INTRODUCTION

Crops commonly ensiled in Canada and the United States for on-farm use as livestock feed are corn, alfalfa and other species of grass. Whole-plant corn silage is very nonhomogeneous because it contains parts of tassels, leaves, stem, cobs and kernels. In general, whole-plant silages are compressible and fibrous substances for which constitutive laws are not available (Jofriet and Negi 1984). Therefore, studies of mechanical and rheological properties of these materials are fundamental to a rigorous understanding of the physical behavior and nature of silages. Some of the work reported herein will be of academic interest only; some is believed to be useful basic research, and some has already found application in the design of top- and bottom-unloading silos.

The principal objectives of this study were to determine the stress-strain relationships, relaxation characteristics, bulk density and internal friction properties of alfalfa and corn silages, and to examine the influence of rate of loading, stress levels and moisture content on these properties. Such basic data on stress-strain behavior should be valuable in determining the optimum method of packing and mechanically compressing silages in storage as well as for viscoelastic characterization of the material. Time constants obtained from relaxation data are used to compare the effects of pressure, hold time, moisture content, length of cut, kind of crop and stage of maturity which may influence compressibility and expansion characteristics of forage and silage materials (Mohsenin 1970; Mahmoud 1975). The average bulk density of silage in a farm tower silo depends upon the moisture content of the silage and the aspect ratio of the cylindrical structure (Canadian Farm Building Code 1977). Quantitative information on this physical property is essential for estimating the loads exerted by the contained material. Angle of internal friction is important in analyzing the storage-bin wall pressures, as well as for calculating the ratio of horizontal to vertical pressure in a silo (Fwa 1976).

MATERIALS AND METHODS

Specimens

The whole-plant silage samples used in this study were taken from a tower silo roughly 3–4 mo after the crop was ensiled. The theoretical length of cut was 10 mm and the moisture content averaged 66% on a wet basis. For moisture determinations, silage samples were dried for 24 h in an electric air oven at 105 ± 2°C. The different levels of moisture were obtained by either drying or rewetting the silage material. The silage was then thoroughly mixed and stored in sealed plastic bags for at least 48 h so that the moisture would reach equilibrium. Several samples were oven-dried to determine the final moisture content.

Compression Tests

All experimental measurements were obtained by applying a compressive force at right-angular to the direction of the silage fibers. For whole-plant silages the orientation of the leafy material and the chopped stems is generally perpendicular to the axis of the container. An Instron Universal Testing Machine, table model TM-M, with standard crosshead speeds of 0.5 to 100 cm/min and 500-kg capacity was used to study rheological behavior.

In conducting a test, the sample of silage material was compressed between two steel plates in a test chamber. This container was fabricated of four cast acrylic plates glued together to form a box having a 175 × 160-mm cross section (inside dimensions) and a 200-mm height. The size of the steel plates was slightly smaller than the inside dimensions of the test chamber. The force-deformation diagrams were plotted directly on the Instron recorder chart at various rates of deformation, stress levels and moisture contents. Hysteresis loops for three loading-unloading cycles were also obtained at various moisture levels. From these measurements the degree of elasticity, hysteresis loss and the energy capacity or resilience were determined.

Relaxation Tests

In the stress relaxation tests, a known quantity of silage was packed in the cast acrylic container and loaded between parallel plates until the load reached a predetermined value of 981 N. Thereafter, the deformation was held constant and the force required to maintain this deformation was continuously recorded on the Instron chart. The force-time curves were considered to represent the stress relaxation process within the silage mass because the deformation and the area of contact were kept constant during the test. To minimize the decay of stresses during the loading process, unless otherwise specified, a rate of deformation of 50 cm/min was employed. The effects of moisture content, deformation rate, amount of deformation and time of observation on the rate of stress relaxation were measured in the experiment.

Shear Tests

The angle of internal friction of silage was measured using a direct shear apparatus and a packing mold. Normal loads
were applied to the 51-mm-square shear cell through a counter-balanced weight hanger system. The shearing force was applied by a hand crank operating through a gear system. Shearing forces were measured by a 100-kg capacity single proving ring assembly. The packing mold consisted of a hollow square metal box with an inverted L-shaped groove at the bottom to fit the shear cell. The test method consisted of preparing a uniformly packed sample of silage and subjecting it to a shearing force under a preselected normal load. The peak shear forces corresponding to normal pressures in the range of 2-40 kPa were recorded at different moisture levels. Three replications of shear strength measurements were made under each normal load.

**Pressure-density Tests**

Experiments were conducted in which alfalfa or whole-plant corn was harvested using a forage harvester equipped with cutting cylinder. Predetermined quantities of the freshly chopped material were loaded into cast acrylic model silos and subjected to three vertical pressure levels, each replicated twice, by a simple lever arrangement made of a steel channel and concrete blocks. Measurements of silage bulk densities were made in each cylinder periodically between 1 and 60 days after ensiling. The test results were used to produce a model for the dry density of silage in terms of vertical pressure, loading time and moisture content. This model was then used to predict the average density for the whole silo in terms of the settled height of silage. The numerical procedure involved an iterative technique of solving silage densities and vertical pressures in finite laminae, starting at the horizontal stress-free upper surface (Jofriet et al. 1982; Negi et al. 1984).

**RESULTS AND DISCUSSION**

**Stress-strain Behavior**

The influence of rate of deformation on stress-strain behavior of whole-plant corn silage is shown in Fig. 1. The faster the rate of deformation, the greater was the stress developed in the material. There was an appreciable increase in divergence of the...
curves beyond a strain of 30–40%. Because of this time-effect phenomenon, and because the strain was mostly non-recoverable upon unloading (see Fig. 2), it is inferred that silage is a nonlinear viscoelastic material. In other words, silage can be characterized as viscoplastic because the ratio of stress to strain is a function of time as well as stress magnitude. There appears to be little difference between whole-plant corn and alfalfa silage insofar as the stress-strain behavior is concerned, and consequently they will be discussed together.

Stress-strain curves for three loading and unloading cycles are presented in Fig. 2 for corn silage. It can be seen that a significant portion of the strain remained after the stress was removed. This residual strain for the initial loading cycle was markedly greater than that for the subsequent loading cycles. Therefore, silages behave like a strain-hardening material; the deformation that takes place under stress increases the rigidity of the material. The degree of elasticity, defined as the ratio of elastic to total deformation, averaged around 20% for the maiden loading cycle. The moisture content sensitivity for a maiden cycle is exhibited by the curves in Fig. 3. A moderate influence of the moisture content on the stress-strain curves is evident.

Also shown in Fig. 3 are hysteresis losses for different moisture levels during the maiden loading cycle. It is seen that hysteresis loss increased slightly with an increase in moisture content. Zoerb and Hall (1960) stated “The difference between the work of compression and the work of retraction represents the hysteresis loss.” Since this energy is dissipated as heat, it is apparent that silage temperature will increase when subjected to loading-unloading cycles. Reference to Fig. 2 shows that the hysteresis loss for the second loading was smaller than that for the initial loading. However, the third loading-unloading cycle produced about the same loss as the second cycle. Also, it is noticeable from Figs. 2 and 3 that the energy capacity or resilience of silage material in the elastic range was extremely low — about 10% of total input — as indicated by the area under the unloading curves.

**Relaxation Characteristics**

The effect of rate of deformation upon the relaxation of stresses within the silage material is illustrated in Fig. 4. The most significant effect of the deformation rate on the relaxation process was observed during the first few seconds after stopping the crosshead. Beyond this initial period of about 1 min, the force (stress)-time curves displayed a parallel relationship indicating that the relaxation time was no longer affected by the rate of deformation. It is apparent from Fig. 4 that the slower the loading rate, the less the stress decay. This is because at slower rates more time was allowed for the stresses to decay during the loading process, i.e., even before the crosshead was stopped. In passing, it is noted that the moisture content in the range of 37–78% had practically no effect on the rate of stress relaxation or on the magnitude of stress decay; thus the results have not been included in the paper.

In order to find whether or not the stress within the silage falls to zero for large values of time, two long-term tests were carried out, one over a period of 10 h (Fig. 5) and another for 100 h (not shown). These tests revealed that the stress continued to decrease with time, and probably will not level off as the time approaches infinity. Finney et al. (1964) reported that such a behavior indicates that after a very long period of observation the silage would not show any elastic after effect upon removal of the parallel plates.

To determine the rate at which a silage material dissipates stress after receiving a sudden force, values of force $F$ and time $t$ were plotted on semi-log paper (log $F$ versus $t$), such as in Fig. 6. The graphical method of successive residuals was used for the analysis of stress relaxation data as depicted in Fig. 6 (Zoerb and Hall 1960; Timbers 1964; Mustafa et al. 1966; Mønsen 1970). It was found that the experimental curves could be described empirically by an equation of the type

$$F(t) = A_1e^{-t/T_1} + A_2e^{-t/T_2} + A_3e^{-t/T_3}$$

where $T_1$, $T_2$ and $T_3$ are the time constants (slope of the straight line segments), and $A_1$, $A_2$ and $A_3$ are the coefficients ($F$ intercepts where $t = 0$). The time constant or relaxation time is the time required for the stress in the Maxwell model, representing stress relaxation behavior, to decay to 1/e or approximately 37% of its original value (Finney et al. 1964).

Three-term exponential equations were obtained to represent the experimental force relaxation curves for three crosshead speeds in two-decade range (0.5–5–50 cm/min) and at different moisture levels. These results showed that the shorter time constants decreased with an increase in the crosshead speed, but the longest relaxation times were relatively unaffected by the rate of loading. Further, the variation of time constants with moisture content did not exhibit a discernible trend.

**Internal Friction Properties**

Shear strength versus normal pressure data were plotted, and straight line failure envelopes were obtained by linear regression. The angle of the envelope was taken as the angle of internal friction, $\phi$, and the intercept on the shear-axis at zero normal pressure was taken as cohesion, $C$. A typi-
cal example of peak shear strength as a function of normal pressure is presented in Fig. 7 for 66% moisture content corn silage. Since it was difficult to discern the effect of moisture content on $C - \phi$ values, the equation in Fig. 7 (significant at 0.01 probability level) was considered to be representative of whole-plant corn silage. Accordingly, $C$ and $\phi$ values of 1 kPa and 30°, respectively, are recommended for this material.

Silage Bulk Density
Each silage has its typical pressure-density characteristics. Of the whole-plant silages alfalfa haylage has one of the highest densities when chopped to about 10-mm length as is common in Canada (Jofriet and Negi 1984). This is attributed to the relatively uniform particle size of alfalfa and consequently a tighter packing.
under the weight of superimposed mass in a silo. It is recommended that the weight of alfalfa haylage be used for determining design loads for silo intended for whole-plant silages.

Curves showing average densities of alfalfa versus total settled depth are given in Fig. 8 over a range of moisture contents, $M$ and aspect ratios, $AR$. For an undrained silo containing 70% moisture content alfalfa, there is a buildup of hydrostatic pressure in the lower part of the silo because the contained material becomes saturated when a sufficiently high density is reached. Thus, a lower average density is used below the saturation level in water-tight, undrained silos as the submerged density of silage decreases with an increase in moisture content (Negi and Jofriet 1984). The average bulk density obtained from Fig. 8 is used in the Janssen formula for calculation of wall pressure distributions in tower silos.

**CONCLUSIONS**

Based on the results of this study the following conclusions were drawn:

1. Silage is a nonlinear viscoelastic material which exhibits a low resilience and consequently a high hysteresis loss — about 90% of the total input. The hysteresis loss for the maiden cycle is greater than that for the second cycle, which produces about the same loss as the third cycle.

2. The rate of deformation has a significant influence on the relaxation of stresses during the first few seconds after holding the deformation. The faster the loading rate, the greater the stress decay. A long-time test over a period of 100 h indicated that stress continues to decrease with time and is likely to approach zero as time approaches infinity.

3. The stress-time relationship of a silage material subjected to a constant strain can be described by a three-term exponential equation. The longest time constant is relatively unaffected by the rate of loading.

4. Since moisture content in the ranges studied (65-76%) had practically no effect on the angle of internal friction and cohesion of silage materials, average
values for C and \( \phi \) of 1 kPa and 30\(^\circ\), respectively, are recommended.

5. Design curves for obtaining the average bulk density of whole-plant silages in farm silos are provided for various height to diameter ratios, and for silage moisture contents ranging from 40 to 70\%. This is one of the parameters required for the structural design of tower silos.

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REFERENCES
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