

Physical characteristics of barley silage in tower silos

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Negi, S.C., Li, W., Jofriet, J.C. and Ogilvie, J.R. 1992. **Physical characteristics of barley silage in tower silos.** *Can. Agric. Eng.* 34:165-169. Twenty seven pressure-density experiments and eighteen indirect friction tests were carried out in model silos with barley silage ranging from 36 to 63% moisture content. The results were used to produce a model for the dry density of "barlage" in terms of vertical pressure, loading time, and moisture content. This model was then used to predict silo capacities and wall pressures. The results indicated that for barley silage the density and silo capacity are less than for alfalfa and more than for corn silage. The products of friction coefficient and pressure ratio were smaller for the higher moisture material. Wall pressures based on measurements in laboratory silos compared favourably with the predictions of the new Canadian Farm Building Code. Average bulk densities of barley silage were computed over a range of moisture contents and silo diameters for inclusion in the new code.

Vingt-sept expériences de pression/densité et dix-huit essais de frottement indirect ont été effectués dans des modèles de silos avec un ensilage d'orge dont le taux d'humidité variait de 36 à 63 %. Les résultats ont servi à produire un modèle pour la masse volumique sèche de l'ensilage en termes de pression verticale, de temps de chargement et de taux d'humidité. Ce modèle a permis de prévoir des capacités de silos et des pressions sur les parois. Les résultats ont indiqué que, pour l'orge, la densité et la capacité des silos sont inférieures à celles de la luzerne et supérieures à celles de l'ensilage de maïs. Les produits du coefficient de frottement et du taux de compression étaient inférieurs pour les matières à taux d'humidité plus élevé. Les pressions exercées sur les parois, déterminées à partir de mesures faites en silos de laboratoire, étaient comparables aux prévisions du nouveau code de construction des bâtiments agricoles. Les masses volumiques moyennes en vrac de l'ensilage d'orge ont été calculées à partir de toute une série de taux d'humidité et de diamètres de silos, afin de les inclure dans le nouveau code.

INTRODUCTION

Barley is grown in the lower heat-unit regions of Canada for livestock feed instead of corn or other forage crops. It is especially popular in northern Ontario, British Columbia and the Maritimes. This is because spring barleys mature in a short season of two to three months and all varieties of barley can be grown on many soils and are tolerant of cold climatic conditions (Janick et al. 1969). Since the crop contains considerable grain when it is harvested, the product is a high-energy silage with more digestible energy than grass and legume silages. Accordingly, it is used as the only source of forage in rations for beef cattle. It is also highly palatable feed and may be stored for long periods (Goodrich and Meiske 1973).

Barley is generally planted in rotation and may be har-

vested for silage at several moisture contents. The barlage can be divided into three groups on the basis of moisture level and storage facility: (1) high-moisture or direct-cut silage for horizontal silos, 65 - 75% moisture; (2) wilted silage for top unloading silos, 60 - 70% moisture; and (3) low-moisture silage for oxygen-limiting silos equipped with bottom unloaders, 40 - 55% moisture. However, in most cases the harvesting is done by a swather when the grain is in the late-milk to early-dough stage.

Much attention has been given to malting varieties of barley but very little research reported on the physical properties, storage and handling characteristics of barley as silage for animal feed (Brubaker and Pos 1965; Mohsenin 1978). Thus, the present study was undertaken with the following objectives: (1) to determine pressure-density relationship and wall friction properties of whole-plant barley silage with medium to high dry matter content, and (2) to use this information for predicting silo capacities and structural loads on tower silo walls. Because of the practical problems associated with measurements of moisture-density-pressure interrelationships of "barlage" in full-scale silos, the real situation was simulated as closely as possible with respect to fibre orientation and material density in model silos.

EXPERIMENTAL PROCEDURE

A barley crop for silage was grown during the summer of 1989 at the Arkell Research Station of the University of Guelph. The barley was harvested by hand when the grain was in the late-milk to early-dough stage, as well as a week prior to and a week after this stage. The freshly harvested material was chopped to about 10 mm length by a forage harvester equipped with cutting cylinder. Known quantities of the material were loaded into 203 mm diameter PVC cylinders and subjected to three vertical pressure levels (98.9, 48.9 and 9.2 kPa), each replicated three times. The vertical pressure on top of the specimen was applied through a lever arrangement made of a steel channel and a weight hanger system. Measurements of silage bulk densities were made in each cylinder periodically between 1 and 60 days after ensiling. The density was determined by dividing the mass of silage loaded in the cylinder by its volume. The latter was found by periodic observations of the compressed height of the specimen. Samples from each batch were weighed and dried at 105°C for 24 hours to determine the moisture contents.

A second series of tests was carried out to determine the product of the friction between the barley silage and the wall

of the laboratory silo, μ , and the ratio of horizontal to vertical pressure, K . In these experiments, 600 mm long sections of 203 mm diameter painted steel, PVC, and concrete sewer pipes were filled with barley silage to a depth of about 400 mm. The base of the model silo consisted of a slightly smaller (200 mm diameter) plywood disc supported on a load cell, which was a strain-tube type pressure transducer. Each transducer consisted of a square stainless steel tube with four strain gauges bonded to its surface to form a wheatstone full-bridge circuit. These transducers were calibrated in the laboratory by measuring strains for incremental loading/unloading and plotting pressure versus strain. The pressure on top of the sample was applied by means of the aforementioned lever arrangement. Measurements of the load carried by the silo base and the compressed height of the specimen were taken at 24-h intervals over a 5-day period.

RESULTS AND DISCUSSION

Density model

In a model silo, assuming the density of the silage, ρ , to be uniform, the vertical pressure, q , at a depth, z , can be determined from the Janssen equation, modified to allow a surcharge load:

$$q = \frac{\rho g}{\beta} + \left(q_0 - \frac{\rho g}{\beta} \right) e^{-\beta z} \quad (1)$$

where:

- q_0 = pressure applied at top of sample,
- g = gravitational constant,
- $\beta = 4\mu K/D$,
- μ = coefficient of friction between silage and silo wall,
- K = ratio of lateral to vertical pressure, and
- D = diameter of silo.

The average vertical pressure, q_{av} is obtained by integrating Eq. 1 over the height of the test specimen, H , and dividing by H .

$$q_{av} = \frac{\rho g}{\beta} + \frac{q_0 - \frac{\rho g}{\beta}}{\beta H} (1 - e^{-\beta H}) \quad (2)$$

The pressure-density relationship of silage can be expressed as (Negi et al. 1984):

$$\rho = \rho_0 + a (1 - e^{-bq}) \quad (3)$$

where:

- ρ_0 = initial density at stress-free surface, and
- a, b = material parameters.

The pressure-density data for the three moisture contents of 36.3, 58.9 and 63.4% were used to calculate dry matter densities and average vertical pressures (Eq. 2), and then to find the best-fit values for ρ_0 , a and b (Eq. 3) using the statistical procedure NLIN (SAS 1985). The parameters ρ_0 and b were averaged for all moisture contents, and the functional dependence of parameter a upon moisture content $M(\%)$ and load duration T (days) was found using a stepwise regression computer program. As a result of these operations the following density model ($R^2 = 0.84$) was obtained:

$$\rho = 120 + (2838 - 654 \ln M + 31.5 \ln T) (1 - e^{-0.03q}) \quad (4)$$

where:

- ρ = dry matter density of barley silage (kg/m^3), and
- q = vertical pressure (kPa).

This model applies to whole-plant barley silage with moisture contents in the range of 36 - 63%. In this paper $T = 30$ days was used in Eq. 4 since consolidation becomes negligible after this time period.

The predicted and observed dry densities are compared in Fig. 1 which shows a reasonably good fit of the data with the exception of some low density values at low dry matter content. In Fig. 2 the pressure-density relationship of barley silage is compared to those of two other commonly used whole-plant silage materials. For a given vertical pressure, the resulting density of barley silage is less than that of alfalfa haylage but more than that of corn silage. This indicates that the leafy material of alfalfa packs better than the leaf/grain combination of barley, which in turn packs tighter than the chopped stems, cobs, kernels, leaves and tassels of whole-plant corn silage.

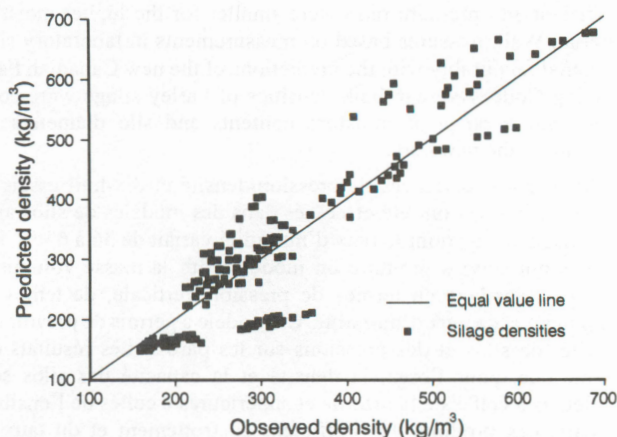


Fig. 1. Predicted vs observed dry matter densities for all pressure-density tests.

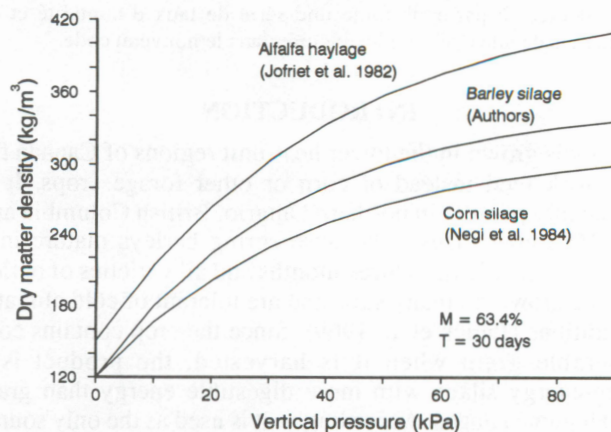


Fig. 2. Comparison of pressure-density relationship obtained from density models for barley silage, alfalfa and corn silage.

Indirect friction tests

The product of the friction coefficient and the pressure ratio, μK , is required for the calculation of average pressure (Eq. 2) in the foregoing data reduction, as well as for the determination of silo capacities discussed in the following section. This product is given by

$$\mu K = 0.25 \beta D \quad (5)$$

where β is derived from Eq. 1:

$$\beta = \frac{1}{z} \ln \left[\frac{q_0 - \rho g \beta}{q - \rho g \beta} \right] \quad (6)$$

As the parameter β occurs on both sides of Eq. 6, a process of successive approximations must be used to obtain a solution, but convergence is rapid.

The results for μK from the experiments are presented in Table I. The effect of moisture content of the ensiled crop on μK was strong for all three types of silo wall materials. Indeed, in all cases the μK values decreased with an increase in moisture content. However, there appears to be little difference between concrete and steel, which is possibly due to microscopic build-up on the walls of steel containers. The present results are also somewhat higher than those reported in the literature for other whole-plant silages: $\mu K = 0.12$ for alfalfa on concrete at $M = 62.3\%$ (Jofriet and Negi 1983); $\mu K = 0.16$ for corn and grass silages in steel silos (NRC 1990). However, there are no data available on barley for a true comparison of μK values.

Table I: Experimental results for the product of friction coefficient and pressure ratio, μK

Moisture Content of barlage (%)	μK		
	PVC	Painted steel	Concrete
63.4	0.112	0.183	0.187
58.9	0.165	0.226	0.219
36.3	0.275	0.318	0.340

The main advantage of this indirect method of testing is that the test situation closely resembles the real tower silo situation. The orientation of the leafy material and the chopped stems tends to be at right-angles to the wall surface. The disadvantage is that the friction coefficient is not determined, but rather the product μK . Another shortcoming is the effect of silo size (203 mm diameter) on the μK results primarily due to the difference in curvature between a full-scale silo and a model silo.

Silo capacities

In a tower silo, the stored silage mass can be treated as consisting of a large number of finite laminae, each having a constant density and a linear variation of vertical pressure from top to bottom. Accordingly, the distribution of densities, vertical pressures and silo capacities were obtained by solving Eqs. 1 and 4 iteratively for 305 mm laminae, starting

at the stress-free surface.

The estimated silo capacities for barley silage at moisture contents of 40, 50 and 60% are given in Table II. Since the values of μK for steel and concrete silos did not differ significantly, a combined silo capacity table for the two wall materials was prepared. The μK values corresponding to the three moisture levels were obtained by linear regression analysis of the relevant experimental data on the variation of μK with moisture content (Table I).

The capacities of four large concrete silos for barley silage are shown in Fig. 3, together with capacities for alfalfa and corn silage calculated from their respective density models (Jofriet et al. 1982; Negi et al. 1984). It is seen that the dry matter capacity of a silo for "barlage" is less than for alfalfa and more than for corn silage. This outcome can be expected since reference to Fig. 2 shows that barley is more compressible than corn but less compressible than alfalfa.

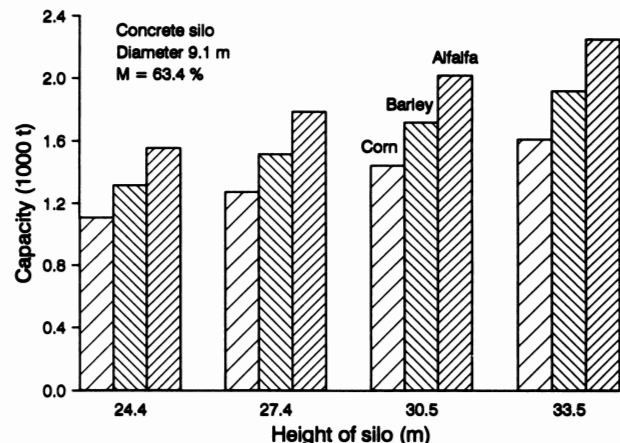


Fig. 3. Comparison of concrete silo capacity for barley silage, alfalfa and corn silage.

Silo pressures

Since the density of silage materials increases with overburden pressure, or equivalently, depth of fill, an exponential function similar to Eq. 3 can be used to describe the depth-density relationship:

$$\rho = \rho_0 + c(1 - e^{-dz}) \quad (7)$$

where c and d are material constants. This equation is used for the calculation of silage pressures in a tower silo.

The average bulk density, ρ_{av} , is found by integrating Eq. 7 over the settled depth of silage, H , dividing by H and neglecting a small exponential term:

$$\rho_{av}H = (\rho_0 + c)H - \frac{c}{d} \quad (8)$$

The dry matter capacities of all silos were used in a linear regression analysis for $\rho_{av}H$ to find the material constants c and d . The dry matter density-depth relationship thus obtained is given by:

$$\rho = 120 + 260(1 - e^{-0.08z}) \quad (9)$$

The vertical pressure in a tower silo without a surcharge

and variable density represented by Eq. 7 is given by (Jofriet et al. 1982) as:

$$q = \frac{(\rho_o^* + c^*)g}{\beta} (1 - e^{-\beta z}) + \frac{c^*g}{\beta - d} (e^{-\beta z} - e^{-dz}) \quad (10)$$

where:

$$\rho_o^* = \rho_o / (1 - 0.01M), \text{ and}$$

$$c^* = c / (1 - 0.01M).$$

The lateral wall pressure, p , is then computed from:

$$p = Kq \quad (11)$$

Figure 4 illustrates the influence of μK on the magnitude and distribution of lateral pressure, p . Also, the lateral pressures predicted by the new Canadian Farm Building Code (NRC 1990) are shown for comparison. It is evident that the CFBC recommended pressures are quite safe for silos constructed in steel ($\mu K = 0.183$) and concrete ($\mu K = 0.187$). However, the design code underestimates the horizontal loading on the walls of a PVC silo ($\mu K = 0.112$) below a depth of about 13 m. Assuming a constant K , the lateral pressures attenuate as μ or the roughness of the wall increases.

The effect of moisture content on silo wall pressures is shown in Fig. 5. As can be expected, the magnitude of horizontal pressure increases with an increase in moisture content. Evidently the Canadian Farm Building Code gives a conservative estimate of the lateral wall pressures over the entire height of the silo. The new code takes into account the compressibility of the silage material and the moisture variation of the ensiled crop, and those are significant improvements on the previous version. However, the new code requires data on average bulk densities of silage as a function of moisture content and silo diameter. Therefore, average bulk density values for barley silage were calculated from the silo capacity data in Table II. The results are pre-

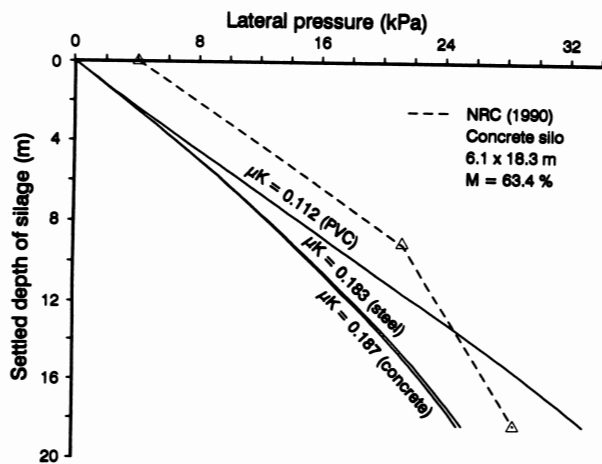


Fig. 4. Effect of wall material on lateral pressures in tower silos.

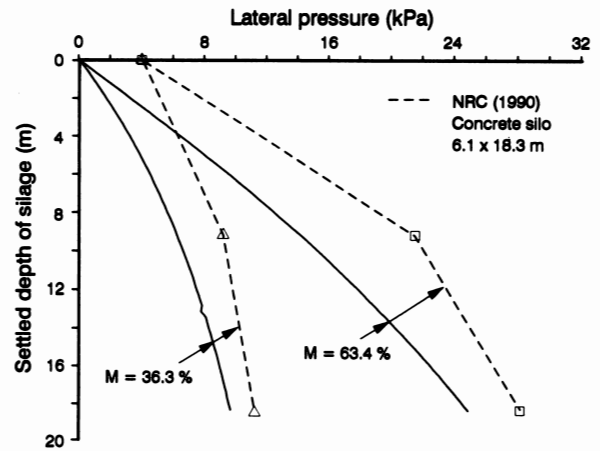


Fig. 5. Effect of moisture content on lateral pressures in tower silos.

sented in Table III for crop moisture contents of 40, 50 and 60%, and silo diameters of 3.7, 4.3, 4.9, 5.5, 6.1, 7.3 and 9.1 m. These values can now be incorporated in the Canadian Farm Building Code beside similar data on alfalfa haylage and corn silage.

CONCLUSIONS

The density model indicates that for a given vertical pressure the resulting density of barley silage is below alfalfa and above corn silage. Thus it follows that barley is less compressible than alfalfa but more compressible than corn, and the dry matter capacity of a silo for "barlage" is less than for alfalfa and more than for corn silage. The estimated capacities for barley silage in concrete and steel tower silos are reported at moisture contents of 40, 50 and 60%.

The indirect friction test results indicate that the product of the coefficient of friction between silage and silo wall, and the pressure ratio is strongly influenced by the moisture content of barlage. The values of the product are smaller for the higher moisture material.

Lateral pressures increase with an increase in the wetness of the ensiled crop and a decrease in the roughness of the silo wall. Wall pressures based on measurements in model silos compared favourably with the predictions of the new Canadian Farm Building Code. The average values of bulk density for barley silage are provided over a range of silage moisture contents and silo diameters. This is one of the parameters required in the new code for the calculation of silo wall pressures.

ACKNOWLEDGEMENT

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Table II: Estimated tower silo capacities for barley silage

Silo size (m)	Capacity (t)		
	Moisture content (%)		
	40	50	60
3.7 x 9.1	30.1	33.4	38.0
3.7 x 12.2	42.5	46.7	52.6
3.7 x 15.2	55.2	60.3	67.5
4.3 x 12.2	60.8	65.8	73.1
4.3 x 15.2	79.8	85.7	94.3
4.3 x 16.8	89.5	95.8	105.1
4.9 x 15.2	109.6	116.0	125.9
4.9 x 18.3	137.3	144.2	155.2
4.9 x 19.8	151.4	158.6	170.0
5.5 x 15.2	144.7	151.2	162.1
5.5 x 18.3	182.5	188.9	200.4
5.5 x 21.3	221.3	227.4	239.4
6.1 x 18.3	234.7	239.9	251.6
6.1 x 21.3	285.9	289.8	301.1
6.1 x 24.4	338.1	340.5	351.2
7.3 x 18.3	360.5	361.1	371.8
7.3 x 21.3	438.2	441.9	446.2
7.3 x 24.4	517.0	521.7	525.5
7.3 x 27.4	596.9	598.1	610.6
9.1 x 24.4	841.1	852.1	886.2
9.1 x 27.4	966.0	986.7	1033.4
9.1 x 30.5	1092.0	1123.0	1182.8
9.1 x 33.5	1218.9	1260.5	1333.8

Table III: Average bulk density of barley silage in tower silos

Silo diameter (m)	Average bulk density (kg/m ³)		
	Moisture content (%)		
	40	50	60
3.7	320	350	400
4.3	360	390	420
4.9	400	420	450
5.5	420	440	460
6.1	460	470	480
7.3	490	500	510
9.1	550	560	590

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