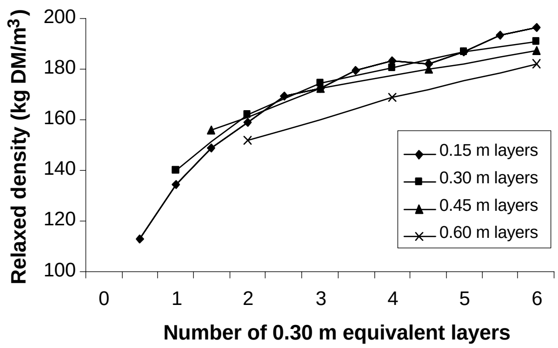

Figure 4. Relaxed density observed in experiment 3 (20 Sept.) as a function of layer thickness compressed at 40-kPa pressure for 5 s per layer on chopped and processed whole-plant corn with DM averaging 34%.

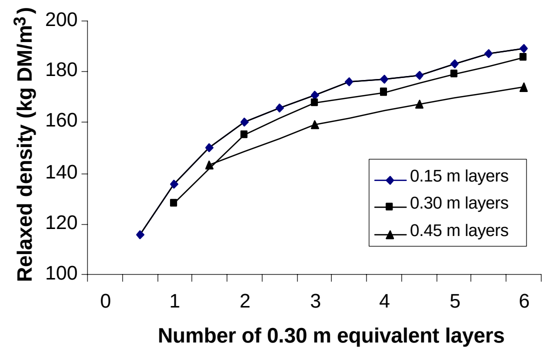

Figure 6. Relaxed density observed in experiment 5 (27 Sept.) as a function of layer thickness compressed at 40-kPa pressure for 5 s per layer on chopped whole-plant corn with DM averaging 36%.

Figure 7 shows results of experiment 6 for four pressures. Results are similar to those reported in figure 3 with lower pressure resulting in lower density.

Figure 8 illustrates the relaxed densities of experiment 7 for four times of compaction. The density after a compaction time of 1 s was lower than densities after times of compaction of 2, 5, and 10 s, as expected. The difference in density diminished as time of compaction increased.

Multiple Regression Analysis

In addition to the three controlled factors (pressure, time of compaction, layer thickness), the DM content and the processing treatment were included in the regression analysis. A stepwise deletion procedure was used to eliminate factors that were not significant at the probability level of 0.10. The following models resulted:

$$a = 118.9 + 8.53 \times PROC + 0.228 \times P \qquad (2)$$

$$b = 29.2 - 23.0 \times z + 0.189 \times P \qquad (3)$$

where z is layer thickness (m), P is compaction pressure (kPa), and PROC is processing (PROC = 0 for unprocessed crop, PROC =1 for processed crop). The coefficients of determination (R^2) were 0.273 and 0.429 for equations 2 and 3, respectively.

Pressure was the most important factor in increasing both parameters a and b in the logarithmic model, and in increasing the DM density of chopped whole-plant corn. This result agrees with findings of earlier studies such as those of Darby and Jofriet (1993), Ruppel et al. (1995), Muck and Holmes (2000), and Bernier-Roy et al. (2001) where tractor weight or pressure was a primary factor. In the range of experimental pressures used (20 to 80 kPa) with typical values for other factors (z = 0.30 m; PROC = 0), the final density after six layers was estimated to range between 170 and 204 kg DM/m^3 between the lowest and highest pressure.

Processing significantly increased parameter a in equation 2 by a value of 8.5 kg DM/m^3 compared to non-processed corn, independently of the number of layers. The effect of layer thickness on density was significant on parameter b. In the experimental range of thickness (0.15 to 0.60 m) and for six layers, an increase of 18 kg DM/m^3 was estimated with thin layers compared to thick layers. Muck and Holmes (2000) also found a negative correlation between layer thickness and density. Bernier-Roy et al. (2001) found that layer thickness significantly affected grass silage density but not corn silage density while current results and Muck et al. (2004) showed the opposite: a layer thickness effect on corn density and no layer thickness effect on alfalfa and grass density. Further investigation is required to determine when layer thickness has an effect on density.

The time of compaction had no significant effect on parameters a and b in the logarithmic model when all 25 tests were considered for the given experimental range (1 to 10 s). However when density was calculated after six layers (N = 6) and correlated with packing time in experiments 1 and 7 only (seven tests) where time was the main variable, time of compaction (TC, s) was found to be well correlated (R^2 = 0.772) with density (ρ = 175 + 1.56 TC). Packing time

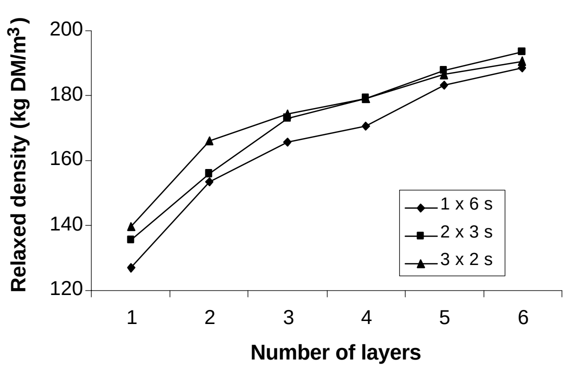

Figure 5. Relaxed density observed in experiment 4 (25 Sept.) after 6-s total compression time per layer applied in one, two or three compression cycles (40- kPa pressure, 0.30-m layers of chopped whole-plant corn with DM averaging 44%).

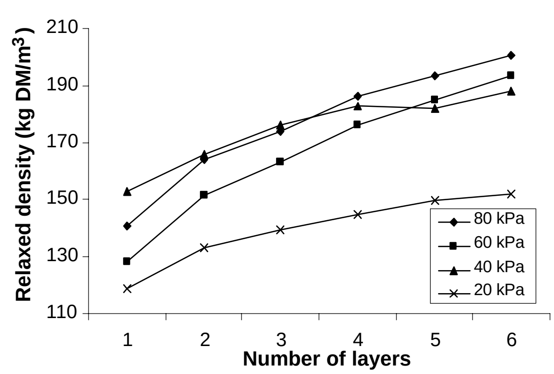

Figure 7. Relaxed density observed in experiment 6 (2 Oct.) as a function of pressure applied for 5 s per layer on 0.30-m layers of chopped whole-plant corn with DM averaging 37%.

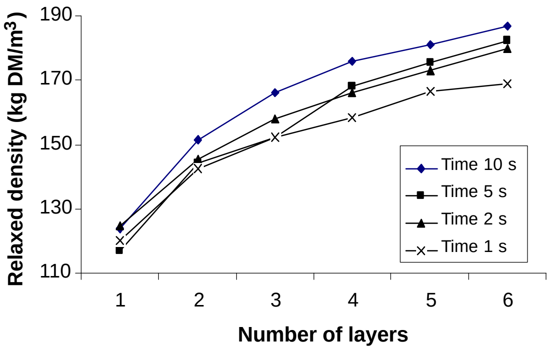

Figure 8. Relaxed density observed in experiment 7 (4 Oct.) as a function of the time of compaction applied at 40-kPa pressure on 0.30-m layers of chopped whole-plant corn silage with DM averaging 38%.

appears to be highly significant initially for short periods between 0 and 1.2 s (Bernier-Roy et al., 2001) but less important for longer times such as the compaction times (up to 10 s) used in the present study. The moderate effect of time of compaction on density observed in the present study is in partial agreement with Muck and Holmes (2000), who found that density increased with the square root of packing time per tonne of fed crop in a survey of 168 silos. Ruppel et al. (1995), surveying 30 silos, observed a linear increase in density with packing time per unit area.

In Appendix A, DM content was a factor often identified as affecting bunker silo density in models developed from field-scale silos. Thus, the lack of effect of DM content on density in the current study was unexpected. This discrepancy may be due to the small number of layers in our compaction studies relative to the large number of layers in field-scale silos. Messer and Hawkins (1977a, b) did find the effect of DM content on density to be lower in corn than in grass, and DM content was not a factor in studies by either Darby and Jofriet (1993) or Ruppel et al. (1995).

The average values of parameters a and b for typical factors (z = 0.30 m, TC = 5 s, P = 40 kPa, DM = 35%, PROC = 0) were estimated from equations 2 and 3 to be 128 and 29.9 kg DM/m^3, respectively. Using these average values and equation 1, the average relaxed density in a bunker silo would be 182 kg DM/m^3 for six layers (within the experimental range) and 230 kg DM/m^3 for 30 layers (extrapolation to a common bunker silo size). While even the extrapolated relaxed density seemed reasonable, in-field validation is necessary to verify these results. Further distinction is required between crop species as was indicated in the study on alfalfa and grass (Muck et al., 2004).

Considering results from the present study and earlier studies, pressure (or tractor weight) appears to be the most important factor. Packing time, layer thickness and crop processing affect density to a lesser degree. More research, particularly on a field-scale, is needed to determine with greater precision the specific changes in density caused by varying these packing factors.

Conclusions

- A logarithmic curve ($\rho = a + b \ln N$) fit very well the final relaxed densities (ρ) of chopped whole-plant corn as a function of the number of 0.30-m layers (N). The coefficient of determination (R^2) was greater than 0.93 in 24 out of 25 tests.
- Two controlled variables, pressure and processing, were significantly correlated with parameter a in the logarithmic model. Pressure and layer thickness were significantly correlated with parameter b. Density was higher with increased pressure, thinner layers, and processing.
- The laboratory setup was generally used for only six layers of 0.30 m thickness because of height limitations. The logarithmic model seemed reasonable to predict and extrapolate DM densities in bunker silos. Field-scale research will be necessary to validate the model for a large number of layers (≥ 30) typical in deep bunker silos, and for different forage crops.

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APPENDIX A: REVIEW OF SILAGE DENSITY MODELS IN BUNKER SILOS

This appendix is based partly on a review from a paper by Bernier-Roy et al. (2001). Messer and Hawkins (1977a, 1977b) related silage DM density in horizontal silos to a single factor, DM content. They suggested one model for grass and another for corn.

$$\rho_{grass} = 92.2 + 1.67 \, DM \quad \text{(A-1)}$$

$$\rho_{corn} = 139 + 1.38 \, DM \quad \text{(A-2)}$$

where ρ is the silage DM density (kg DM/m^3) and DM is the dry matter content (%). In the expected DM range for grass silage (25% to 50%), the density is predicted to vary between 134 and 176 kg DM/m^3. In the expected DM range for corn silage (25% to 40%), the density would range between 174 and 194 kg DM/m^3. On average, Messer and Hawkins (1977a, 1977b) observed densities of 150 kg DM/m^3 for grass and 180 kg DM/m^3 for corn. Tractors that compacted silages in their experiments had masses between 2.6 and 7.0 t.

McGechan (1990) reviewed silage density data for horizontal silos in Europe up to 1985. The reported data for grass silage ranged between 200 and 900 kg wet matter/m^3. He presented the following prediction model for DM density based on DM content only:

$$\rho = 45.9 + 4.96 \, DM \quad \text{(A-3)}$$

For DM contents between 25% and 50%, the density would range between 170 and 295 kg DM/m^3. McGechan (1990) did not indicate the tractor masses used to compact the silage.

Darby and Jofriet (1993) indicated that large bunker silos in North America are often compacted with heavy tractors of 20 t and more. They reported a model to predict silage density as a function of tractor mass only:

$$\rho = 200 + 4 \, m_v \quad \text{(A-4)}$$

where m_v is the mass of the compacting vehicle (t). This model suggests that silage density in bunker silos would typically range between 220 and 280 kg DM/m^3. Ruppel et al. (1995) observed a relationship between silage density, packing time, tractor mass, and silo area in surveying 30 bunker silos. Their model was as follows:

$$\rho = 189 + 83.6\left(\frac{m_v \, t}{A}\right) \quad \text{(A-5)}$$

where t is the total compacting time (h) and A is the horizontal surface of the silo (m^2). Ruppel et al. (1995) reported that the packing factor (m_v t / A) ranged between 0.14 and 1.7 in SI units, across the survey. The density would therefore range between 200 and 330 kg DM/m^3. This model has practical implications with regards to tractor size and minimum compacting time. For example, on a bunker silo 10 m wide × 30 m long (A = 300 m^2), a small 3-t tractor would have to pack for a minimum of 14 h to achieve a minimum density of 200 kg DM/m^3. A tractor twice the size (6 t) would need half the time (7 h) to reach this minimum density, or such a tractor would achieve a 212-kg DM/m^3 density in the same time (14 h) as the smaller tractor. Muck and Holmes (2000) reported density data from 168 commercial bunker silos in Wisconsin. Dry matter density ranged from 106 to 434 kg DM/m^3. As Ruppel et al. (1995), they found that tractor mass and packing time were important factors. However, they suggested a packing time per unit of wet mass rather than per horizontal area, thereby considering the depth implicitly. They also found that initial layer thickness and silage height influenced the final density. The model of Muck and Holmes (2000) may be written as:

$$\rho = \left[136 + 0.42\left(\frac{m_v}{L}\right)\sqrt{10 \, t_u \, DM}\right](0.818 + 0.0446 \, H) \quad \text{(A-6)}$$

where L is the layer thickness (m), t_u is compacting time per tonne of wet forage in the silo (h/t) and H is silage height (m). These authors called the term $\{m_v \, [10 \, t_u \, DM]^{1/2} \, L^{-1}\}$ the packing factor that could range between 0 and 600, suggesting a density range between 136 and 388 kg DM/m^3. The average experimental data were a density of 237 kg DM/m^3 at 42% DM content for hay crop silage, and a density of 232 kg DM/m^3 at 34% DM content for corn silage.

Bernier-Roy et al. (2001) measured the effect of dynamic compaction of chopped forage in the laboratory. The pre-compressed height of forage was limited to 0.30 m. They obtained the following regression models for whole-plant corn and grass:

$$\rho_{corn\text{ - }dynamic} = 84 + 0.755 \, P \quad \text{(A-7)}$$

$$\rho_{grass\text{- }dynamic} = -46 + 3.49 \, DM + 0.685 \, P - 84 \, L \quad \text{(A-8)}$$

where P is wheel pressure against the forage (kPa). During their tests, the pressure was either 39 or 64 kPa, suggesting a range of density between 114 and 133 kg DM/m^3 for corn. In the case of grass, the experimental range was 35% to 50% for DM content, 39 to 64 kPa for wheel pressure and 0.1 or 0.2 m for layer thickness. The grass model indicates that the low and high limits for estimated DM density were 86 kg DM/m^3 (at DM = 35%, P = 39 kPa, L = 0.2 m) and 164 kg DM/m^3 (at DM = 50%, P = 64 kPa, L = 0.1 m). Because the maximum pre-compressed height was only 0.30 m, equations (A-7) and (A-8) represent only parameter a in equation (A-9) below.

Muck et al. (2004) compressed in the laboratory six or more layers with a height of 0.30 m prior to compression. They suggested the following model as a function of the number of layers:

$$\rho = a + b \ln N \quad \text{(A-9)}$$

where a is a parameter indicating the compressed density of the first uppermost layer, b is a parameter related to density increase as a function of the number of 0.30-m layers, N. Both parameters may be influenced by time of compaction, pressure, layer thickness, DM content, crop species, chop length, and processing.