LABORATORY ASSESSMENT OF BUNKER SILO DENSITY PART I: ALFALFA AND GRASS

R. E. Muck, P. Savoie, B. J. Holmes

ABSTRACT. *A laboratory apparatus was developed to simulate pressure, time of compaction, and layer thickness as applied in a bunker silo. Chopped alfalfa or orchardgrass was placed in layers of 0.15, 0.30, and 0.45 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 2 and 10 s. A total of 23 tests (17 with alfalfa, 3 with grass, and 3 with mixed alfalfa-grass) were conducted; dry matter (DM) concentration ranged between 20% and 54%. The pre-compressed density of the first layer (0.30 m high) averaged 72 and 55 kg DM/m^3 for alfalfa and grass, respectively. The highest compressed density ranged between 138 and 339 kg DM/m^3 with an average of 220 kg DM/m^3. After releasing pressure, the relaxed density of the first, uppermost layer ranged between 81 and 152 kg DM/m^3 with an average of 127 kg DM/m^3 . After six layers, the average relaxed density was 181 kg DM/m^3, 18% lower than the average highest compressed density. As successive layers were added, the cumulative DM density increased according to a logarithmic model. The model suggested that density would continually increase, slowly but without reaching a plateau, as the silo height increased. Within the experimental range, parameters of the logarithmic model were significantly affected by pressure, DM content, crop species and chop length, but not by layer thickness or time of compaction. More laboratory data are needed to understand interactions between the variables while field validation is necessary to extrapolate results to deep bunker silos.*

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

Density is an important variable in maintaining silage quality and in predicting available feed on livestock farms. Previous research has shown that dry matter (DM) density in bunker silos is very variable, between 106 and 434 kg/m^3 according to a survey of 168 commercial bunker silos in Wisconsin (Muck and Holmes, 2000). A high silage density is desirable to increase storage capacity and reduce porosity, thereby reducing oxidation loss and preserving a high feed value. However, obtaining a high silage density can be expensive because of requirements for heavy compaction equipment, prolonged compaction time, suitable layer placement, and thickness.

Several models have been proposed to estimate DM density in bunker silos; they are reviewed in detail by Savoie et al. (2004). Most models were empirical and reflected site-specific conditions. Models developed in the 1970s considered moisture as the most important factor (Messer and Hawkins, 1977). Models developed in the early 1990s included tractor mass as a wider range of equipment became available for compacting silos (Darby and Jofriet, 1993). Recently, other factors such as time of compaction, layer thickness, and silo height have been included to predict DM density in bunker silos (Ruppel et al., 1995; Muck and Holmes, 2000).

To develop a more general prediction model, the relationships between density and the influencing factors need to be better understood. Previous experimental work was conducted by Laue (1990) who compared two tractor masses and dual versus single tires on the density of bunker silos. Bernier-Roy et al. (2001) evaluated the effect of two wheel pressures, two layer thicknesses, and the number of passes on silage density in a small (0.30 × 2.4 m long) bunker in the laboratory. These previous studies provided some information on specific treatment comparisons but did not provide general relationships between the factors and bunker silo density.

The objective of this research was to develop more general relationships between bunker silo density and various factors. The present article describes a laboratory set-up that was developed to simulate pressure, time of compaction, and layer thicknesses similar to those encountered in real bunker silos. Experimental data from chopped alfalfa and grass are analyzed and used to propose mathematical relationships that might be applied more generally to predict density in bunker silos. A second article (Savoie et al., 2004) presents data related to corn silage and discusses further model development.

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METHODOLOGY

EXPERIMENTAL APPARATUS

A platen press was set up to compress successive layers of chopped forage in a rectangular container (figs. 1a and 1b).

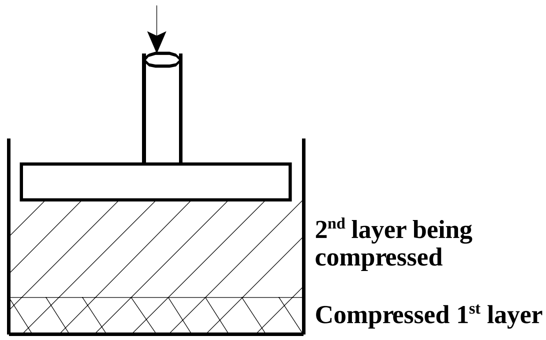

Figure 1a. Schematic of the platen press used to compress consecutive layers of forage.

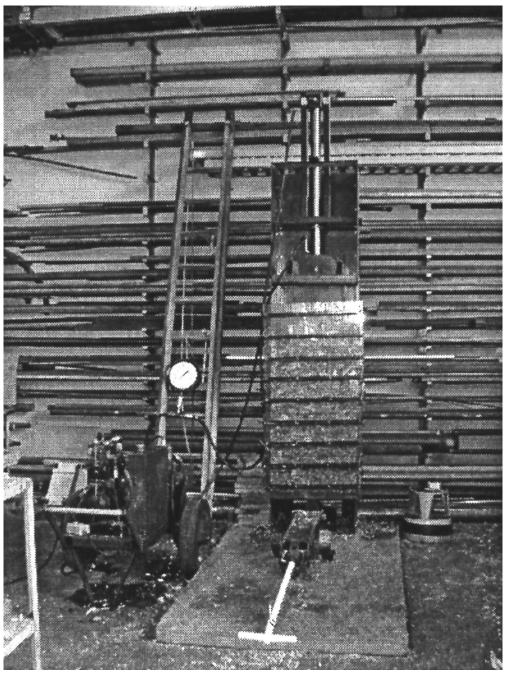

Figure 1b. Actual apparatus used to compress successive layers of forage as a function of pressure, time of compaction, and layer thickness.

The platen was 0.584 m long × 0.483 m wide and 0.054 m thick (23 × 19 in. and 2 1/8 in.). The chosen contact area simulated the footprint of a typical tractor tire of 1.753 m diameter × 0.483 m width (69 × 19 in.). This tire size was the most common observed in a survey of bunker silo compaction reported by Muck and Holmes (2000). The footprint was assumed to be the tire width by one-third the diameter.

The platen was composed of a 3-mm (1/8-in.) thick steel flat plate reinforced with a 51-mm (2-in.) box tube. The forage container walls were made of steel plates sprayed with enamel paint; inside horizontal dimensions of the container were 0.597 m long × 0.496 m wide (23 ½ in. × 19½ in.) and slightly larger than horizontal dimensions of the platen. The height of the container could handle at least six successive 0.30-m (12-in.) thick layers of forage.

The pressure was transmitted to the top layer by a hydraulic cylinder with a diameter of 64 mm (2 ½ in.) pressing against the platen. 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 measured at the hydraulic cylinder by a gauge with a resolution of 25 psi, i.e. a resolution of 1.9 kPa at the forage surface). In addition, the mass of the platen and cylinder was 34 kg (75 lb) and 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. The total pressures were rounded to 20, 40, 60, and 80 kPa, respectively, for purposes of treatment identification in tables and figures.

The most frequent pressure used experimentally was 40 kPa. This pressure was comparable to the average pressure applied by four equally sized tires from a 4600-kg (10,100-lb) tractor, considering the same assumptions as previously described regarding tire size and footprint. The range of 20 to 80 kPa used in the laboratory was expected to cover the likely range of tire pressures in real bunker silos, considering a wide range of tractor weights, tire sizes, and front-to-rear weight ratios.

Experimental Variables

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

Layers of chopped forage were laid in non-compacted thicknesses of 0.15, 0.30, and 0.45 m (6, 12, and 18 in.). A thickness of 0.30 m was the one used most frequently because it corresponded to common farming practice. The mass of forage was adjusted experimentally for the initial layer at each test date and for each thickness; subsequent layers were of the same constant mass.

After each layer was placed in the container, the platen was lowered at the designated pressure over times varying between 1 and 10 s. The most frequently used time of compaction was 5 s. This time was designed to represent four passes of two tires of a tractor moving at 3.4 km/h, assuming a 0.584-m footprint length as explained earlier.

After compaction, the forage was left to relax about 1 min before the next non-compacted layer was placed. This time interval between two layers was shorter than the one usually observed in real bunker silos where typically 4 to 12 loads per hour are unloaded, spread, and compacted (5- to 15-min intervals). However, empirical observation indicated that much of the relaxation occurs a few seconds after passage of the packing tractor. In the laboratory experiment, 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, usually set to 10-mm (3/8-in.) theoretical length of cut, and blown into the back of a pickup truck for transport to the press.

Two forage samples were taken per test and duplicate analyses of dry matter were made [oven-drying for 24 h at 103°C according to ASAE (2001) standard method S358.2]. The average of the four determinations was used for calculating dry matter density per test.

EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS

Alfalfa and orchardgrass were mowed between 24 May and 29 August 2001. Seven experiments were carried out to evaluate the effect of pressure, layer thickness, and time of compaction on density. Each experiment included three to five tests carried out in a single day, except for the first two experiments, which were conducted over several days. Table 1 lists the seven experiments, 23 tests, and specific experimental conditions.

Densities were measured at three stages: pre-compression, compressed, and relaxed density. In practice, the relaxed density is the most important variable because it represents the actual final density and the basis to estimate storage capacity. Statistical analysis was done only on the relaxed density.

A logarithmic model was found to fit well the experimental data of the relaxed density as a function of the number of layers compressed. The general model was:

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

where ρ is the dry matter density (kg DM/m^3), a is a parameter reflecting the density of the uppermost compacted layer, b is a parameter reflecting the increase in density with an increasing number of layers, and N is the number of 0.30-m thick layers (prior to compression). Parameters a and b have the same units as ρ (kg DM/m^3). For each test, parameter a was obtained as the measured density for the first 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 regression analysis was carried out to determine the effect of pressure, layer thickness, time of compaction, chop length, crop species, and DM on parameters a and b.

RESULTS AND DISCUSSION

DENSITIES MEASURED IN THE LABORATORY

Figure 2 shows a typical sequence of the densities measured in the laboratory starting with deposition (the pre-compressed density), followed by compression (the compressed density), and relaxation (the relaxed density). As new layers were added, the cycle of deposition, compression,

Table 1. Experimental conditions for compaction of alfalfa, grass, or mixed alfalfa-grass.

Date	Crop	Mass per Layer (kg)	Layer Thickness (m)	No. of Layers	Time of Compaction (s)[a]	Pressure (kPa)[b]	DM (% w.b.)
Experiment 1							
2001-05-24a	Alfalfa	15.9	0.30	6	5	20	35.5
2001-05-25a	Alfalfa	15.9	0.30	9	5	40-	35.4
2001-05-25b	Alfalfa	23.6	0.30	10	5	40+	19.8
2001-05-30a	Alfalfa	18.2	0.30	9	5	60	39.2
2001-05-30b	Alfalfa	18.2	0.30	9	5	80	38.6
Experiment 2							
2001-05-31a	Alfalfa	18.2	0.30	6	2	40	41.8
2001-05-31b	Alfalfa	18.2	0.30	6	5	40	42.9
2001-06-01a	Alfalfa	18.2	0.30	6	10	40	43.1
Experiment 3							
2001-06-08a	Grass	16.8	0.30	6	5	20	30.6
2001-06-08b	Grass	8.6	0.15	12	5	20	30.6
2001-06-08c	Grass	25.5	0.45	4	5	20	31.6
Experiment 4							
2001-07-05a	Alfalfa	18.2	0.30	8	5+	40	34.5
2001-07-05b	Alfalfa	18.2	0.30	8	5	40	37.5
2001-07-05c	Alfalfa	18.2	0.30	8	5 * 1 s	40	37.1
Experiment 5							
2001-07-06a	Mixed[c]	32.7	0.45	6	5	40	35.4
2001-07-06b	Mixed	21.8	0.30	6	5	40	37.1
2001-07-06c	Mixed	10.9	0.15	12	5	40	38.1
Experiment 6							
2001-07-10a	Alf./long[d]	13.6	0.30	7	1 * 6 s	40	48.6
2001-07-10b	Alf./long	13.6	0.30	7	2 * 3 s	40	53.6
2001-07-10c	Alf./long	13.6	0.30	8	3 * 2 s	40	51.3
Experiment 7							
2001-08-29a	Alfalfa	23.6	0.30	7	1 * 6 s	40	25.6
2001-08-29b	Alfalfa	23.6	0.30	7	2 * 3 s	40	25.6
2001-08-29c	Alfalfa	23.6	0.30	6	3 * 2 s	40	25.6

[a] The time of compression was generally counted from the time the designated pressure was achieved. For the tests on 5 July, the time 5+ was counted once the pressure gauge reached 40 kPa whereas time 5 was 5 s from the rapid rise in pressure. Repeated compression of the same layer is shown as in the example 2 × 3 s, i.e. twice three s.

[b] Pressure was generally the same for each layer, with three exceptions. On 24 May, the 20-kPa pressure was applied three times followed by three times 16 kPa. On 25 May, the 40-kPa pressure was applied eight times followed by once 24 kPa in first test (40-); 40 kPa was applied nine times followed by once 48 kPa in the second test (40+).

[c] A mixture of alfalfa and grass.

[d] Alfalfa, grass and mixed crop were generally chopped short (10-mm theoretical length of cut) except on 10 July where particles were chopped long (19-mm TLC).

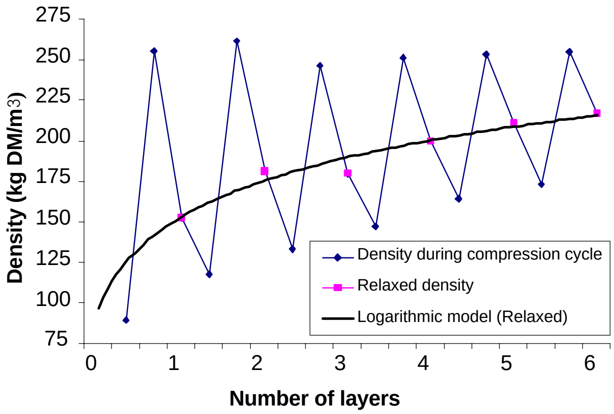

Figure 2. Example of the sequence of density after layer deposition, compaction, relaxation, addition of a new layer, and so forth. Based on 31b May test with chopped alfalfa at 43% DM applied in 0.30-m layers and compressed under 40-kPa pressure for 5 s for each layer.

and relaxation was repeated; new densities were calculated as the average of the cumulative layers.

A logarithmic curve on figure 2 is seen to fit relatively well along the relaxed density data points as a function of the number of layers. For this specific example (31b May), measured parameter a was 152 kg DM/m^3 and estimated parameter b was 34.6 kg DM/m^3 with a coefficient of determination of 0.870 (table 2). For alfalfa and grass, the coefficient of determination to estimate parameter b in the logarithmic model was generally very good, with $R^2 \geq 0.90$ in 21 out of 23 tests.

Table 2 also reports the lowest pre-compressed densities. The minimum value always occurred in the first pre-compressed layer because subsequent pre-compressed densities were the average of the upper uncompressed layer plus one or more compressed-relaxed layers underneath. The average pre-compressed density of a 0.30-m thick single layer was 72 kg DM/m^3 for alfalfa and 55 kg DM/m^3 for grass (values of experiment 5 were considered alfalfa because a large proportion of the mix was composed of alfalfa). Data were insufficient to estimate the effect of layer thickness on pre-compressed density that tended to increase with layer thickness (experiments 3 and 5).

The highest compressed density ranged between 138 and 339 kg DM/m^3 with an average of 221 kg DM/m^3 (table 2). Out of 23 tests in alfalfa and grass, the highest compressed density was observed 10 times in the first layer, 5 times in the second layer, and 5 times in the last layer (sixth to ninth layer depending on test).

Table 2. Lowest density of pre-compressed layers, highest compressed density, measured and estimated parameters of the logarithmic model for the relaxed density of alfalfa, grass, or mixed alfalfa-grass. 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 Compress 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							
201-05-24a	20 kPa	61	165	100	24.5	0.762	14
2001-05-25a	40 kPa	67	239	120	26.7	0.905	89
2001-05-25b	40 kPa	58	199	113	28.2	0.947	21
2001-05-30a	60 kPa	78	276	138	40.4	0.906	30
2001-05-30b	80 kPa	76	339	148	37.3	0.932	169
Experiment 2							
2001-05-31a	2 s	83	249	142	33.2	0.933	25
2001-05-31b	5 s	89	261	152	34.6	0.870	23
2001-06-01a	10 s	86	273	150	37.5	0.978	27
Experiment 3							
2001-06-08a	0.30 m	56	146	80	22.0	0.938	20
2001-06-08b	0.15 m	52	150	80	24.3	0.925	18
2001-06-08c	0.45 m	62	138	80	21.8	0.966	14
Experiment 4							
2001-07-05a	5+ s	70	234	138	26.6	0.908	38
2001-07-05b	5 s	76	220	132	30.0	0.965	19
2001-07-05c	5 * 1 s	79	222	139	28.6	0.991	18
Experiment 5							
2001-07-06a	0.45 m	86	220	130	33.3	0.984	15
2001-07-06b	0.30 m	87	229	130	37.9	0.902	14
2001-07-06c	0.15 m	74	236	130	41.8	0.924	13
Experiment 6							
2001-07-10a	1 × 6 s	71	220	120	27.1	0.954	40
2001-07-10b	2 × 3 s	69	251	121	39.8	0.968	26
2001-07-10c	3 × 2 s	70	219	115	35.7	0.942	18
Experiment 7							
2001-08-29a	1 × 6 s	66	204	124	26.4	0.997	21
2001-08-29b	2 × 3 s	68	203	129	25.3	0.953	19
2001-08-29c	3 × 2 s	66	195	114	31.5	0.957	13

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

After releasing pressure, the relaxed density of the first layer was equivalent to parameter a , whose values ranged between 80 and 152 kg DM/m^3 with an average of 123 kg DM/m^3 (table 2). Relaxation caused an average density reduction of 44% in the first layer. However as the number of layers increased, the effect of relaxation on density reduction decreased. The average value of parameter b for all tests was 31.1 kg DM/m^3. After six layers, the average relaxed density was 179 kg DM/m^3, 19% less than the average highest compressed density. If the logarithmic curve is extrapolated, the average relaxed density after 23 layers actually becomes equal to or greater than the average highest compressed density observed experimentally (221 kg DM/m^3). For each individual test, the theoretical number of 0.30-m layers required to reach the highest compressed density was calculated from equation 1 and parameters a and b. Values reported in table 2 show that this theoretical number of layers (N) varied between 13 and 169. In a real 3-m high bunker silo, the number of uncompressed 0.3-m layers would be in the order of 32 assuming a non-compressed density of 72 kg DM/m^3 and a compressed-relaxed density of 230 kg DM/m^3 ($\rho_{ave.} \approx 123 + 31 \times \ln 32$). Therefore, the average relaxed density in a deep bunker silo is likely to be greater than the highest compressed density observed in six to nine layers in the experimental laboratory silo.

The Boussinesq equations, used by Zhao and Jofriet (1992) to estimate vertical and normal stresses under a silo compaction vehicle, indicated a reduced, albeit important tractor load effect to compacted depths of a least 1 m below the surface. The vertical stress σ_z under the line of action of a vertical load Q as a function of depth z is estimated as $\sigma_z = 3Q/(2\pi z^2)$. For example with a 4600 kg tractor weight spread evenly over four wheels (0.584- × 0.482-m contact area each), a uniform vertical pressure of 40 kPa is expected between the surface and a depth of 0.37 m while reduced pressures of 20, 4, and 0.4 kPa would occur at depths of 0.52, 1.16, and 3.67 m, respectively. The extrapolation of increasing density with increasing depth is also plausible because the weight of cumulative layers will exert, in addition to the tractor mass, a pressure on the crop as height increases. Validation of the logarithmic model to predict density requires observations in field-scale bunker silos with a large number of layers.

Effect of Pressure, Time and Layer Thickness on Density

Figure 3 shows the relaxed density of five tests during experiment 1 as a function of pressure between 20 and 80 kPa. The lowest pressure resulted in the lowest density, as expected. The two tests at 40 kPa were very close to each other, although one was done with forage at a low DM content (19.8% for 40+ kPa) and the other was done with drier forage (35.4% DM for 40- kPa). The densities at 60 and 80 kPa were higher than densities at lower pressures, and they were equal among each other up to five layers. The density at a pressure of 80 kPa became slightly higher than the density at a pressure of 60 kPa beyond five layers. Validation with field-scale bunker silos is required to evaluate whether the difference between two high pressures such as 60 and 80 kPa would increase or remain constant as the number of layers increases beyond the number that could be observed in the laboratory. This information would be useful to determine whether increasing the tractor mass is always beneficial to increase the density or whether there is an upper limit on the effect of pressure. Values of parameter a in table 2 indicate an 18- to 25-kg DM/m^3 density increase between 40 and 60 kPa and an additional 10-kg DM/m^3 increase at 80 kPa. Parameter b increased nonlinearly with pressure.

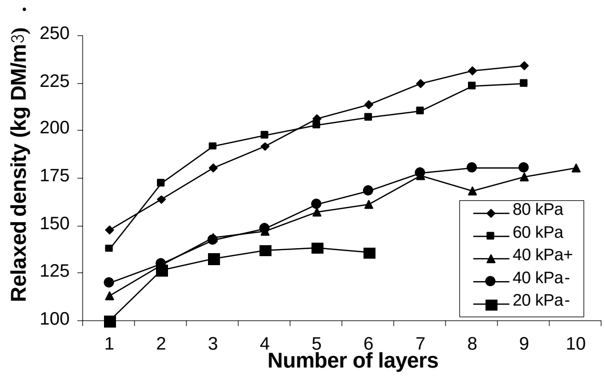

Figure 3. Relaxed density observed in experiment #1 (24 to 30 May) as a function of pressure applied for 5 s on 0.30-m layers of chopped alfalfa (10 mm) with DM ranging between 35% and 39% except for 40 kPa+ test (DM = 20%).

Figure 4 shows the relaxed densities during experiment 2 for compaction times of 2, 5, and 10 s per layer. The density after 2 s was clearly lower than density after 5 and 10 s of compaction per layer. The difference was initially about 10 kg DM/m^3 based on parameter a (142, 152, and 150 kg/m^3 for 2, 5, and 10 s, respectively, in table 2). From the results of experiment 2, increasing compaction time from 2 to 5 s would appear to be justified, but not up to 10 s.

Figure 5 shows the relaxed densities of experiment 3 for grass at low pressure (20 kPa) as a function of layer thicknesses between 0.15 and 0.45 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 and four layers of 0.45 m. These equivalent numbers of 0.30-m layers were also used to estimate parameters a and b on a common basis (i.e., N varied from 1 to 6 in all three tests). A uniform value of parameter a was used for all three tests in experiment 3 because experimental measurements in two tests out of three did reproduce the initial 0.30-m layer. The measured parameter a after compression-relaxation of a single 0.30-m grass layer was 80 kg DM/m^3. Estimated parameter b was 24.3, 22.0, and 21.8 kg DM/m^3 for 0.15-, 0.30-, and 0.45-m

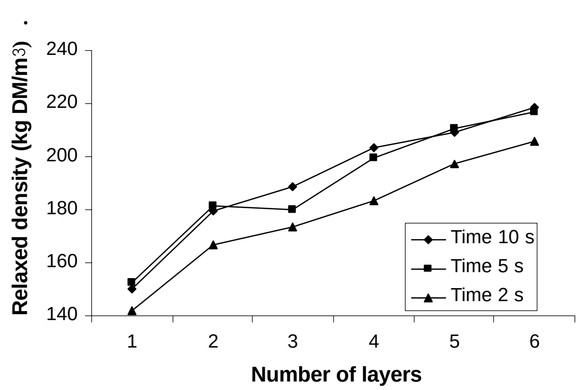

Figure 4. Relaxed density observed in experiment #2 (31 May to 1 June) as a function of the time of compaction applied at 40-kPa pressure on 0.30-m layers of chopped alfalfa (10 mm) with DM averaging 43%.

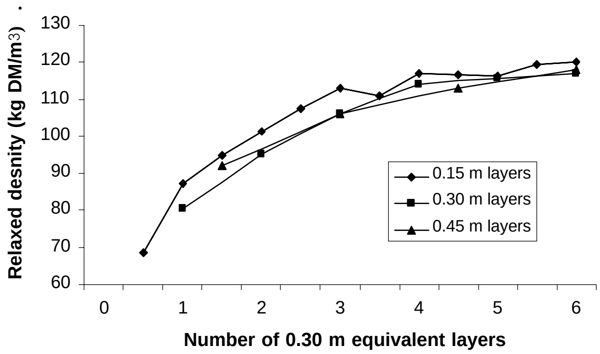

Figure 5. Relaxed density observed in experiment #3 (8 June) as a function of layer thickness compressed at 20-kPa pressure for 5 s on chopped grass (10 mm) with DM averaging 31%.

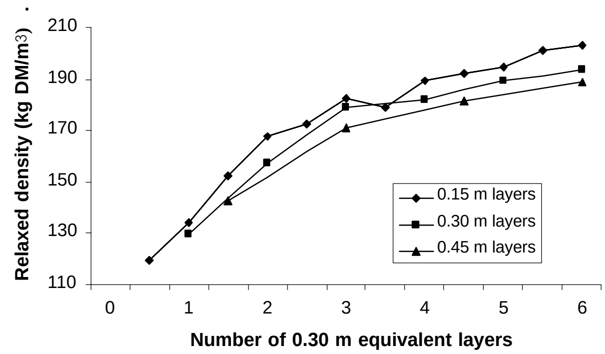

Figure 7. Relaxed density observed in experiment #5 (6 July) as a function of layer thickness compressed at 40-kPa pressure for 5 s on chopped mixed alfalfa-grass (10 mm) with DM averaging 37%.

layer thickness, respectively. The decrease in parameter b was consistent as the layer thickness increased but of small effect on actual density (about 4-kg DM/m^3 higher density with a thin layer compared to the thick layer after six layers). Grass was less compressible than alfalfa at a similar pressure of 20 kPa (24a May, a = 100 kg DM/m^3). More data are required however to make a general statement on differences between grass and alfalfa.

Figure 6 shows the relaxed densities of experiment 4 where three patterns of time of compaction were applied. The treatment 5+, where a pressure of 40 kPa was applied for 5 s after the gauge had reached the desired level, had a time of compaction a fraction of a second longer than treatment 5, where the same pressure was applied for 5 s as soon as the platen touched the forage and before the pressure gauge had reached full pressure. The third treatment consisted of compressing each layer of forage five times for 1 s. The first and third treatments had slightly higher values of parameter a (138, 132, and 139 kg DM/m^3, respectively) while the second treatment had a slightly higher value of parameter b (26.6, 30.0, and 28.6 kg DM/m^3, respectively). As a result, it is difficult to observe differences between the three patterns of time of compaction. The total time of compaction is therefore more important than the way the time is spread. In practice, these results suggest that a slow moving compaction tractor and a fast moving compaction tractor are likely to generate similar relaxed densities if they are used for the same amount of time to compress the same mass of forage over the same area.

Figure 7 illustrates the relaxed densities of experiment 5 for three layer thicknesses of alfalfa compressed at 40 kPa. After six equivalent 0.30-m layers, the thin layer treatment of 0.15 m resulted in densities about 7 and 14 kg DM/m^3 higher than densities obtained with layers of 0.30 and 0.45 m, respectively.

Figures 8 and 9 illustrate results from experiments 6 and 7 where the same time of compaction was applied in three different patterns: once 6 s, twice 3 s, or three times 2 s. In experiment 6, the alfalfa was relatively dry (51% DM) and chopped long (19 mm). In experiment 7, the alfalfa was relatively wet (26% DM) and chopped short (9 mm). In figure 8, the 2- × 3-s pattern appeared to result in slightly higher densities after seven layers. A high value of parameter b in this case (39.8 kg DM/m^3) explains this tendency. However, with wetter alfalfa in figure 9, there was no trend for the 2- × 3-s pattern to produce higher densities than the other patterns. Here again, one could conclude that total time of compaction was more important than the pattern in which the time was applied, as in experiment 4 (fig. 6).

Multiple Regression Analysis

In addition to the three controlled factors (pressure, time of compaction, layer thickness), three other variables (dry matter, species, chop length) 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. This resulted in the following relationships:

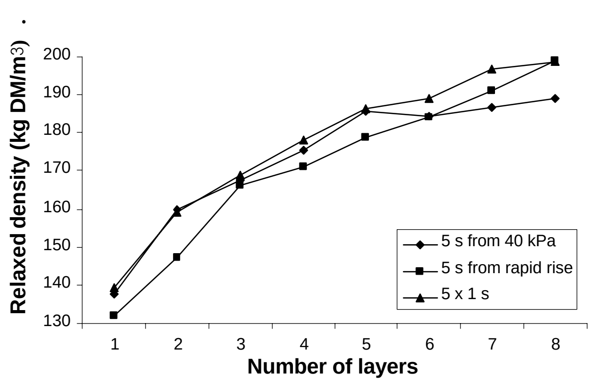

Figure 6. Relaxed density observed in experiment #4 (5 July) as a function of the pattern for time of compaction (5 s from 40 kPa being slightly longer than 5 s from rapid rise or 5 × 1 s) applied on 0.30-m layers of chopped alfalfa (10 mm) with DM averaging 36%.

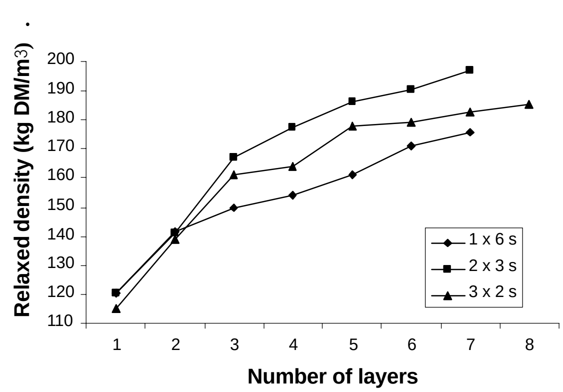

Figure 8. Relaxed density observed in experiment #6 (10 July) as a function of time of compression cycle applied at 40-kPa pressure for 6 s on 0.30-m layers of long chopped alfalfa (19 mm) with DM averaging 51%.

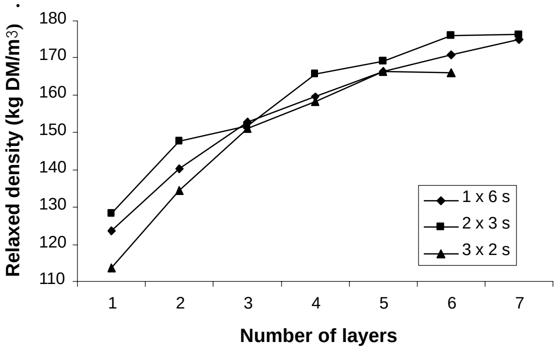

Figure 9. Relaxed density observed in experiment #7 (29 August) as a function of time of compression cycle applied at 40-kPa pressure for 6 s on 0.30-m layers of chopped alfalfa (10 mm) with DM averaging 26%.

$$a = 123.1 + 0.599 \times P + 1.37 \times DM - 28.8 \times SP - 34.8 \times CL \quad (2)$$

$$b = 9.03 + 0.262 \times P + 0.324 \times DM \quad (3)$$

where P is compaction pressure (kPa), DM is dry matter (%), SP is crop species (1 for alfalfa, 2 for grass, and 1.5 for mixed alfalfa-grass) and CL is chop length [1 for short chop length (10 mm) and 2 for long chop length (19 mm)]. The coefficients of determination (R^2) were 0.830 and 0.566 for equations 2 and 3, respectively.

Within the experimental range, layer thickness (0.15 to 0.45 m) and time of compaction (2 to 10 s) were not significant and eliminated from the final regression model. For alfalfa only, a thin layer increased mildly (7 to 14 kg DM/m^3) the density compared to thicker layers (fig. 7) after six layers. However, layer thickness had a very small effect on grass (fig. 5). There may be interactions between layer thickness, species, and pressure level. In a real bunker silo where filling may extend over several days, cell breakdown might also contribute to increase final density. More data are required to confirm impact of time of filling and interactions between factors on final density.

Similarly, the time of compaction had a small effect [about 10 kg DM/m^3 (fig. 4)] over the range of 2 to 10 s. With all other variables in the regression, the time of compaction did not have a significant effect. Bernier-Roy et al. (2001) compressed chopped grass and whole-plant corn for much shorter times using a rolling wheel of 0.721 m diameter × 0.165-m width travelling at 1 m/s. Assuming a contact footprint equal to one-third the diameter (0.24 m), the time of contact for each pass was 0.24 s. During eight consecutive passes over the last uppermost layer, these authors found average increases of DM density of 49.9, 8.1, 3.3, 4.6, 1.8, 1.2, -1.4, and 2.6%, for the eight passes, respectively. They also determined that the DM density increase was statistically significant until the 5^{th} pass, and non-significant for the sixth, seventh, and eighth passes. Therefore, DM density significantly increased until 1.2 s of wheel contact, but not beyond.

In the case of parameter a predicted by equation 2, the levels of significance (probabilities) were 0.009 for P, 0.001 for DM, 0.0006 for SP and 0.0007 for CL. In the case of parameter b in equation 3, the levels of significance were 0.002 for P and 0.009 for DM. Equation 2 indicates that alfalfa had a higher density than grass by an average of 29 kg DM/m^3. A longer chop length resulted in a lower density by 35 kg DM/m^3. These results should be used with caution because of the limited number of tests, both in the case of grass and longer chop length.

The results point to the need for more experimental data, especially for variables that were not controlled in this experiment, i.e. dry matter, crop species, and chop length because of their significant effect on model parameters.

The average values of parameters a and b for typical factors (layer thickness = 0.30 m, time of compaction = 5 s, P = 40 kPa, DM = 35%, alfalfa, and a short chop length) are 131 and 30.9 kg DM/m^3, respectively, based on equations 2 and 3. Using these parameter values and equation 1, the average relaxed density in a bunker silo would be 187 kg DM/m^3 for six layers (within the experimental range) and 236 kg DM/m^3 for 30 layers (extrapolation to a common bunker silo size of about 3-m compacted height). This latter density is similar to average densities for alfalfa measured in surveys of bunker silos (Ruppel et al., 1995; Muck and Holmes, 2000). While even the extrapolated value seems reasonable, in-the-field validation is necessary to verify these results. A non-linear regression, notably for pressure, could further improve the estimation of DM density in bunker silos.

Conclusions

- A laboratory set-up was constructed to simulate pressure, footprint area, and time of compaction of a packing tractor on bunker silos. The set-up was used to control pressure, time of compaction, and layer thickness for alfalfa and grass.
- A logarithmic curve fit very well the final relaxed densities as a function of the number of layers ($R^2 \geq 0.90$ in 21 out of 23 tests).
- DM density of alfalfa and grass was positively correlated with pressure and dry matter content. DM density was also significantly higher for alfalfa compared to grass and for a short chop length (10 mm) compared to a long chop length (19 mm). Layer thickness and time of compaction were non significant in estimating the two parameters in the logarithmic model. Further data are required to understand interactions between the independent variables.
- The laboratory set-up was used for only six to nine 0.30-m equivalent layers because of height limitations. The logarithmic model predicted that DM density would continue to increase as the number of layers increased. In-the-field measurements are necessary to validate the model for a large number of layers ($\geq$30) typical in deep bunker silos.

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