Juice flow from silages

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Tang, J., Jofriet, J. C. and LeLievre, B. 1988. **Juice flow from silages**. Can. Agric. Eng. **30**: 99–106. Ensiling whole-plant material with moisture contents over 65% in tower silos leads to saturation of the silage in the bottom portion of the silo. This results in an outflow of silage juice, loss of nutrients and, for sealed silos, high lateral wall pressures. It is necessary to be able to predict the seepage losses from the saturated zone in tower silos. This requires a better understanding of the effluent-producing process. The hypothesis that the amount of juice pressed from the silage after saturation is a linear function of the volume change was used to derive a linear relationship between the volume of juice expressed per unit of silage mass and the natural logarithm of the ratio of the dry matter density of the silage to the dry matter density at apparent saturation. The factor of proportionality is a material constant, k. Twenty-one isotropic triaxial consolidation tests were carried out to measure the volume of juice expressed at various densities of alfalfa and whole-plant corn silages. Fifty-six other consolidation tests carried out by Nilsson in Sweden provided similar information for grass, whole-plant corn and beet pulp silages. The results of these tests were used to find values for the constant k. It was found to range from 0.435 to 0.576 m^3/t.

INTRODUCTION

Ensiling is a process for conserving animal feed by controlled fermentation. The advantage of this method over other conservation methods is that it is less dependent on the weather and the need to harvest crops at an advanced stage of growth.

Difficulties are encountered, however, in the silage-making process when the moisture content of the silage is greater than 65% (wet basis). When compacted, such wet crops lose moisture, which drains out of the silo as effluent. This effluent is corrosive to both steel and concrete, and on exposure to air, develops a highly disagreeable odor. The expelled juice contains readily digested soluble proteins and minerals, resulting in loss of nutrients. Seepage losses in making silages have long been a subject of investigation. Many projects have been carried out measuring seepage loss from full-scale silos. The first attempt was carried out in 1914 by Shaw et al. (1921). Various researchers found experimentally that seepage losses in small tower silos varied from 2.2 to 18% by weight of the ensiled material (Anonymous 1941). McDonald (1981) concluded from previous research results that the weight loss due to seepage flow rarely exceeded 3% of fresh weight for silage ensiled at 70% moisture content and that the volume of effluent produced from a silo is affected mainly by the moisture content of the ensiled crop. Various researchers developed effluent prediction equations from full-scale tests. McDonald (1981) summarized these and discussed their merit.

The available prediction equations relate volume of effluent only to the moisture content of the silage. It is logical, however, that the type and dimensions of the silo and the type of ensiled material also have a significant effect on seepage losses, but little has been published on this.

The work described in this paper is part of a larger research project that has the objective to provide a simulation tool for predicting hydraulic pressures in, and juice flow from farm tower silos. The objective of the research project described in this paper is to seek a basic relationship that characterizes the effluent-producing process. This basic relationship will aid in the understanding of the process and allow the prediction of seepage losses from wet silage with a simulation model based on real behaviour.

MECHANISM OF EFFLUENT PRODUCTION

Silage behaves like a visco-elastic material. It can be represented by an analog model consisting of masses, springs, voids and liquid (see Fig. 1). Three solid masses (M_{s1}, M_{s2}, M_{s3}) and the springs (E_1 and E_2) make up the structure of the silage. Springs E_1 and E_2 model the elasticity of silage material. Their displacements are time-dependent and exhibit a strain-hardening type of behavior. The visco-elastic properties represented by E_1 and E_2 depend upon the type of silage material. The deformational behavior of the silage under load are governed by these properties.

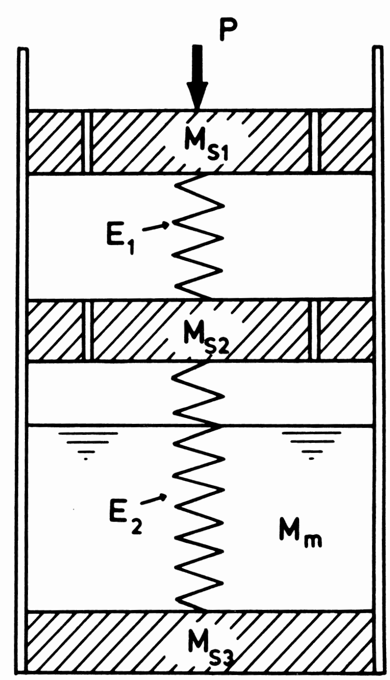

Figure 1. Mass/spring/void/liquid model of a body of silage.

The voids in the silage can be divided into two categories, macro-voids and micro-voids. The macro-voids are those between the particles of the chopped plant material which is represented in Fig. 1 by the space between masses M_{s1} and M_{s2}. Micro-voids are those created by the cellular structure of the plant material. The moisture is contained mainly in these micro-voids. The space between masses M_{s2} and M_{s3} in Fig. 1, representing the micro-voids, thus contains the moisture in the silage, M_m.

Under load, both the macro-voids and micro-voids are reduced in size and the dry matter density increases accordingly. At a particular point the micro-voids become too small to contain the liquid. Consequently, some of the liquid starts to be expelled from the micro-voids as free juice. This state is termed ''apparent saturation''. If further consolidation of silage takes place, more juice is forced from the micro-voids into the macro-voids and out of the silage. This expelled juice seeps through the silage, in most cases, and drains out of the silo, causing nutrient losses and environmental problems.

A criterion was proposed by Tang et al. (1988) to predict the occurrence of ''apparent saturation'' with the expression:

$$\rho_{ds} = 961 - 9.92\,M \tag{1}$$

where ρ_{ds} is the dry matter density at apparent saturation in kg/m^3 and M is the moisture content in percent. Equation 1 was based on experimental results for alfalfa and whole-plant (WP) corn silage in Canada, as well as Swedish test data for grass, WP corn silage and beet pulp. Thus it can be used to predict ''apparent saturation'' for a wide variety of silage materials.

After apparent saturation has been reached, juice is expelled. The amount of juice pressed from the silage depends upon the volume change of the silage material; therefore, it is reasonable to assume that the volume of juice pressed from a unit mass of silage is proportional to the volumetric strain. That is:

$$\frac{v_j}{M_0} = k.\epsilon_v \tag{2}$$

where v_j = volume of expressed juice, M_0 = total mass of the silage, ϵ_v = volumetric strain of silage under load, and k = a material constant.

Due to the large displacement involved in silage consolidation, strain increments have to be expressed in terms of the current state. Consequently, if compressive strains are considered positive, the increment of volumetric strain is defined as:

$$d\epsilon_v = \frac{dv}{v} \tag{3}$$

Integrating on both sides of Eq. 3 and using the apparent saturation state of strain as the initial condition leads to:

$$\int_0^v d\epsilon_v = - \int_{v_s}^{v} \frac{dv}{v} \tag{4}$$

resulting in an expression for the volumetric strain at the onset of apparent saturation, ϵ_v:

$$\epsilon_v = \ln\left(\frac{v_s}{v}\right) \tag{5}$$

where v_s = volume of the silage at apparent saturation, and v = current volume of the silage.

Assuming that the dry matter loss is negligible, Eq. 5 can be rewritten as:

$$\epsilon_v = \ln\left(\frac{M_s/v}{M_s/v_s}\right) \tag{6}$$

where M_s is the mass of the dry matter.

Equation 6 can also be written as:

$$\epsilon_v = \ln(\rho_d/\rho_{ds}) \tag{7}$$

where $\rho_d = \dfrac{M_s}{v}$, the current dry matter density and

$\rho_{ds} = \dfrac{M_s}{v_s}$, the dry matter density at ''apparent saturation''.

Substitution of Eq. 7 into Eq. 2 yields:

$$\frac{v_j}{M_0} = k.\ln(\rho_d/\rho_{ds}) \quad \text{when } \rho_d > \rho_{ds} \tag{8}$$

Equation 8 indicates a linear relationship between the volume of juice expelled from the silage and the natural logarithm of the dry matter density of the silage.

TEST EQUIPMENT AND PROCEDURES

A triaxial test apparatus modified for testing highly compressible materials (LeLievre and Jofriet 1982a,b) was used for 21 isotropic consolidation tests. Both alfalfa and WP corn silage were tested. The material was consolidated by increasing the cell pressure from the minimum to the maximum value (see Tables I and II) in four or five steps. The change in sample volume, the onset of saturation and the volume of expelled juice were measured frequently. The initial moisture content and bulk density of 10 alfalfa test specimens are listed in Table I; Table II has similar information for 11 WP corn silage specimens. Both tables also indicate the duration of the tests.

The details of the experimental techniques and sample preparation are provided in LeLievre and Jofriet (1982b). Only a brief description of the most relevant features is presented here.

Specimens of 100-mm diameter by approximately 200-mm height were prepared in a 0.4-mm-thick rubber membrane on the base of the triaxial cell. The tops of the specimens were capped with a perforated plastic disk and the head space was connected with a small-diameter tube to a beaker so that the volume of the expelled juice could be measured. The volume change of the specimens was monitored by measuring the inflow of water into the triaxial cell.

The specimens were subjected to stepwise increasing cell pressures. All but the last increment were maintained for about 1 d. The last load was maintained for 3 or 4 d. In two cases the last load was maintained for more than 20 d. Measurements were taken 0.02, 0.10, 0.25, 0.5, 1.1, 1.6, 2.72, 3.5, 11 and 24 h after the application of each new load increment. Apparent saturation was noted when silage juice entered the perforations in the plastic cap on the specimen.

TEST RESULTS

All alfalfa tests are listed in Table I. In Fig. 2, measured juice volumes per unit of silage mass are plotted against the natural logarithm of dry matter density for a representative test (HIMC5). Juice started to appear at point A. Further consolidation of silage forces more juice out of the sample. Thus, a larger juice volume corresponds to a higher dry matter density

Table I. Parameters for alfalfa silage tests

Test no.	Moisture content (WB) (%)	Initial wet density (kg/m³)	Min. cell pressure (kPa)	Max. cell pressure (kPa)	Test duration (d)
VLMC2	60.4	465	13.79	289.6	14
VLMC3	60.3	430	13.79	275.6	29
VLMC4	60.0	474	13.79	275.6	28
LOMC1	70.5	601	13.79	206.8	7
LOMC2	70.5	558	13.79	206.8	7
LOMC3	69.9	551	13.79	206.8	6
LOMC4	70.0	534	13.79	206.8	7
HIMC2	79.3	709	13.79	151.7	6
HIMC3	79.8	733	13.79	151.7	7
HIMC5	81.6	785	13.79	151.7	6

Table II. Parameters for whole-plant corn silage tests

Test no.	Moisture content (WB) (%)	Initial wet density (kg/m³)	Min. cell pressure (kPa)	Max. cell pressure (kPa)	Test duration (d)
CHMC1	71.7	639	13.79	248.2	7
CHMC2	72.2	669	13.79	248.2	8
CHMC4	71.7	720	13.79	248.2	7
CMMC1	67.8	529	13.79	193.0	7
CMMC2	68.8	534	13.79	206.8	7
CMMC3	67.4	569	13.79	248.2	7
CMMC4	66.9	464	13.79	248.2	7
CLMC1	62.6	480	13.79	248.2	7
CLMC2	61.7	462	13.79	248.2	7
CLMC3	60.7	490	13.79	248.2	7
CLMC4	59.2	470	13.79	248.2	7

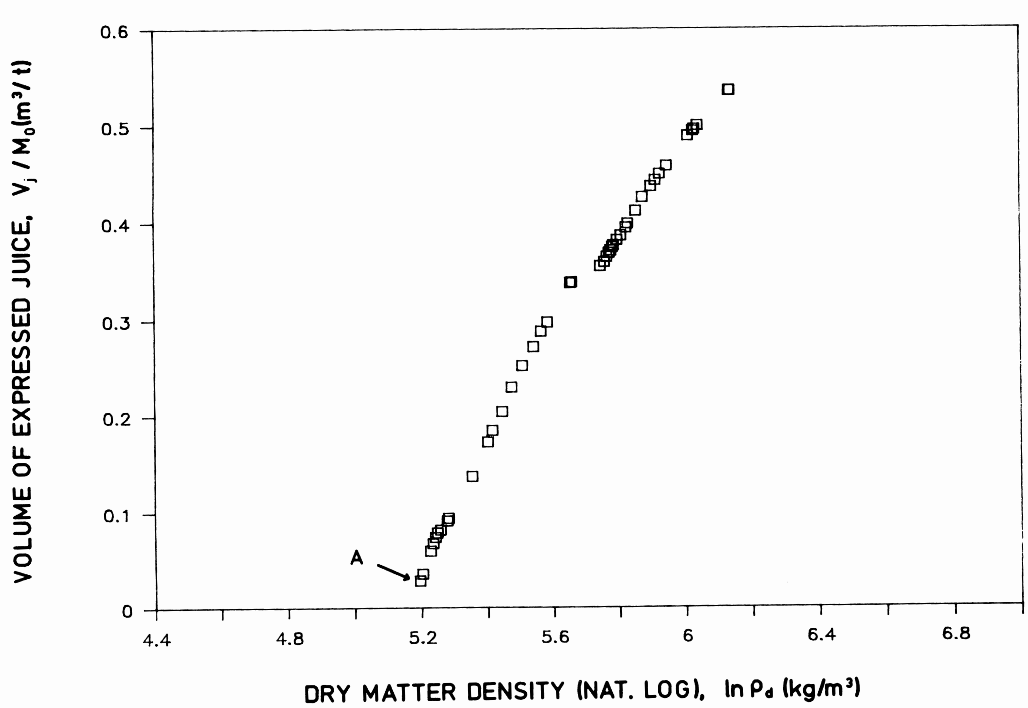

Figure 2. Volume of expelled juice per unit of silage mass versus the natural logarithm of dry matter density for 81.6% moisture content alfalfa silage (test HIMC5).

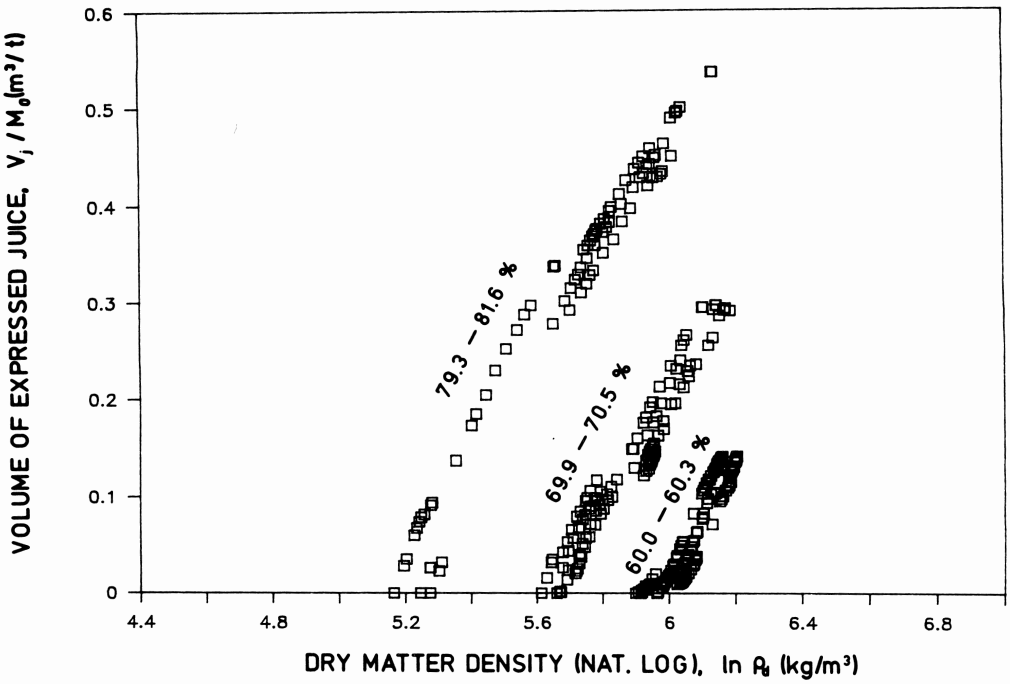

Figure 3. Volume of expelled juice per unit of silage mass versus the natural logarithm of dry matter density for 10 alfalfa silage tests.

of the silage. The plot indicates that a fairly linear relationship exists between volume of expelled juice and the natural logarithm of dry matter density. The intercept of this straight line with the abscissa indicates the dry matter density at the "apparent saturation" state ($\ln\rho_d = \ln\rho_{ds}$). The value of ρ_{ds} can be predicted with Eq. 1.

Figure 3 presents the test results of all 10 alfalfa tests. The experimental data for the alfalfa samples follow a trend similar to that of sample HIMC5. It is obvious from the diagram that the moisture content of the samples has a strong influence on the experimental results. Low moisture contents correspond to the grouping of points on the right of the diagram and high moisture contents to that on the left.

Similar results were obtained from the WP corn silage tests. Figure 4 shows the results of test CHMC2 which is a representative WP corn silage sample with a moisture content of 72.2%. Again, the plot indicates a fairly linear relationship between the volume of juice expelled from a unit mass of silage

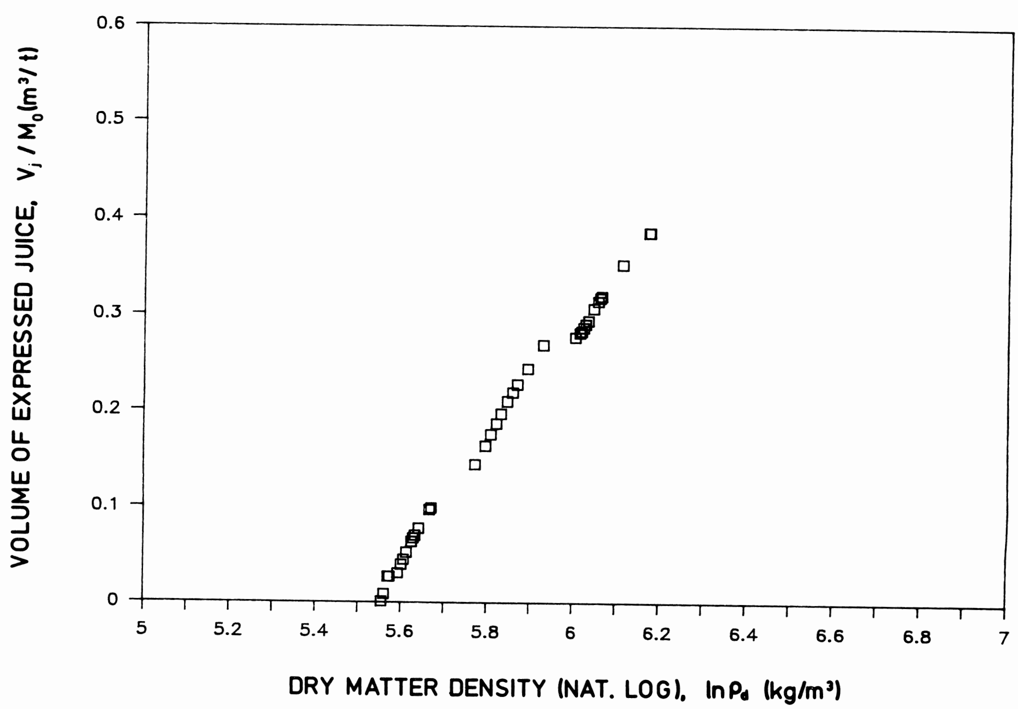

Figure 4. Volume of expelled juice per unit of silage mass versus the natural logarithm of dry matter density for 72.2% moisture content whole-plant corn silage (test CHMC2).

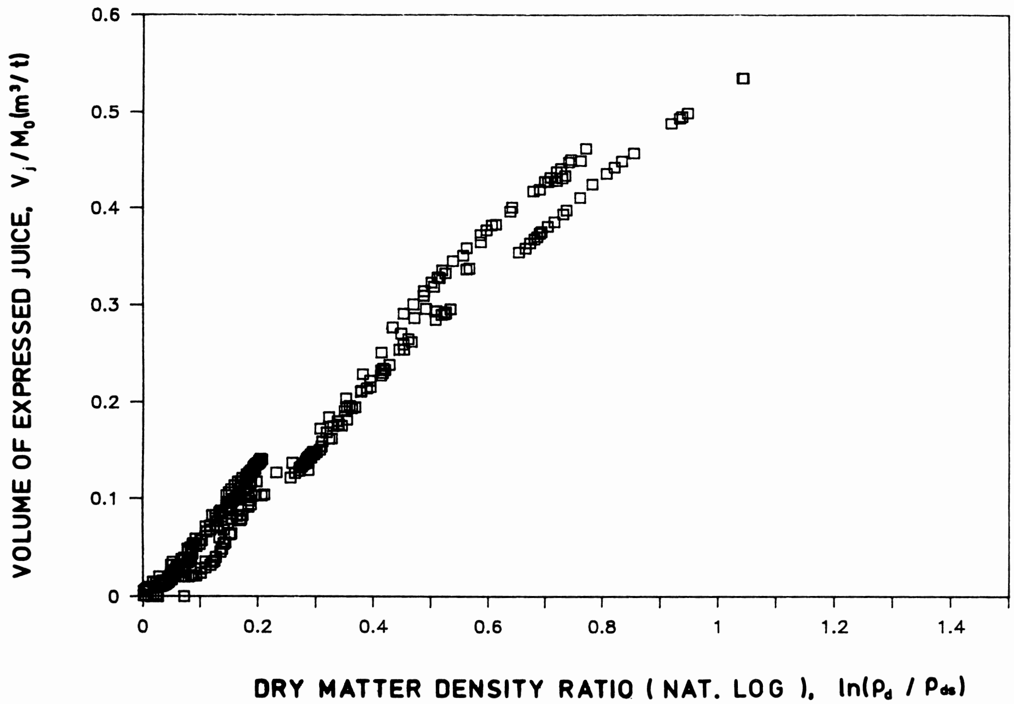

Figure 5. Volume of expelled juice per unit of silage mass versus the natural logarithm of the ratio of dry matter density to the dry matter density at apparent saturation for 10 alfalfa silage tests.

and the natural logarithm of dry matter density. The relationship is very similar to that for alfalfa silage of similar moisture content (Fig. 3).

Equation 8 would provide an excellent relationship for predicting the volume of juice expelled from a unit mass of silage. Therefore all experimental results were replotted versus the natural logarithm of the ratio of the dry matter density and the dry matter density at "apparent saturation", $\ln(\rho_d/\rho_{ds})$ (Figs. 5 and 6). In both cases the data can be fitted reasonably well with a straight line through the origin thus providing a value for the material parameter k in Eq. 8. Values of k, 0.569 and 0.550 m^3/t for alfalfa and WP silages, are listed in Table III, together with the R^2 and the standard error. The F-test shows that the values of k are significant at 0.1% confidence level.

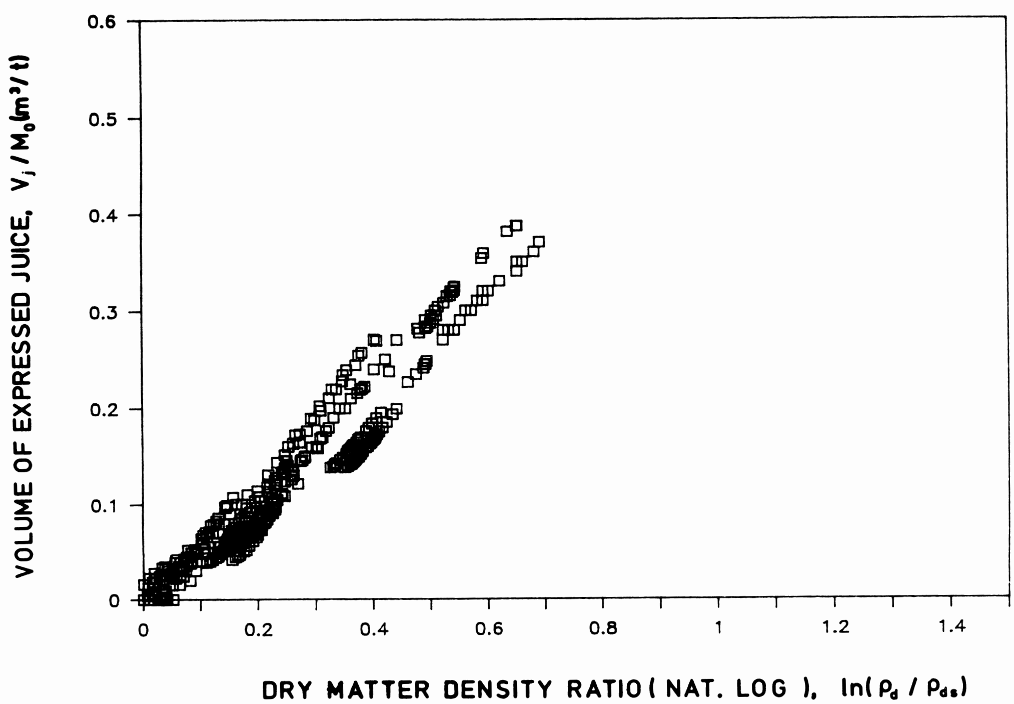

Figure 6. Volume of expelled juice per unit of silage mass versus the natural logarithm of the ratio of dry matter density to the dry matter density at apparent saturation for 11 whole-plant silage tests.

Table III. Material parameters for Eq. 8

Material parameter	Alfalfa	WP corn	Grass (Nilsson)	WP corn (Nilsson)	Beet pulp (Nilsson)
k (m³/t)	0.569	0.550	0.435	0.502	0.576
R^2	0.98	0.93	0.96	0.99	0.99
Standard error	0.0045	0.0076	0.0048	0.0089	0.0076
PR > F	0.0001	0.0001	0.0001	0.0001	0.0001

Equation 8 was also tested using data provided by Nilsson (1982) from tests on ensiled grass, WP corn and beet pulp, carried out in Sweden. The test procedure used by Nilsson differed greatly from the present triaxial tests. Silage materials were consolidated in rigid 188-mm-diameter model silos under constant vertical stress for periods ranging from 42 to 57 d. Juice was collected in bottles linked with plastic tubes to the bottom of the model silos. A detailed description of the test equipment and procedures is provided by Nilsson (1982). A summary of the specimens is in Table IV.

The plot in Fig. 7 presents Nilsson's test results for 42 individual consolidation tests of grass silage at six different moisture contents (Table IV). Linear relationships between the volume of the juice expelled per unit mass of silage and $\ln(\rho_d)$ are again obvious, in spite of the fact that Nilsson used a different test procedure than that used to obtain the present results. The test results for all moisture levels of grass silage by Nilsson were plotted in Fig. 8 versus $\ln(\rho_d/\rho_{ds})$ to obtain the value of the constant k in Eq. 8.

Figure 9 presents Nilsson's WP corn silage and beet pulp test results in the same manner. Again the slope of the straight line approximating the relationship between volume of juice expelled and $\ln(\rho_d/_{ds})$ provides values for the material constant k. They too have been included in Table III together with the value of R^2, the standard error, and the confidence level determined with the F-test.

DISCUSSION OF RESULTS

The test results for the material constant k ranged from 0.435 to 0.576 m³/t. The range is narrow considering the wide variety of ensiled materials and the difference in test methods employed for the present tests and those carried out previously in Sweden. As well, the values for R^2 indicate good consistency within each set of tests.

The relationship Eq. 8, the predicted values for ρ_{ds} with Eq. 1, and the values of k will allow the prediction of seepage losses from a body of silage. In future research, Eq. 8 will be incorporated in a real-time simulation procedure of the consolidation of a body of silage that includes provisions for the flow of the silage juice through the silage and drainage along any boundary. The objective of this real-time simulation is to find realistic saturation levels in tower silos.

SUMMARY

An improved understanding of the mechanism of seepage loss from a body of silage is important for predicting effluent loss

Table IV. Parameters for consolidation tests by Nilsson (1982)

Material and M (%)	Applied press. (kPa)	Test dur. (d)	Juice expelled Y or N	Material and M (%)	Applied press. (kPa)	Test dur. (d)	Juice expelled Y or N
Grass 79.8%	121.2	56	Y	Grass 65.8%	115.6	54	Y
	81.6	56	Y		80.9	54	Y
	60.1	56	Y		59.0	54	N
	39.2	56	Y		39.2	54	N
	20.1	56	Y		20.1	54	N
	9.0	56	Y		9.0	54	N
	1.8	56	N		1.7	54	N
Grass 78.4%	121.2	56	Y	Grass 55.1%	115.6	56	N
	81.6	56	Y		80.9	56	N
	60.1	56	Y		59.0	56	N
	39.2	56	Y		39.2	56	N
	20.1	56	Y		20.1	56	N
	9.0	56	N		9.0	56	N
	1.8	56	N		1.7	56	N
Grass 73.1%	118.0	55	Y	W.P. corn 76.4%	121.2	57	Y
	80.9	55	Y		81.6	57	Y
	60.8	55	Y		60.1	57	Y
	38.5	55	Y		39.2	57	Y
	20.1	55	Y		20.1	57	Y
	9.0	55	N		9.0	57	N
	1.6	55	N		1.8	57	N
Grass 68.7	118.0	56	Y	Beet pulp 87.2%	59.0	42	Y
	80.9	55	N		39.2	42	Y
	60.8	55	N		20.1	42	Y
	38.5	55	N		14.1	42	Y
	20.1	55	N		9.0	42	Y
	9.0	55	N		5.2	42	Y
	1.6	55	N		1.7	42	N

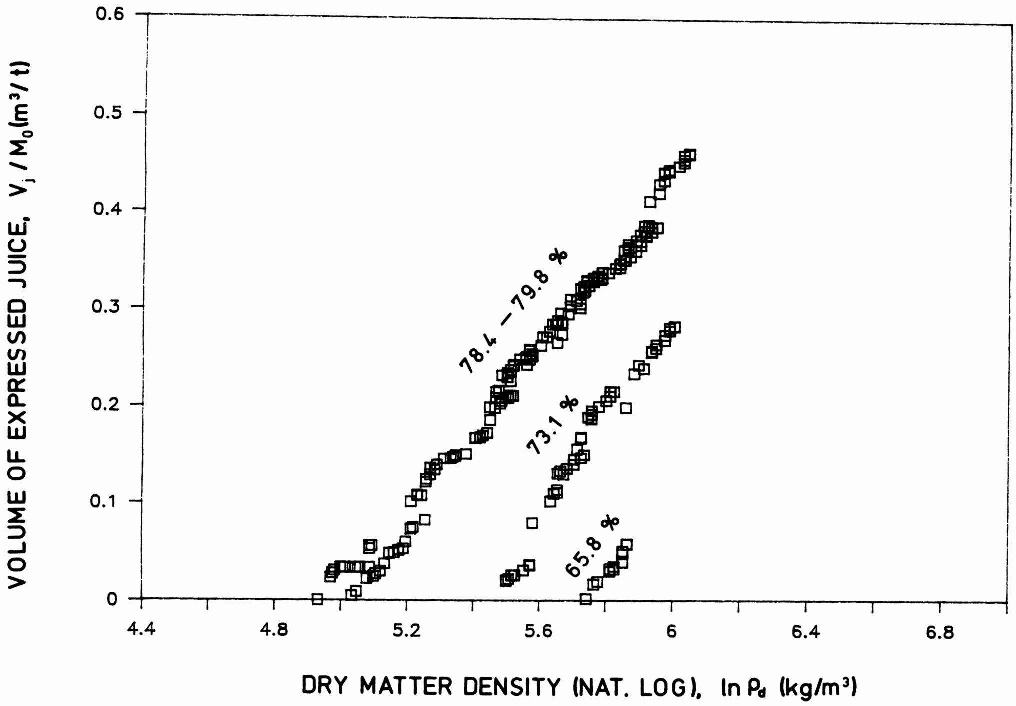

Figure 7. Volume of expelled juice per unit of silage mass versus the natural logarithm of dry matter density for 28 grass silage tests by Nilsson.

and for determining the saturation level in a tower silo being filled with plant materials with moisture content over 60%.

An analog model of silage material has been used to hypothesize that the volume of juice expelled from a mass of silage is a linear function of the volumetric strain. For large strains this would mean that the volume of juice expelled can be related to the natural logarithm of the ratio of dry matter density to the dry matter density at apparent saturation.

The hypothesis was tested with the results of 21 isotropic consolidation tests of alfalfa and WP corn silage carried out in a modified triaxial cell. As well, the results of eight series of consolidation tests carried out by Nilsson in Sweden on grass,

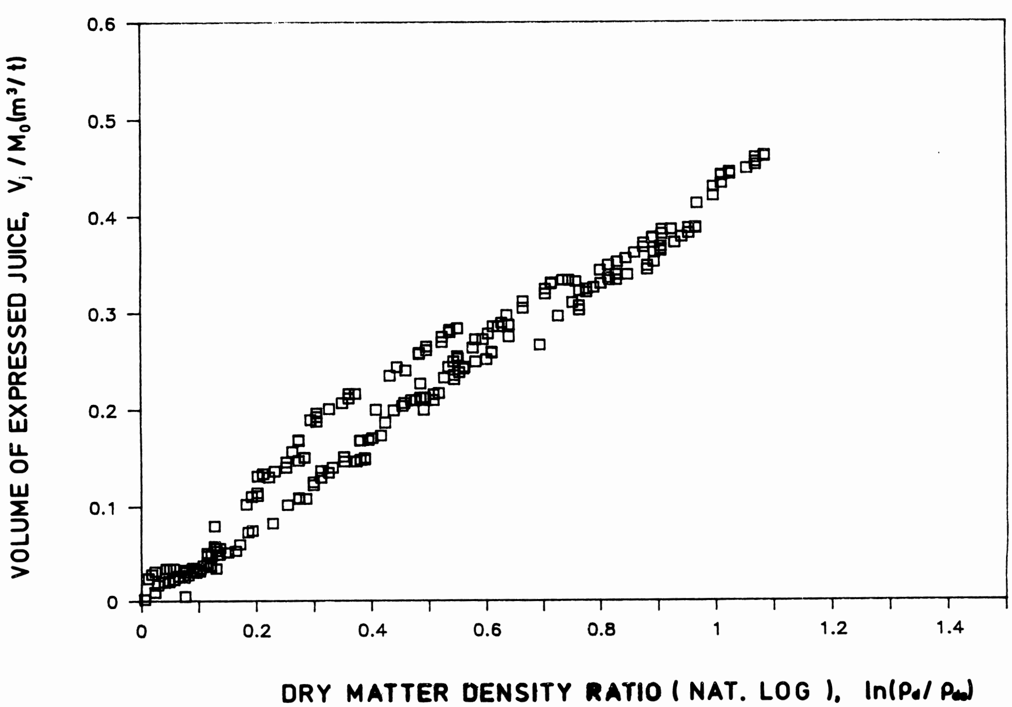

Figure 8. Volume of expelled juice per unit of silage mass versus the natural logarithm of the ratio of dry matter density to the dry matter density at apparent saturation for 28 grass silage tests by Nilsson.

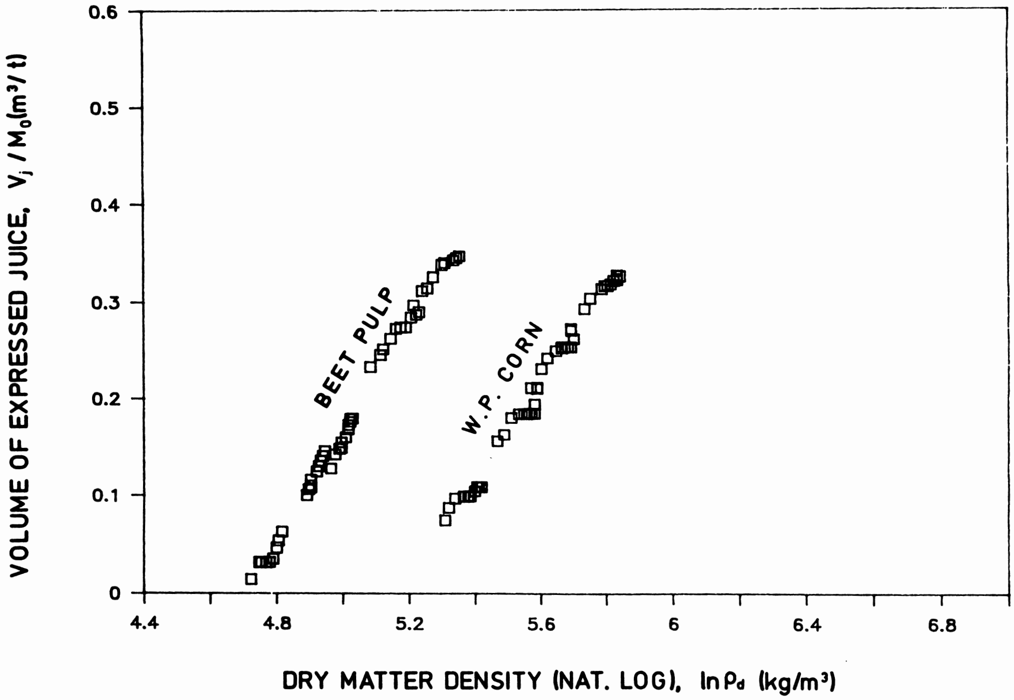

Figure 9. Volume of expelled juice per unit of silage mass versus the natural logarithm of dry matter density for seven whole-plant corn silage and six beet pulp tests by Nilsson.

WP corn and beet pulp silage were incorporated in the evaluation.

The test results showed that the volume of expelled juice per unit of mass is indeed related linearly to $\ln(\rho_d/\rho_{ds})$. The material constant of proportionality, k, ranges from 0.435 to 0.576 m³/t.

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