A saturation criterion for ensiled plant materials

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Tang, J., Jofriet, J. C. and LeLievre, B. 1988. **A saturation criterion for ensiled plant materials.** Can. Agric. Eng. **30**: 93–98. In many parts of North America and Europe the moisture content of silage often exceeds 65%. Under those circumstances the silage in the lower part of the silo is likely to become saturated. None of the available saturation criteria is sufficiently comprehensive to predict accurately saturation in plant materials commonly ensiled in Ontario. This became evident from 21 isotropic consolidation tests of silages using a modified triaxial testing apparatus. A silage model consisting of masses and springs, that includes microvoids (plant cells) and macrovoids helped to formulate a hypothesis that indicates that dry matter density is a good predictor of saturation. The results of the 21 tests (10 alfalfa silage and 11 whole-plant corn silage) were combined with those of 42 tests of grass silage from Sweden to propose a new saturation criterion. It is based on dry matter density and includes the effect of the moisture content, M%. The criterion predicts saturation when the dry matter density exceeds the value $(961 - 9.92M)$kg/m^3.

INTRODUCTION

In many parts of North America and Europe a variety of plant materials are ensiled in tower silos for on-farm use as livestock feed. In Europe grass and corn are the predominant materials; in Canada and the U.S.A. alfalfa, corn and barley are the feeds most often used for ensiling.

The moisture content of silages ranges from 45 to 80% (wet basis), depending on the climatic conditions of the growing area and on the type of crop. For silages with moisture contents over 65% the high stresses that occur in the bottom of a tower silo will, in many cases, cause silage juice to be expelled from the plant cells. Unless sufficient drainage is provided, the free juice will saturate the silage and cause a build-up of hydrostatic pressure. This results in considerably higher lateral pressures on the silo wall, of which the structural designer has to be aware.

Even in cases where good drainage is present, free silage juice can be a problem. The jointed wall of a stave silo, for instance, provides good drainage; however, the expelled silage juice is extremely corrosive to concrete and steel. Furthermore, the drained silage juice contains nutrients which are lost thus adding to the total ensiling loss. Hence, a thorough knowledge of the physical behavior of relatively wet silages under pressure is of importance to the structural engineer and the animal nutritionist.

The Canadian Farm Building Code (1983) has provisions for dealing with saturated silage in the bottom of a tower silo. However, there is no clear direction on the height of the saturated zone. It states in part: "There is no precise guideline for determining the saturation depth. Rough estimates for alfalfa silage are 30 m for 65%, 16 m for 70% and 11 m for 75% moisture."

In order to prevent the occurrence of silage becoming saturated, or to design a silo that is capable of withstanding possible fluid pressures with some confidence, a better understanding of the saturation mechanism is necessary. Saturation criteria were developed in both North America and Europe to predict the onset of juice expulsion. However, these criteria are not comprehensive enough to deal with the plant materials commonly ensiled in Ontario.

The objectives of this paper are to review critically the existing saturation criteria and to propose a more general criterion that is suitable for most silage materials in use in North America and Europe.

LITERATURE REVIEW

Wood (1970a, 1970b) carried out a comprehensive investigation of the physical properties of grass and corn silage. One of the conclusions from his consolidation tests was that effective saturation of silage occurs when about 10% of the total silage volume remains as gas, and that further consolidation can only be achieved by expelling the liquid. Based on this assumption he derived a criterion which predicts effective saturation when the bulk density, ρ_{bs}, reaches the value:

$$\rho_{bs} = 1440 - 5.4M \qquad (1)$$

where ρ_{bs} is in kg/m^3 and M is the moisture content (w.b.) in percent.

Based on the same assumption of remaining gas in the silage, 't Hart et al. (1979) presented the bulk density at saturation as:

$$\rho_{bs} = 1440 / (1 + 0.006M) \qquad (2)$$

Arnold (1976) carried out compression tests on whole-plant corn silage in 200-mm model silos. He concluded that the minimum vertical pressure at which seepage would occur is:

$$\ln P_v = 14.69 - 0.1174M \qquad (3)$$

where P_v is the vertical pressure in g/cm^2 (= 10 kPa), M is the moisture content (w.b.) in percent. Equation 3 is limited to whole-plant (WP) corn silage.

Nilsson (1982) carried out 56 consolidation tests, 42 of grass, 7 of whole-plant corn and 7 of beet pulp silage. Each series of seven tests dealt with one moisture content and seven consolidation pressures, ranging from about 2 to 120 kPa, sustained from 42 to 55 days. As a result of these tests he proposed that under sustained pressure the material first reaches "apparent saturation", then "effective saturation" when all gas is expelled, i.e., complete saturation. "Apparent saturation" was defined by Nilsson as the state at which juice first appears when silage is being consolidated.

Nilsson observed that "apparent saturation" occurred at a constant value of "moisture density", which he defines as the difference between bulk density and dry matter density (i.e., weight of juice over total volume). This saturation criterion was developed in Sweden mainly from tests of grass silage.

LeLievre and Jofriet (1984) carried out three isotropic consolidation tests of alfalfa silage with a suitably modified triaxial test apparatus. The tests of 70% moisture content material showed that juice releases at gas contents ranging from 18 to 23% of the total void volume; the values of the "moisture density" at "apparent saturation" varied from 600 to 650 kg/m^3.

A detailed examination of the test results from different research has shown that neither the constant remaining gas volume nor the constant "moisture density" criterion can predict the onset of juice expulsion from a wide variety of silages. Available test results from past research will be combined with new results to propose a saturation criterion with a wider scope.

PROCEDURE

The triaxial test apparatus modified for testing highly compressible materials, such as silages (LeLievre and Jofriet 1982a), was used for 21 further isotropic consolidation tests. The prime objective of these tests was to find a suitable saturation criterion for silages. The test was identical to those described in detail by LeLievre and Jofriet (1982a). A brief summary of the test procedure follows.

Samples of silage, 100 mm in diameter by approximately 200 mm in height, were prepared inside a 0.4-mm-thick rubber membrane on the base of the triaxial cell. A temporary rigid plastic former was used to provide the correct cylindrical shape to the specimens. The initial specimen density was kept to the minimum practical.

The triaxial cell was assembled after removal of the temporary former. The testing was started as soon as the triaxial cell was filled completely with water.

The specimens were supported on a porous stone base so that the pore pressure in the silage could be monitored. The top 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 vertical strain was determined separately from vertical displacements of the cap. An overview of the test arrangement is shown in Fig. 1.

The specimens were subjected to stepwise increasing cell pressures. All but the last increment were maintained for 1 d. The last load step was maintained for 3 or 4 days, and in some cases more than 20 days. Measurements were taken at 0.02,

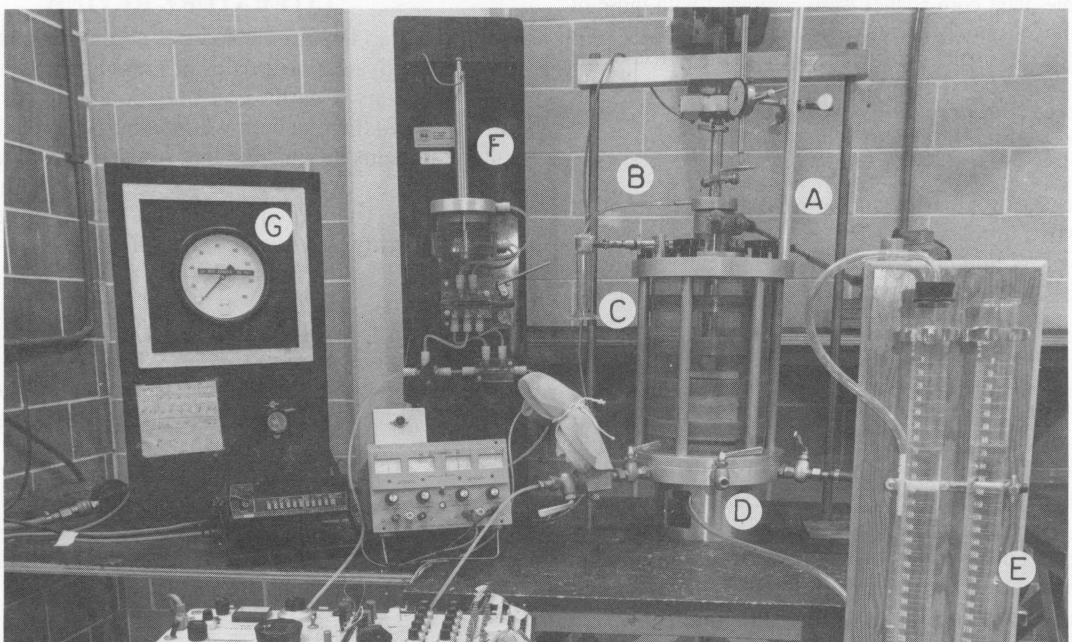

Figure 1. Typical triaxial test set-up.

Table I. Parameters for alfafla silage tests

Test no.	Moisture contents (WB) (%)	Initial wet density (kg/m³)	Init. air vol. / silage vol. (%)	Min. cell pressure (kPa)	Max. cell pressure (kPa)	Test duration (days)
VLMC2	60.4	465	60.4	13.79	289.6	14
VLMC3	60.3	430	63.4	13.79	275.8	29
VLMC4	60.0	474	59.7	13.79	275.8	28
LOMC1	70.5	601	46.6	13.79	206.8	7
LOMC2	70.5	558	50.4	13.79	206.8	7
LOMC3	69.9	551	51.1	13.79	206.8	6
LOMC4	70.0	534	52.6	13.79	206.8	7
HIMC2	79.3	709	34.6	13.79	151.7	6
HIMC3	79.8	733	32.2	13.79	151.7	7
HIMC5	81.6	785	26.9	13.79	151.7	6

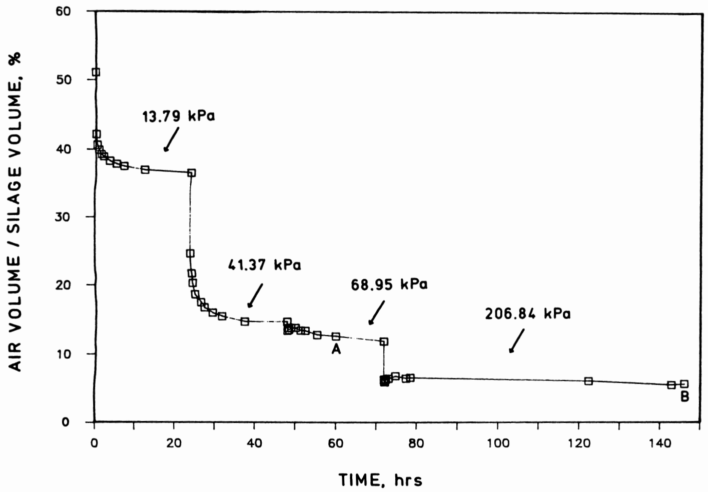

Figure 2. Air volume percentage vs. time for alfalfa silage test LOMC3.

0.10, 0.25, 0.5, 1.1, 1.6, 2.72, 3.5, 11 and 24 h after the application of a new load increment. "Apparent saturation" was noted when silage juice entered the perforations in the plastic cap on the specimen.

The initial moisture content, the bulk and dry matter densities, and the air volume percentages are listed in Table I for 10 tests with alfalfa silage. The same data for 11 WP corn silage tests are shown in Table II. Both tables also indicate the loading range and the duration of the various tests. The moisture contents are the mean of three oven drying tests.

RESULTS

Figure 2 shows the decrease in air volume, expressed in percent of the total volume, for test LOMC3 versus time. LOMC3 is 69.9% moisture content alfalfa silage and is representative of all tests listed in Table I. The almost instantaneous reduction in air volume upon load application is followed by a much more gradual volume change with time. As the density increases under increasing stress, the material becomes stiffer and the volume changes per unit load increment decrease in magnitude.

Figure 3 shows similar results for one of the WP corn silage tests (CMMC3). It may be seen that the general behavior of the corn silage under increasing stress is very similar to that of alfalfa. At all pressure levels, the air volume percentage is higher for corn silage. The results in Figs. 2 and 3 confirm that silages are highly compressible, and exhibit viscous, strain hardening behavior under stress (Handtoff 1970; LeLievre and Jofriet 1984; Wood 1970a,b).

In test LOMC3, juice expulsion started at an air volume of 14.7% of the total (point A, Fig. 2). In test CMMC3, the percentage was 22% (point A, Fig. 3). The air volume percentage decreased further after "apparent saturation" was attained. The air volume at the end of the test is indicated with the letter B in Figs. 2 and 3. A similar type of behavior was observed in all tests.

The squares in Fig. 4 are the air volume percentages at "apparent saturation" for the 10 alfalfa silage tests. Also shown in Fig. 4 are the air volume percentages at the completion of each test (+). The letters A and B in Fig. 4 indicate the "apparent" and final air volume percentages from test LOMC3. Figure 5 illustrates the air volume percentages at "apparent" saturation and at the end of the 11 WP corn silage tests listed in

Table II. Parameters for whole-plant corn silage tests

Test no.	Moisture contents (WB) (%)	Initial wet density (kg/m³)	Init. air vol. / silage vol. (%)	Min. cell pressure (kPa)	Max. cell pressure (kPa)	Test duration (days)
CHMC1	71.7	639	42.9	13.79	248.2	7
CHMC2	72.2	669	40.1	13.79	248.2	8
CMHC4	71.7	720	35.7	13.79	248.2	7
CMMC1	67.8	529	53.4	13.79	193.0	7
CMMC2	68.8	534	52.8	13.79	206.8	7
CMMC3	67.4	569	50.0	13.79	248.2	7
CMMC4	66.9	464	59.3	13.79	248.2	7
CLMC1	62.6	480	58.8	13.79	248.2	7
CLMC2	61.6	462	60.4	13.79	248.2	7
CLMC3	60.7	490	58.2	13.79	248.2	7
CLMC4	59.2	470	60.2	13.79	248.2	7

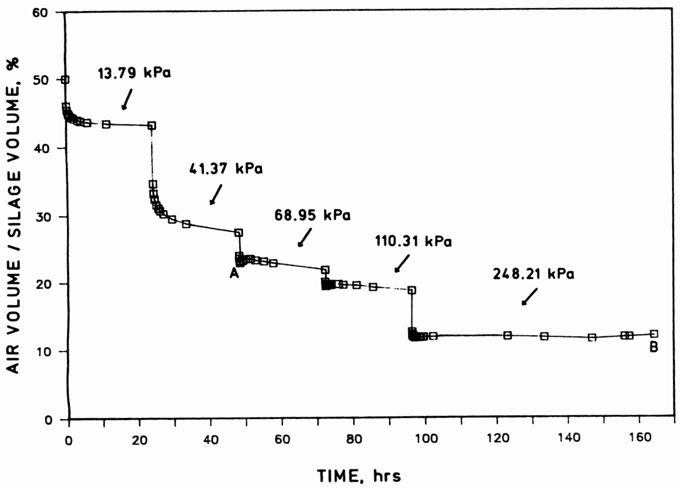

Figure 3. Air volume percentage vs. time for whole-plant corn silage test CMMC3.

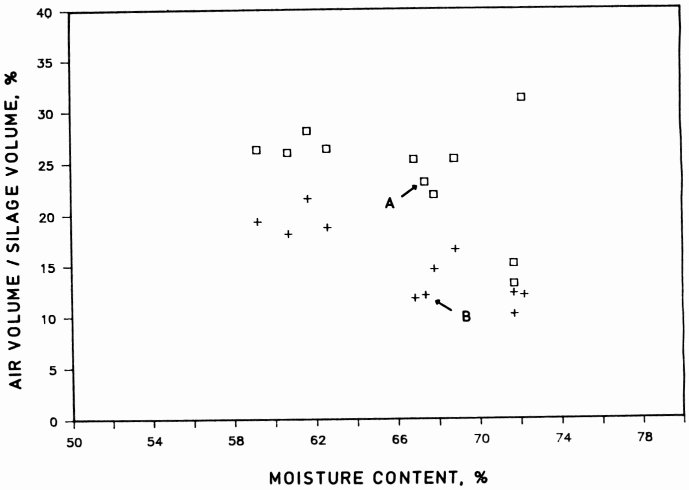

Figure 5. Air volume percentage vs. moisture content for all whole-plant-corn silage tests; at apparent saturation (□) and at completion of test (+).

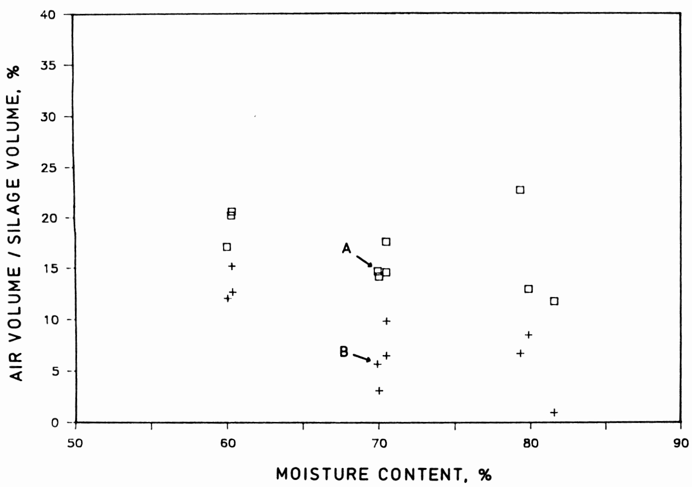

Figure 4. Air volume percentage vs. moisture content for all alfalfa silage tests; at apparent saturation (□) and at completion of test (+).

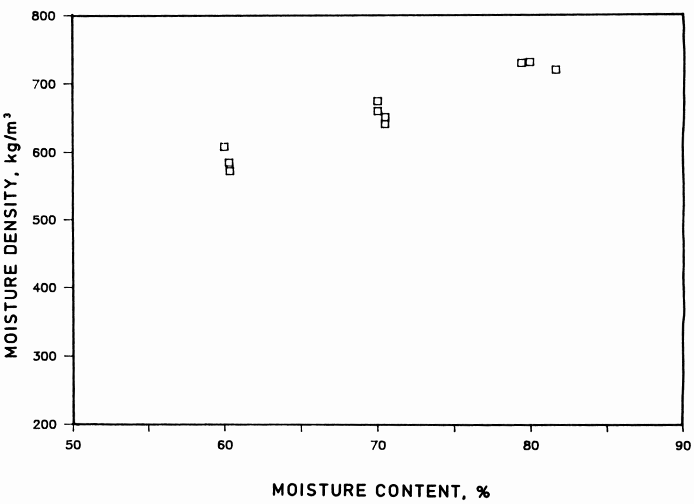

Figure 6. Moisture density vs. moisture content for all alfalfa silage tests.

Table II. The letters A and B correspond to those in Fig. 3 and indicate the points for test CMMC3.

It is apparent from Figs. 4 and 5 that the percent air remaining is not a good indicator for the onset of silage juice expulsion (apparent saturation) in the present tests. Percent air remaining at apparent saturation varies from about 11 to 23% for the alfalfa tests and from 13 to 31% for the WP corn silage. Wood's criterion of 10% air remaining at effective saturation is also not valid for all conditions. The results in Figs. 4 and 5 clearly show the effect of moisture content.

It is possible that Wood's low value is due to his testing method. He consolidated silage samples in a totally enclosed cylindrical chamber without an outlet for juice and considered the material saturated when juice squeezed past the seals of the compression piston (Wood 1970a, p. 399).

In order to provide a check on Nilsson's (1982) criterion, the "moisture densities" were determined for all tests. These are presented in Fig. 6 for alfalfa silage and in Fig. 7 for WP corn silage. The moisture density values range from about 570 to 730 kg/m³ for alfalfa and from 520 to 660 kg/m³ for WP corn silage. Nilsson's criterion for predicting the onset of apparent

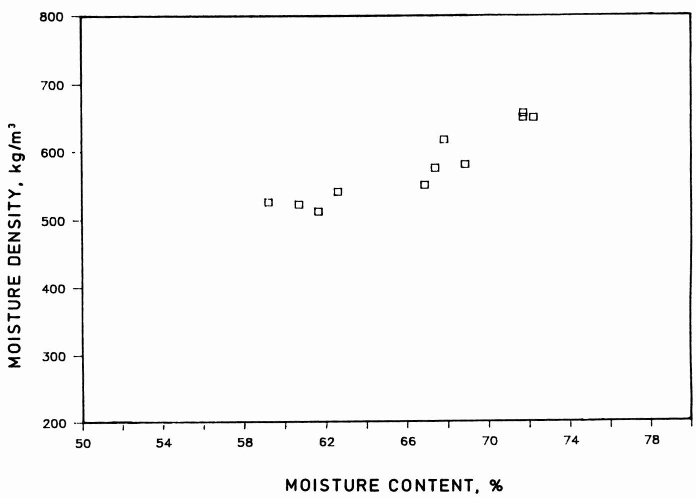

Figure 7. Moisture density vs. moisture content for all whole-plant corn silage tests.

saturation is also not adequately comprehensive to include the present test results. A new saturation criterion will be proposed in the next section.

A NEW SATURATION CRITERION

Silage can be represented by a model consisting of masses, springs, voids and liquid (see Fig. 8). Three solid masses (M_{s1}, M_{s2}, M_{s3}) make up the structure of the silage. The springs E_1 and E_2 model the elasticity of the silage material. E_1 and E_2 are time-dependent and exhibit a strain-hardening type of behavior.

The voids in the silage can be divided into two categories. The macrovoids are those between the particles of the chopped plant material. This is represented in Fig. 8 by the space between masses M_{s1} and M_{s2}. Microvoids are those created by the cellular structure of the plant material. The space between M_{s2} and M_{s3} in Fig. 8 are the microvoids. The moisture in the silage is contained mainly in the microvoids. It is shown in Fig. 8 inside the bottom space.

Under load both the macro- and the microvoids will be reduced in size and the dry matter density will increase. At a particular point the size of the microvoids becomes too small to contain all the liquid and "apparent saturation" occurs. The masses and the total voids at this point occupy a given volume, and therefore a given dry matter density corresponds to this point. Thus, it is hypothesized that dry matter density can be used to serve as a predictor of "apparent saturation".

It is also apparent from Fig. 8 that a higher moisture content of the silage means a higher water table in the bottom space. This will lead to earlier saturation at a larger overall volume, and thus a lower dry matter density. It can be expected then that moisture content will have an effect on the dry matter density at saturation. The second hypothesis is that the dry matter density at "apparent saturation" will be lower at higher values of the moisture content of the silage.

Dry matter density at apparent saturation is plotted versus moisture content in Fig. 9 for all alfalfa silage tests. A similar plot for WP corn silage is Fig. 10. Both reveal a linear relationship of the dry matter density at saturation with moisture content. Nilsson's (1982) grass silage data for dry matter density at apparent saturation have been plotted in the same manner as the present data (Fig. 11) and they too exhibit a linear relationship with moisture content. The experimental data in Figs. 9, 10 and 11 support the hypothesis that the dry matter density at "apparent saturation" is less as the moisture content increases.

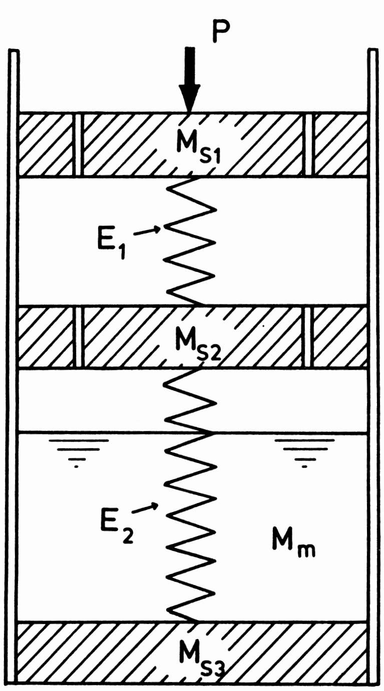

Figure 8. Silage model.

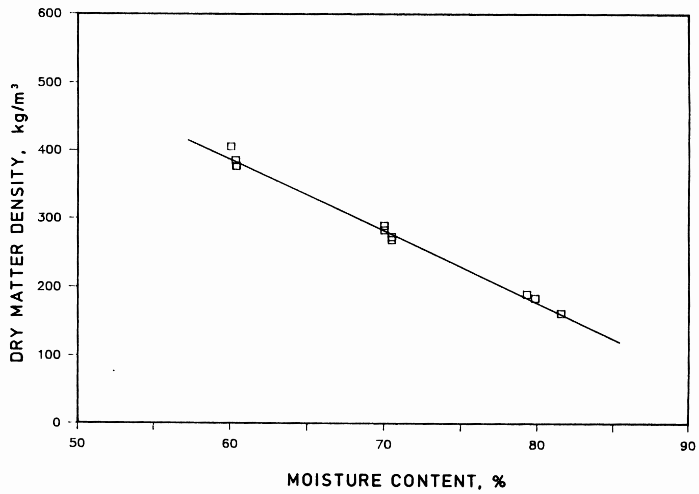

Figure 9. Dry matter density at apparent saturation vs. moisture content for all alfalfa silage tests.

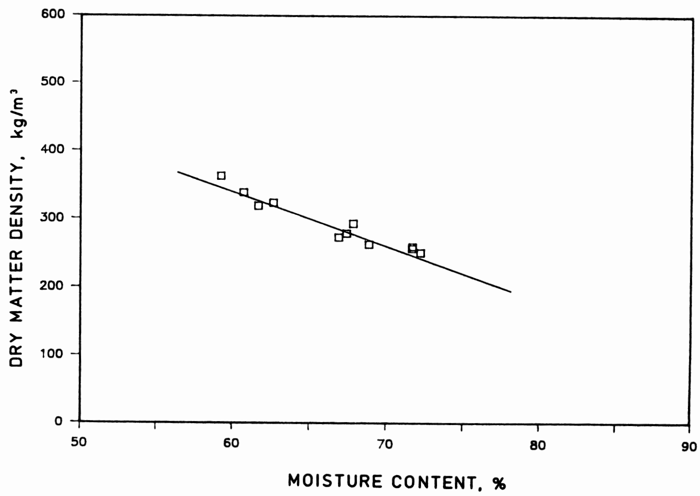

Figure 10. Dry matter density at apparent saturation vs. moisture content for all whole-plant corn silage tests.

The best-fit linear relationship for the dry matter density, ρ_{ds}:

$$\rho_{ds} = a + b \times M \quad (4)$$

was obtained for each of the three sets of data in Figs. 9, 10 and 11. The values for a and b, together with the standard errors of a and b, and R^2, are listed in Table III. The significance levels of the regression equation (Eq. 4) as determined by F-tests have also been included in Table III. The alfalfa silage results and those by Nilsson fit a straight line relationship extremely well ($R^2 = 0.99$). The WP corn silage results fit less well, but the fit is good ($R^2 = 0.93$).

For the purpose of engineering design it is inconvenient to have different saturation criteria for different silage materials.

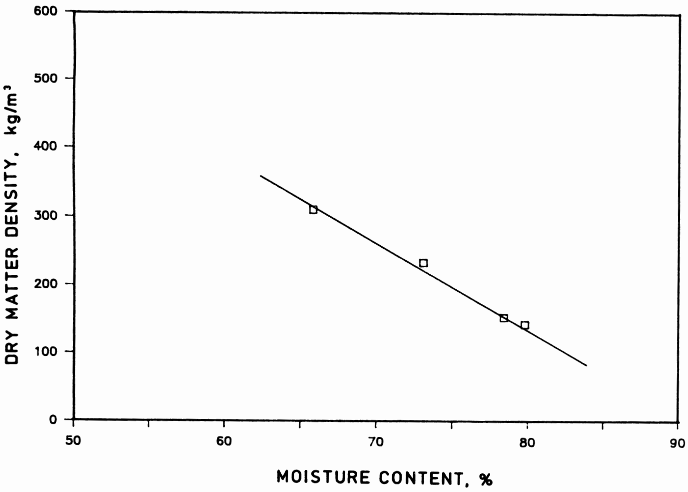

Figure 11. Dry matter density at apparent saturation vs. moisture content for grass silage tests (Nilsson 1982).

Therefore a single linear relationship was found for all data from the present tests and those for grass silage by Nilsson (1982). The resulting expression is:

$$\rho_{ds} = 961 - 9.92M \quad (5)$$

in which ρ_{ds} is in kg/m³ and the moisture content, M, is in percent. The R^2 of this prediction equation is 0.93, the standard errors of a and b are 40.0 and 0.575, respectively.

A plot of all data upon which Eq. 5 is based is presented in Fig. 12 together with Eq. 5. Also shown in Fig. 12 are the dry matter densities at saturation from two other tests, both by Nilsson (1982). One is a single test for WP corn silage with a moisture content of 76.8%, the other is for beet pulp with a moisture content of 87.2%. Both points are very close to the line representing Eq. 5.

The test procedure used by Nilsson differed greatly from the present tests. The silage material was consolidated in rigid 200-mm-diameter model silos under constant vertical stress for periods up to 55 days. Despite that difference, Eq. 5 using dry matter density as the predictor appears to fit the Swedish data as well as those derived with the Canadian silage materials. It is proposed that Eq. 5 be used as the saturation criterion for all silages.

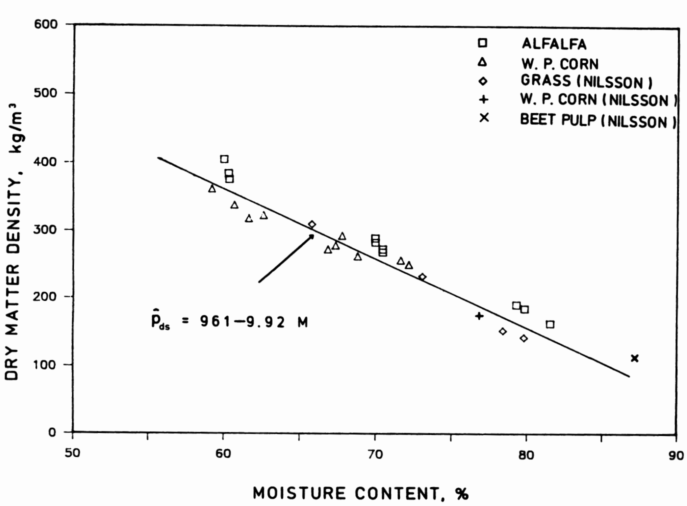

Figure 12. Dry matter density at apparent saturation vs moisture content for all tests.

Table III. Material parameters for eqs. 4 and 5

Material parameter	Alfalfa silage	WP corn silage	Grass silage	Eq. 5
a (kg/m³)	1020	806	1124	961
Standard error of a	24.7	46.3	57.3	40.0
b (kg/m³)	−10.50	−7.73	−12.32	−9.92
Standard error of b	0.349	0.696	0.769	0.575
R^2	0.99	0.93	0.99	0.93
$PR > F$ (%)	0.01	0.01	0.39	0.01

SUMMARY AND RECOMMENDATION

The structural design of storage structures for wet silages requires a design criterion for the onset of juice expulsion so that hydrostatic pressures can be taken into account properly. Existing criteria do not predict well the mechanical behaviour of the silage materials used in Canada.

The results of 21 isotropic consolidation tests of alfalfa and whole-plant corn silage were combined with those by Swedish researchers for grass to provide a more comprehensive criterion to predict apparent saturation. The criterion is a linear function for the dry matter density at the onset of juice expulsion from a silage specimen, in terms of its moisture content. The prediction equation (Eq. 5) can be used for a wide variety of materials used in Canada and Europe.

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