PHYSICAL PROPERTIES OF ENSILED GRASS AND CORN, SILO CAPACITIES AND SILAGE PRESSURES IN CYLINDRICAL TOWER SILOS

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ABSTRACT

Forage ensiled in tower silos is compressed solely by its own weight. The relationship between silage density, pressure, and time, as well as seepage losses, were studied in the laboratory. This included consolidation tests and friction coefficient measurements.

The dry density could be expressed as function of pressure and time:

$$\rho_t = A_t + B_t\ (\log p)^2$$

where $A_t = a_1 + a_2 \log t$ and $B_t = a_3 + a_4 \log t$

ρ_t = dry density in kg dm/m^3 after t hours, p = vertical pressure in kN/m^2

a_1, a_2, a_3 and a_4 are coefficients related to the forage.

The coefficients a_1 to a_4 depend on the kind of material, and for grass they vary with chop length and stage of maturity.

The wall material is the most important parameter for the friction coefficients.

Seepage commenced at theoretical gasvolumes between 10 and 15%.

Capacities and pressures in silage tower silos were calculated using Janssen's theory as modified by Wood for varying density and the behaviour of silage at effective saturation.

Silage characteristics were obtained for grass and whole-plant corn. The results were compared with settled depths measured in 10 silos filled with grass and 6 silos filled with corn. Pressure measurements were made once for grass and once for corn. The agreement between calculations and measurements was reasonable.

For Dutch circumstances directives for standard capacities of steel tower silos with D = 7 m diameter are:

for grass $\rho_{av} = 195 + 5.85\ h_s$ kg/m^3

valid for 50% dm and av. maturity (crude fibre 22-28%)

for corn $\rho_{av} = 178 + 4.76\ h_s\ kg/m^3$

valid for 30% dm

where ρ_{av} = average dry density in kg/m^3

valid for h_s = settled height in m between 9.30 and 21.30.

Corrections are given for changes in dry matter-content, maturity of the material, D, and wall roughness.

INTRODUCTION

This report deals with a few agricultural and structural aspects of storing silage in tower silos. The user of a silo is interested in a certain capacity. He has to be able to store a sufficient quantity of silage, expressed in tons of dry matter, to feed his herd during a given time period.
Based upon this information a silo of the required capacity must be designed such that it can safely withstand the forces exerted by wind and silage (lateral pressures and frictional forces).
There are data available on both aspects such as ASAE Data compiled by Aldrich (1963) and standards such as NSA Design Standards for Concrete Stave Silos (1974), Canadian Farm Building Code (1975), British Standard 5061 (1974), and the German Standard DIN 1055 Blatt 6 (1964). However, these data and standards present such widely varying values that is was considered necessary to start our own research program to find better answers for Dutch circumstances.
In 1973 and 1974 a few consolidation tests were made on whole-plant corn silage with a consolidation machine described by and made available to us by Wood (1971). To conduct these investigations on a larger scale we found the method used by Daynard et al. (1974, 1978) more suitable.
In 1976 we installed a laboratory with 110 cylinders, which made it possible to do the tests on 22 samples at one time at five different pressure levels.
In 1978 an existing tower silo at our experimental dairy farm was instrumented with pressure measuring panels and a second bottom on four load cells.
This report describes:

a. pressure consolidation tests up to saturation on grass and corn (laboratory tests)
b. measuring friction coefficients between silage and various building materials for silos (laboratory tests)

c. measuring capacities and settled depths on full scale towersilos
d. measuring pressures in a full scale towersilo
e. comparison of results obtained under c and d with model predictions based on results obtained under a and b
f. calculation of standard silo capacities based on these results.

LABORATORY TESTS

Laboratory tests included consolidation tests and friction coefficient measurements (Figures 1 and 2). The basis of the consolidation study was that used by Wood (1971) and Daynard et al. (1974, 1978). A weighed quantity of forage was ensiled in polyethylene bags and placed in PVC cylinders (Ø 0.2 m, height 0.6 m). With steel levers and various steel weights different vertical pressures were exerted on top of the silage, ranging from 2 to 120 kN/m^2.
The volume was measured at 1, 3, 10 and 30 days after filling. The volume was also measured at the time the seepage flow started.
Consolidation tests were performed on grass in various stages of maturity and on chopped and unchopped material. The moisture content ranged between 30 and 65% (wet basis).
On whole-plant corn silage consolidation tests were made with moisture content ranging between 75 and 65%. To measure friction coefficients between forage and different wall surfaces small cylinders (Ø 0.1 m, height 0.3 m) were filled at the same time and with the same material as used in the consolidation tests. The samples were prepared at two pressure levels and measurements were made after time intervals ranging from 1 to 30 days. We also measured the friction coefficient of forage on a polyethylene sheet moving over a PVC surface, similar to the conditions in the consolidation cylinder. The average vertical pressure during the consolidation tests was computed taking into account the weight of each sample and the estimated frictional forces on the cylinder wall. The ratio of lateral to vertical pressure ($k = \frac{h}{p}$) was assumed to be 0.5 for grass and 0.33 for corn.
The friction coefficient in the cylinders was estimated at 0.29 based upon the friction tests.

RESULTS

The relationship between pressure, time, and dry density could be expressed as: $\rho_t = A_t + B_t\ (\log p)^2$

where $A_t = a_1 + a_2 \log t$

$B_t = a_3 + a_4 \log t$

ρ_t = dry density (kg dm/m^3) after t hours

p = vertical pressure (kN/m^2)

a_1, a_2, a_3, a_4 = coefficients related to the kind of silage.

Table 1 shows coefficients for chopped and unchopped grass. The chop length was set at 12 mm. The coefficients a_1 and a_3 for chopped grass are higher and coefficients a_2 and a_4 are lower than those for unchopped material. This means that dry densities are initially the highest in ensiled chopped grass, but these differences decrease with time. The stage of maturity, indicated by the crude fibre content, greatly influences the density. Coefficients for different fibre contents are given in Table 2. Young and leafy grass has about 1.5 times the density of mature material. This large difference is not reduced by time and hardly by pressure.
The moisture content also influences the coefficients. As long as the saturation point is not reached this influence is very small for unchopped grass. For chopped grass a_1 and a_3 are lower and a_2 and a_4 are higher at high moisture content. This means that differences in dry density caused by moisture content decrease with time.
The average coefficients a_1 to a_4 of whole-plant corn, determined over a 3 year period, were 120.5, 1.25, 32.1 and 7.29 respectively. The average moisture content of these samples was 68.4% and average crude fibre 22.4%.
Generally speaking corn is less compressible than grass.

Comparison with results of others

Wood (1971) reported only on consolidation tests on grass, Daynard et al. (1974, 1978) only on corn. Their density-pressure-time relationships are given below.

Wood (1971): grass silage

Dry density $\rho_{dry} = 23 \log (E + FV \times 10^{-3}) + C_d \log T$ in lb/ft^3

V = vertical pressure in lb/ft^2

T = time in hours

E = 1.8

F = 6.5 for young leafy grass (crude protein 20%)

F = 3.7 for average maturity grass (crude protein 12%)

F = 1.8 for mature grass (crude protein 8%)

$C_d = V \times 10^{-3}$ for $0 < V < 500$

$C_d = 0.375 + 0.25\, V \times 10^{-3}$ $500 < V < 2500$

$C_d = 1$ $2500 < V < 5000$

Daynard (1978): whole-plant corn silage

$$\rho_{wet} = -1.86 + 6.20\, M \times 10^{-2} - 4.09\, M^2 \times 10^{-4} - 3.93\, T^2 \times 10^{-5} + 3.92\, \bar{P} \times 10^{-4} - 3.47\, \bar{P}^2 \times 10^{-7} + 4.34\, MT \times 10^{-5} + 8.60\, M\bar{P} \times 10^{-6} + 1.81\, T\bar{P} \times 10^{-6}$$

Wet density ρ_{wet} in g/cm^3

M = moisture content in %

$\bar{P}$ = mean vertical pressure in gf/cm^2

T = time in days.

To determine standard silo capacities we used the densities after 30 days, given below.

Dry density $\rho_t = A_t + B_t (\log p)^2$ in kg/m^3

t = time in hours

p = vertical pressure in kN/m^2

grass silage: $A_{720} = 150.8$, $B_{720} = 85.3$ for average maturity (crude fibre 22-28%)

$A_{720} = 169.7$, $B_{720} = 90.6$ for young leafy grass (crude fibre <22%)

$A_{720} = 117.0$, $B_{720} = 76.5$ for mature grass (crude fibre >28%)

corn silage: $A_{720} = 120.0$, $B_{720} = 61.0$

Figures 3 and 4 show the comparison of our results with those of Wood and Daynard respectively. We found better compressibility for grass under our circumstances than Wood.

For corn with 30% dm our results and Daynard's agreed closely.

Friction coefficients

The most important parameter for the friction coefficient was the roughness of the wall material. The friction coefficient for forage on a rough concrete surface was about 40% higher than on a steel surface. The friction coefficient for grass on a steel surface after about one week at a pressure of 65 kN/m^2 was 0.5. When the pressure was reduced to 20 kN/m^2 the friction coefficient was about 20% higher.The friction coefficient decreased with time. After 4 weeks it was 15% lower than after one week. The friction coefficients for corn were about 10% higher than for grass.
The friction coefficient for forage on a polyethylene sheet moving over a PVC surface was 0.29 and was not significantly influenced by time and pressure.

Seepage

There is a maximum theoretical density for silage, corresponding to zero porosity (no entrapped gas). Effective saturation occurs in silage at a certain remaining gasvolume. At this effective saturation the fluid pressure starts to rise and the rate of increase of the dry density is controlled by the rate of effluent drainage.
The dry density at effective saturation can be expressed as:

$$\rho_{sat} = \frac{dm\ \%}{100} \times \frac{(1 - \frac{n}{100}) \cdot \rho_s \cdot \rho_w}{\rho_w \times \frac{dm\ \%}{100} + \rho_s \times (1 - \frac{dm\ \%}{100})}\ \text{kg dm/m}^3$$

dm % = dry matter content (% wet basis)
ρ_s = density of completely dry matter at zero porosity in kg/m^3
ρ_w = density of water, can be assumed as 1000 kg/m^3
n = remaining gas volume, in % at effective saturation.

The weight of the gas is neglected.
This formula is derived from a formula given by Berge et al. (1974).
Literature values of ρ_s vary between 1500 and 1700 kg/m^3 (Berge et al. 1974, and Holdren et al. 1974).
Figure 5 gives ρ_{sat} as a function of dm % and different remaining gas volumes for ρ_s = 1600 kg/m^3.
For n = 10% remaining gas and moisture content M = 100-dm %, the wet saturation density can be given as

$\max \rho_{wet} = 1440\ (0.006\ M + 1)^{-1}\ kg/m^3$.

Effective saturation was reached at gas volumes generally between 10 and 15% for grass and at an average of about 20% for corn. For chopped grass the calculated gas volume tended to be a little lower than for unchopped grass.

MEASURING CAPACITIES AND SETTLED HEIGHTS IN TOWER SILOS

Up till now in this continuing study 16 silos were filled with weighed quantities of forage. Each silo was sampled to determine moisture content and consolidation characteristics of the forage. Settled depths were registered until at least 30 days after bringing in the last material.

Settled heights for 30 days or longer after bringing in the last material, were calculated using Janssen's (1895) theory as modified by Wood (1971), using a finite lamina method with varying densities. The ratio (k) of lateral to vertical pressure was assumed to be 0.5 for grass and 0.33 for corn. The friction coefficients (μ) were taken somewhat lower than the values obtained in the friction tests in the laboratory. During the pressure measurements in a tower silo these coefficients appeared to decrease with time and especially with wetness of material.

The filling with corn of each of the silos lasted between two days and one week, in accordance with normal farming practice. The filling with grass was extended over several months, with one exeption. The silo in which the pressure measurements were made was filled in two days to get better controlled conditions. Tables 3 and 4 give a comparison between registered an calculated settled heights for grass and corn respectively. The formulas used in these calculations are given in the appendix. For the majority of silos there is reasonable agreement between actual and calculated settled heights.

PRESSURE MEASUREMENT IN A FULL SCALE TOWER SILO

A glass lined steel silo (Ø 6.19 m, utilized height 15.50 m, see Figure 6), was provided with four pressure measuring panels on each of three different levels. The lateral pressure and the vertical friction could be measured, as well as the fluid pressures when the saturation density was exceeded. In Table 5 the fluid pressures are given in parentheses.

These panels were of the type developed by Hierlein (1977). Changes had to be made to:

a seal the gap between the measuring part and the surrounding silo wall

b control the horizontal displacement of the panels under load to keep the edge of the measuring part even with the silo wall.

The operating principle of these panels is indicated in Figure 7. The lateral pressure on the silo wall can be determined by the strain gages q while the strain gages p serve to measure wall friction.

The silo was provided with a second bottom on four load cells to register the total load on the floor. This made it possible to calculate the total frictional force on the wall. The silage effluent which drained through a narrow gap between the silo wall and the second bottom was led to a sump and measured.

The panels didn't function optimally during the first filling with grass and needed some improvements. As a result the second filling, with corn, yielded a greater number of satisfactory data. The results of the pressure measurements are given in Tables 6 and 7. The measurements indicated that the techniques used for determining silage properties were satisfactory, and that the theoretical model for calculating settled depths and pressures predicted the real behaviour of silage in the tower silo adequately.

Figures 8 and 9 show calculated and measured horizontal pressures after 30 days and a comparison with the values in the German Standard DIN 1055, where

$p_h = p_f + p_p$

p_h = total horizontal pressure

p_f = fibre pressure

p_p = pore pressure

Pressures for corn were also calculated for $k = 0.5$, starting with the calculation of the silage characteristics from the consolidation tests. The results are not given. The agreement between measurements and calculations, especially for the loads on the floor, was not as good as for $k = 0.33$.

STANDARD SILO CAPACITIES

Capacity charts with directives for Dutch circumstances were calculated based upon the results obtained until Spring 1977. The following heights are distinguished in the formulas:

h_c = cylindrical wall height in m;

h_u = maximum filling height in m before settlement = h_c - 1.50 m, 1.50 m is the height of the combined distributor-unloader or a correction for the cone when another distributor is used;

h_s = settled height (for grass after several refillings) = 0.90 h_u in m.

The silage characteristics used in the calculations are related to the densities after 30 days (see Table 7). For a steel tower silo Ø 7 m filled with grass of average maturity (crude fibre 22-28%) and 50% dm the average dry density for the practical range of h_s between 9.30 and 21.30 m is:

$\rho_{av} = 147 + 12.5\ h_s - 0.22\ h_s^2\ kg/m^3$.

For corn with 30% dm (wetter material should be avoided, especially in high silos)

$\rho_{av} = 145 + 9.22\ h_s - 0.15\ h_s^2$

Corrections to be made on ρ_{av}

	grass	corn
for 1 m larger D than 7 m	+ 10 kg/m^3	+ 5 kg/m^3
for 1 m smaller D than 7 m	- 10 kg/m^3	- 5 kg/m^3
for 10% higher dm-content	- 20 kg/m^3	
for 10% lower dm-content	+ 30 kg/m^3	
for 5% higher dm-content		- 15 kg/m^3
for rough concrete silo wall	- 5%	- 4%
for young and leafy grass	+ 13%	
for mature grass	- 23%	

In Table 9 and Figure 10 our directives are compared with those of ASAE D 252 (Aldrich) and British Standard BS 5061.

CONCLUDING REMARKS

It has been shown that capacities of tower silos and pressures exerted on the silo structure by the silage can be calculated with the results of laboratory consolidation tests, and a simple finite lamina method based on Janssen's theory with density varying with vertical pressure. The calculations give reasonable agreement with registered settled heights and measured loads on silo wall and floor.

The instrumented silo was filled again in 1979, first with grass and later with corn. The results are not yet available.

The final measurements will be made in 1980 with grass, starting in the spring with the first cut and adding material mowed later on till about September, in the same way as grass silos are filled in practice.

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Table 1 Coefficients a_1 to a_4 for chopped and unchopped grass, and calculated dry densities in kg/m^3, after 10 h, 100 h and 1000 h at 10 kN/m^2. Average of 5 experiments. Average moisture content 54.7%, average crude fibre 24.5%.

	Chopped	Unchopped	Average
a_1	114.7	93.2	103.9
a_2	8.9	13.8	11.3
a_3	50.2	35.5	42.9
a_4	13.8	17.9	15.8
10 h	187.6	160.4	173.9
100 h	210.3	192.1	201.0
1000 h	233.0	223.8	228.1

Table 2 Coefficients a_1 to a_4 for fibre contents of 21.1, 24.4, and 29.3%. Average for chopped and unchopped grass. Calculated dry densities in kg/m^3 after 10 h, 100 h, and 1000 h at 10 kN/m^2.

	Crude fibre content (%)		
	21.1	24.4	29.3
a_1	117.5	92.5	81.3
a_2	21.0	8.6	10.0
a_3	45.6	37.7	32.8
a_4	17.4	17.4	14.6
10 h	201.5	156.2	138.7
100 h	239.9	182.2	163.3
1000 h	278.3	208.2	187.9

Table 3 Comparison of actual and calculated settled heights in silos filled with grass (k = 0.50).

Silo	Year	Dry matter %	Dry matter t	Assumed wall-friction μ	Settled height in m: time after bringing in last material	Settled height in m: actual	Settled height in m: theor.
Ø 6.70 m	1976	60.3	73.2	0.55	30 days	8.00	8.60
concrete staves	1977	57.5	220.9	0.55	60 days	18.70	20.30
	1978	60.2	115.7	0.55	30 days	11.75	12.35
Ø 6.19 m	1976	51.2	118.2	0.40	100 days	14.50	13.65
steel	1977	51.8	140.7	0.40	30 days	13.90	14.30
	1978[1)]	39.6	122.4	0.20	30 days	10.40	10.70
Ø 7.20 m	1976	54.3	194.6	0.40	30 days	15.25	15.00
steel	1977	51.9	213.6	0.40	50 days	15.25	15.35
	1977	57.4	156.4	0.40	50 days	13.50	14.80
	1978	54.8	210.6	0.40	50 days	15.35	15.70

1) extra load on top of the last material 9 kN/ m^2, during this filling pressure measurements took place.

Table 4 Comparison of actual and calculated settled heights in silos filled with corn (k = 0.33).

Silo	Year	Dry matter %	Dry matter t	Assumed wall-friction μ	Settled height in m: time after bringing in last material	Settled height in m: actual	Settled height in m: theor.[1)]
Ø 6.70 m	1973	32.1	190	0.65	30 days	20.15	20.70
concrete staves	1974	26.3	183	0.65-0.55	30 days	19.60	21.40 (18.60)
	1975	35.2	209	0.65	10 days	21.90	23.90
steel							
Ø 8.03 m	1976	32.0	141	0.40	30 days	10.15	11.70
Ø 8.00 m	1977	28.3	192	0.40-0.25	30 days	14.10	15.55 (14.20)
Ø 6.19 m	1978[2)]	34.6	69.5	0.40	30 days	10.95	11.55

1) the parentheses indicate that the content of the silo was partly saturated. Two figures give settled heights for undrained and 100% drained, respectively.
2) during this filling pressure measurements were made.

Table 5 Comparison of theoretical and measured settled heights, loads on floor, and lateral pressures in a Ø 6.10 m silo filled with 309 t grass with 39.6% dm, chop length 8 mm, plus surface load of 27 t.
$k = 0.50$, $\mu = 0.20$
h = height of pressure measuring panels in m above silo floor.

Time after filling in days	Settled height in m		Load on floor in kN		Lateral pressure in kN/m^2 [1]					
					h = 7.125 m		h = 4.535 m		h = 1.94 m	
	theor.	meas.	theor.	meas.	theor.	meas. [3]	theor.	meas. [2]	theor.	meas. [3]
7	11.15	10.07	2430	2440	17.1	12.8	26.5	18.0	41.7	46.4
								(2.7)	(11.7)	(23.2)
14	10.92	10.63	2500	2560	16.8	13.4	27.5	16.8	47.1	50.8
							(1.7)	(3.0)	(21.2)	(22.3)
21	10.83	10.50	2535	2650	16.7	12.0	33.0	22.4	49.6	53.0
							(8.9)	(6.7)	(25.5)	(20.6)
30	10.70	10.40	2555	2710	16.5	12.0	30.2	29.9	50.9	51.4
							(6.8)	(14.4)	(27.5)	(20.4)

1) In addition to the total pressures the fluid pressures are given in parentheses.
2) Average of two satisfactory panels.
3) Average of three satisfactory panels.

Table 6 Comparison of theoretical and measured settled heights, loads on floor, and lateral pressures in a Ø 6.19 m silo filled with 201 t corn with 34.6% dm, chop length 8 mm.
$k = 0.33$, $\mu = 0.50$, after 30 days $\mu = 0.40$.
h = height of pressure measuring panel in m above silo floor.

Time after filling in days	Settled height in m		Load on floor in kN		Lateral pressure in kN/m^2					
					h = 7.125 m		h = 4.535 m		h = 1.940 m	
	theor.	meas.	theor.	meas.	theor.	meas.	theor.	meas.	theor.	meas.
7	12.10	11.40	1184	1190	5.93	6.85	8.88	10.08	11.51	11.15
14	11.95	11.20	1194	1240	5.79	5.60	8.83	11.28	11.55	11.53
21	11.85	11.00	1201	1260	5.69	5.05	8.79	9.20	11.58	12.03
30	11.55	10.95	1331	1240	5.63	5.18	9.18	8.63	12.55	11.83

Table 7 Silage characteristics assumed for calculations of standard capacity.

	Grass k = 0.50			Corn
Maturity crude fibre	average 22-28%	young leafy <22%	mature >28%	k = 0.33
A_{720}	150.8	169.7	117.0	120.0
B_{720}	85.3	90.6	76.5	61.0
μ steel		0.50		0.55
μ rough concrete		0.67		0.75

Table 8 Comparison average dry density for entire depth in tower silos for capacity determination. Valid for settled height h_s between 9.30 and 21.30 m.

	Source	Silage	dm %	Formula for average dry density ρ_{av} in kg/m^3
A	Aldrich (1963)	grass and corn	30	$185 + 6.5\ h_s - 0.115\ h_s^2$ simplified: $210 + 3\ h_s$
B	BS 5061 (1974)	grass, av. maturity	40	$140 + 7.2\ h_s$
C	't Hart et al. (1979)	grass, av. maturity	50	$147 + 12.5\ h_s - 0.22\ h_s^2$ simplified: $195 + 5.85\ h_s$
D	't Hart et al. (1979)	corn	30	$145 + 9.22\ h_s - 0.15\ h_s^2$ simplified: $178 + 4.67\ h_s$

APPENDIX

Calculations for settled heights and pressures in silos are made in accordance with the following directions and formulas:

The assumption is made that at time t hours after the filling of the silo each layer in the silo has been subjected to its own constant vertical pressure during those t hours. In other words, the forces are assumed stationary. This assumption is not correct and will cause a certain error in the results. Comparing the results for the situation after 1 week, 2 weeks, 3 weeks and 30 days respectively (see Tables 5 and 6) it is clear that this error is acceptable.

1. The contents of the silo with diameter D (in m) is divided in horizontal layers, for example with a thickness of $z = 0.30$ m.

2. A layer with number i is subject to vertical pressure p_i (in kN/m^2) from the overlying silage, causing a downward force $P_i = 0.25\pi D^2 p_i$ (kN).

3. The weight of the silage in layer i is calculated from the dry density with the formula

   $$\rho_t = A_t + B_t (\log p_i)^2 \quad (kg/m^3)$$

   A_t and B_t are consolidation characteristics for the particular silage at t hours after application of the load.

   Wet density = $100\, \rho_t\, (dm\ \%)^{-1}$ (kg/m^3)

   Downwards acting weight

   $W_i = 0.025\, \pi D^2\, z\rho_t g\, (dm\ \%)^{-1}$ (kN)

   g = gravity acceleration (m/s^2)

   Calculations are started with the top layer. Although the pressure on the top layer is zero, its density is assumed to be that for a pressure of 1 kN/m^2.

4. The horizontal pressure in the silage is $h_i = kp_i$ (kN/m^2)

   for grass k = 0.5

   for corn k = 0.33.

5. On layer i is acting an upward frictional force (lift)
$L_i = \mu\, k\, p_i\, \pi\, Dz$ (kN)

6. The underlying layer j exerts on layer i an upward pressure p_j (in kN/m^2) resulting in an upward force $P_j = 0.25\pi D^2 p_j$ (kN)

7. The pressure p_j can be calculated from the equilibrium $P_i + W_i = P_j + L_i$

8. Repeat the preceeding steps for the next layer.

9. When $p_i = p_{sat}$ = vertical pressure giving saturation density, pore pressures p_p start to develop. In the layers with saturated silage the lateral fibre pressure remains constant at $p_f = k\, p_{sat}$.
The upward frictional force $L_i = \mu\, k\, p_{sat}\, \pi\, D\, z$ (kN)
(Fluid pressures on the wall cause no friction)
The weight of the layer
$W_i = 0.025\pi D^2 z\, \rho_{sat}\, g\, (dm\, \%)^{-1}$ (kN)
The pressure at the bottom of the layer is
$p_j = p_{sat} + p_p$ (kN/m^2)
From the equilibrium can be derived

$$p_p = \frac{W_i - L_i}{0.25\, \pi\, D^2} \quad (kN/m^2)$$

The total lateral pressure at the bottom of layer i is

$$p_h = p_f + p_p = k\, p_{sat} + p_p \quad (kN/m^2)$$

Below the saturation level the contents of the silo, the pore pressure as well as the total lateral pressure are increasing linearly with the depth below the saturation level (see Fig. 8).

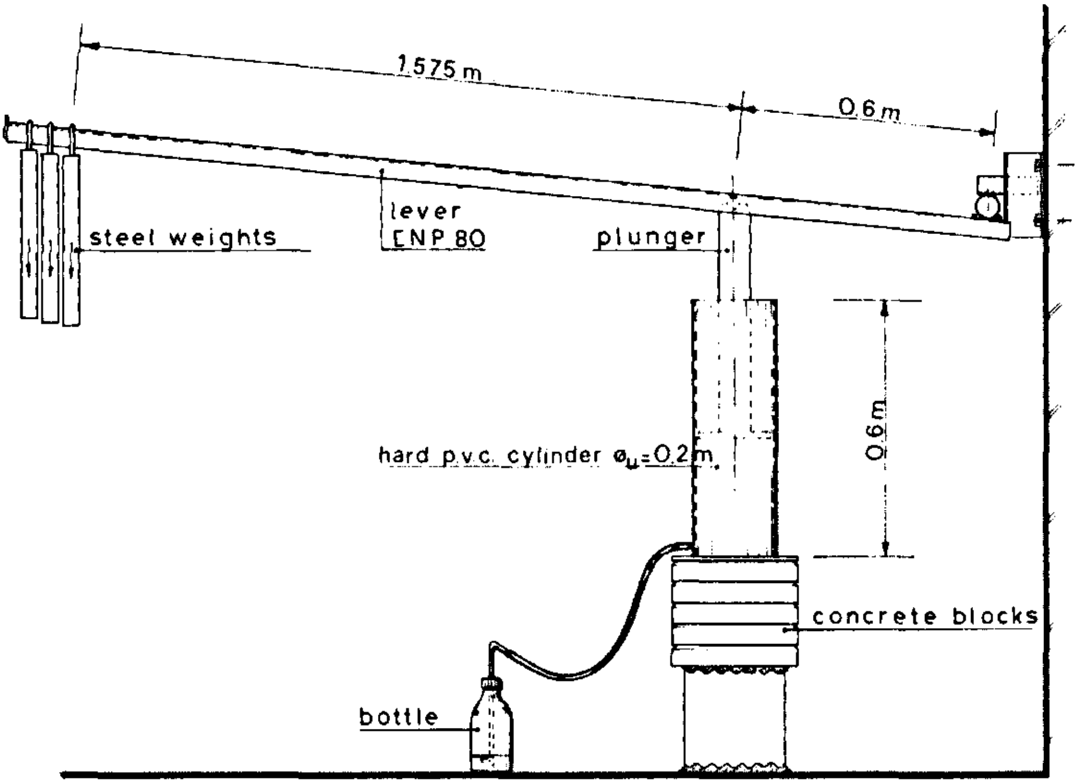


Figure 1 Consolidation of silage sample in cylinder.

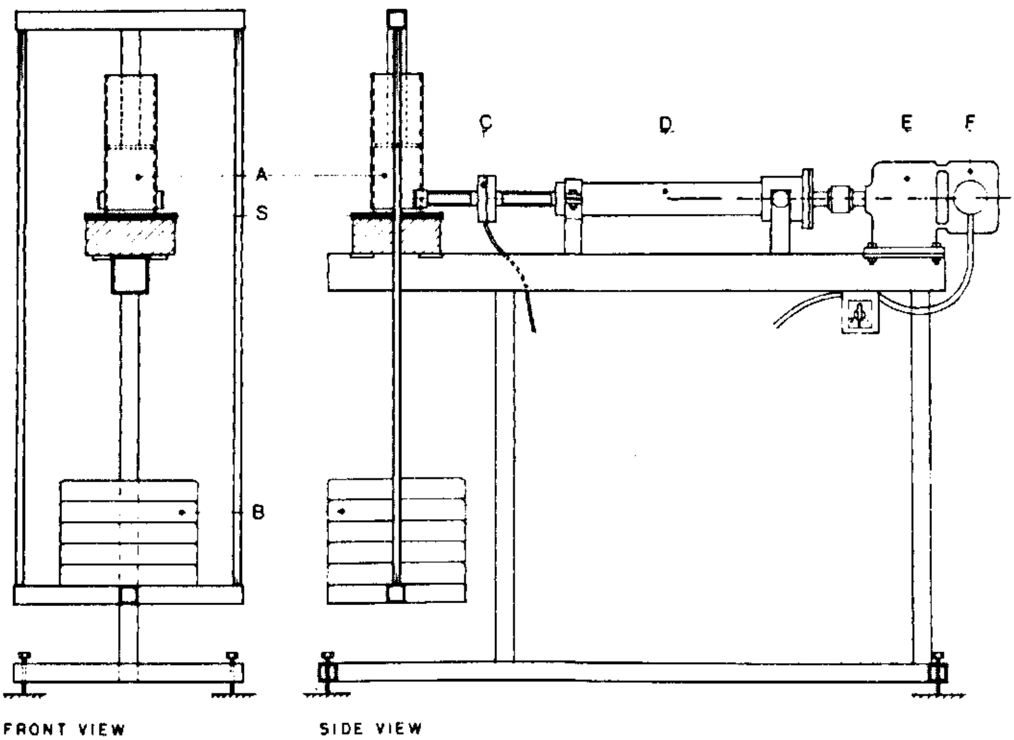


Figure 2 Friction measurement equipment.

A = silage sample in cylinder
B = concrete blocks
C = force transducer
D = linear movement 0.006 m/s
E = gearbox
F = electromotor
S = surface of silo building material

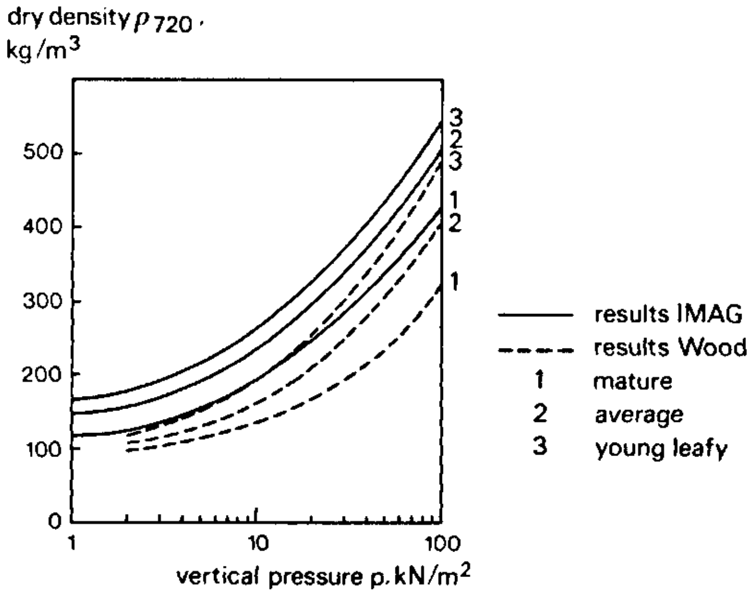


Figure 3 Comparison of grass silage densities.

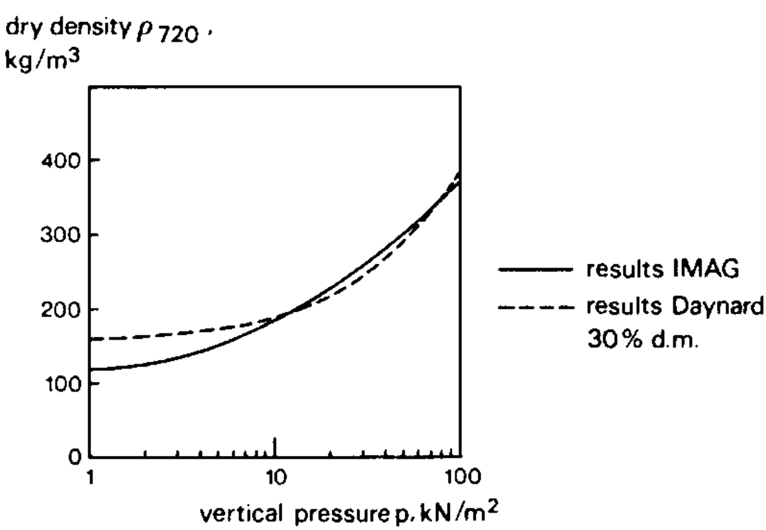


Figure 4 Comparison of corn silage densities.

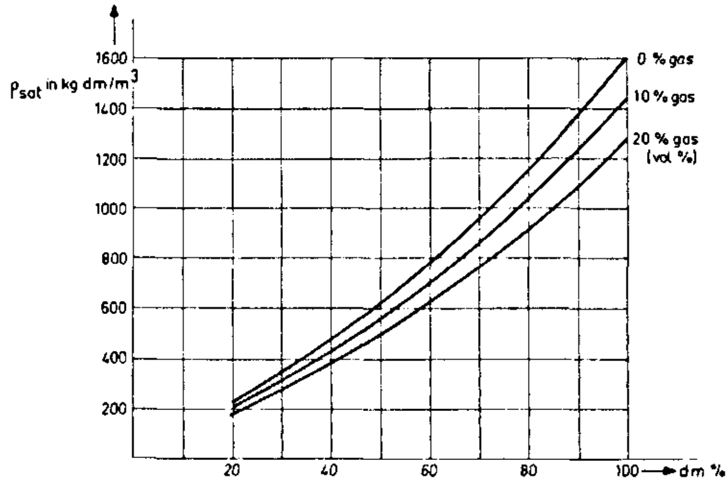
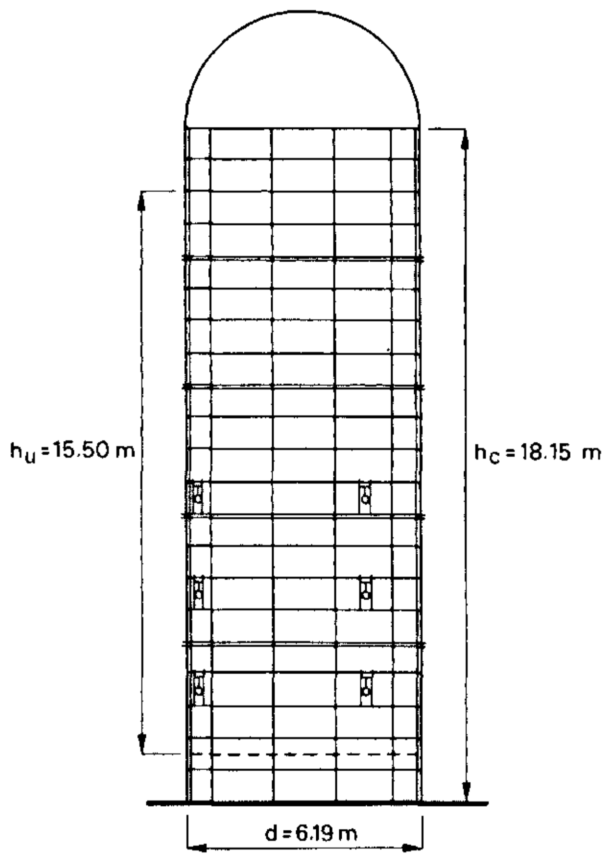


Figure 5 Dry density at effective saturation versus dry matter content, for ρ_s = 1600 kg/m^3.

Figure 6 Tower silo with location of pressure measuring panels.



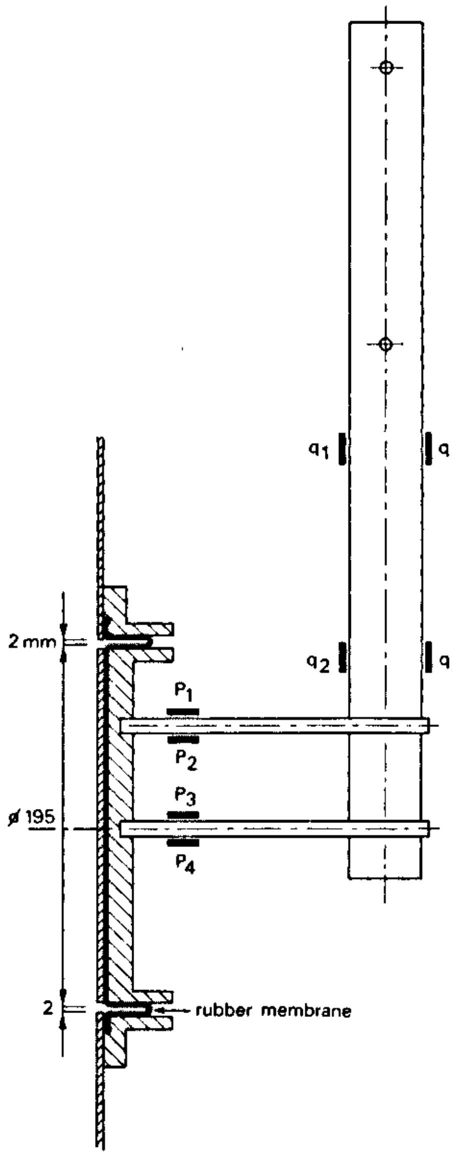


Figure 7 Operating principle of pressure measuring panel.

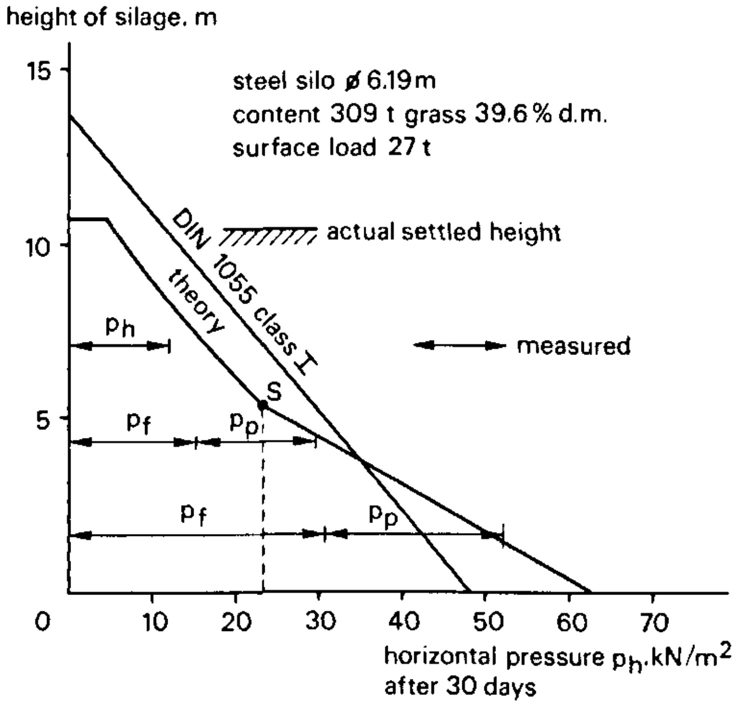


Figure 8   Results of pressure measurements for grass silage.

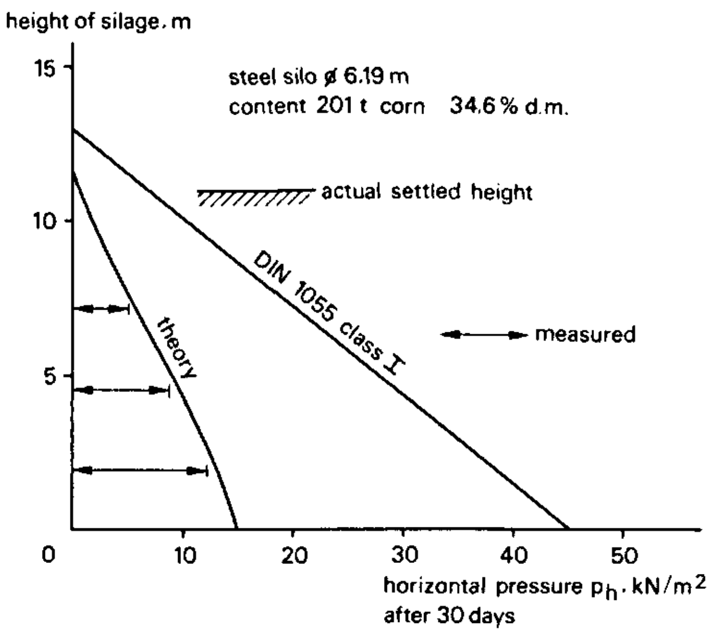


Figure 9   Results of pressure measurements for corn silage.

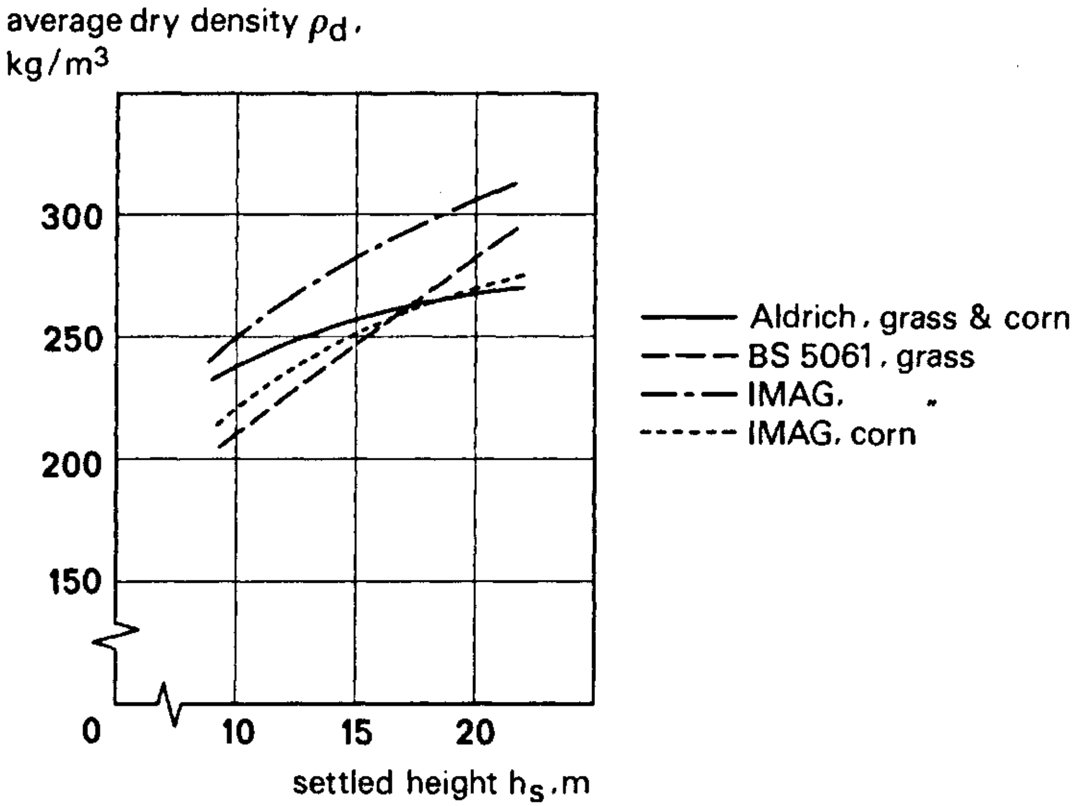


Figure 10 Comparison of average dry densities in tower silos given by different sources.