Compression and relaxation properties of timothy hay

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Abstract: The compression and relaxation characteristics of timothy hay were investigated with respect to hay moisture content, applied load, and hay quality. Experimental trials were performed by using a Baldwin hydraulic universal testing machine model 60 HVL-1254. The applied loads ranged from 90 kN to 240 kN, in 30 kN increments. Two qualities of timothy hay were used, high quality with moisture contents of 7.44%, 10.17%, 12.97%, and 16.42% wet basis (w.b.), and low quality with moisture contents of 6.38%, 8.67%, 16.24%, and 18.94% w.b. The results indicated that the compact density of hay samples increased with increasing moisture content and applied pressure. Less maximum applied pressure was required to achieve the same compact density with increasing moisture content. Models were fitted to the applied pressure-compact density data. Relationships were developed between the model constants and the experimental variables. The use of Faborode-O'Callaghan model for bale densities less than 500 kg/m^3 and the simple power law model for bale densities greater than 500 kg/m^3 are the most appropriate models expressing the relationship between density and pressure during the compression of timothy hay. The relaxation of the hay samples were affected by the initial maximum applied load or pressure and the moisture content. Samples with higher moisture contents had higher percentage relaxation than low moisture content samples. The percent relaxation values ranged from 27.40% to 53.35% for the high quality hay, and for the low quality hay the values ranged from 28.80% to 53.70%. The asymptotic modulus values (E_A) were influenced by the maximum applied pressure or load and moisture content. A linear relationship was developed between the asymptotic modulus, maximum applied pressure, and moisture content.

Keywords: densification, compaction, moisture content, visco-elastic properties, density, asymptotic modulus, disinfestations, Canada

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1 Introduction

Hay has been baled or densified into various sizes, shapes, and weights for many years to minimize storage space, and cut down on transportation costs. A major issue in the business of exporting hay is the phytosanitary

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requirements of the importing countries, due to the possibility of introducing Hessian fly *(Mayetiola destructor* (Say)) from infested hay into importing countries like Japan. The Japanese authorities have set up quarantine procedures in order to exclude infested products from reaching their country. Buntin and Raymer[1] investigated the effect of Hessian fly damage on the forage production of susceptible and resistant cultivars of soft red winter wheat and indicated that the total dry matter yield of the forage was reduced by 14% to 46%.

The Hessian fly pupae live within hollow, stemmed plants (wheat, rice, barley, rye, and *Agropyron* species). In ideal conditions, the fly can have up to two generations in one season. After the larva has reached full growth, the skin hardens, and turns brown; this covering is called the puparium. It is at this point that the insect enters a period of aestivation, or dormancy[2].

Although Hessian fly prefers wheat plants, it can also infest timothy hay bales. It is possible that volunteer plants, such as wheat or barley which may be growing in a timothy hay field, may unintentionally be incorporated once the hay is cut and baled. After field baling, the timothy hay bales are transported to a central processing plant for rebaling or recompression, so as to further increase the bale bulk density and increase the capacity of shipping containers. Disinfestation studies performed by Shaw et al.[3,4] revealed that compressing the bales is an effective way of destroying Hessian fly puparia, thus, disinfesting the hay. Yokoyama et al.[5] determined that compression alone could be a successful means of disinfesting compressed hay, provided that a minimum pressure of 20.6 kPa (0.21 kg/cm^2 or 3 psi) could be achieved at all locations in the bale.

Hay processors in Western Canada already have existing re-baling machines for mechanical recompression of field-compressed (single-compressed) baled hay into double-compressed baled hay for export. Compression characteristics of baled hay depend on the compression machine, initial hay moisture content, quality, harvest cut number (which dictates the coarseness/fineness and fiber content of hay) and type of hay and the time required (hold or grunt time) for compression. Pitt and Gebremedhin[6] experimentally determined pressure-density relationship for chopped alfalfa and grass at different moisture contents, chop lengths, and harvest cut number. They indicated that for alfalfa, the material stiffness (pressure to attain a given change in density) was higher for second-harvest material than for the first-harvest material. However, for grass material, the first-harvest was stiffer than second-harvest. The effects of moisture content and chop length on alfalfa material stiffness were variable.

The objective of this study is to investigate how hay moisture content, applied load, and quality affect the compression and relaxation characteristics of timothy hay. Knowledge of the aforementioned characteristics will allow for the prediction of pressure in any location within the hay bales.

2 Materials and methods

2.1 Materials

Two different qualities of timothy hay were used throughout this experiment. The hays were obtained from Elcan Forage Inc. of Broderick, SK, Canada, a hay processor and exporter. The “first cut” hay contained higher amounts of hay stalks and was designated as high premium (HP) or high quality hay, whereas, the “second cut” hay consisted mainly of leafy material with less amount of stalks and was designated as low premium (LP) or low quality hay. Both hays had an initial moisture content of 14%. Before testing, each timothy hay quality was separated into 4 groups and their moisture contents were adjusted to 6%, 10%, 15%, and 18% wet basis, w.b. In order to achieve moisture contents below the initial moisture content of 14%, the samples were dried until the desired value was achieved. For moisture contents above 14%, a calculated amount of deionised water was sprayed evenly over the fluffy material. All of the samples were sealed in large containers and kept at 5℃ in a walk-in cooler for over 14 days. Prior to the start of the experiment, moisture contents of the samples were again verified to ensure accurate results. Moisture content was determined according to ASABE Standard ASAE S358.2 FEB03[7], where 25 g sample was dried in a convection oven at 103℃ for 24 h. Moisture was determined in triplicates and expressed in percent wet basis (% w.b.).

2.2 Compression and relaxation tests

The compression tests were performed using a Baldwin Hydraulic Universal Testing Machine Model 60 HVL-1254 (Satec System Inc., Grove City, PA). The machine is capable of reaching a maximum load of 250 kN. The loading speed for all the samples was consistently the same, at a value of (1.5±0.25) mm/s. A computer with a Labview (National Instruments, Austin, Texas) generated program was hooked up to the Baldwin machine in order to record time, force, and distance data throughout the test. The computer had a 6024R DAQ card installed, which is a 12 bit multi-purpose input/output card. A cable connected this to a SCXI-1000 chassis, which contained the slots for data acquisition modules. Two modules were used in this testing procedure. The first was a SCXI 1120D w/1305 front plate, which was used to read the voltage input from the load cell as well as the displacement sensor. The other module was a SCXI 1180 w/1302 front plate; this module allowed the user to feed an output voltage from the 6024E DAQ card to control the loading and unloading rate. The interface load cell used had a maximum capacity of 222.4 kN and a resolution of 4.22 mV/V. Linear displacement during compression was recorded with a Temposonics G-Series linear position sensor (MTS Sensors, Cary, NC).

The compression cell used to compress the hay had a cross-sectional area of 70 mm×70 mm. The initial height of the sample was determined by measuring the distance between the upper and lower loading plates with a digital calliper. During compression, the displacement measured by the linear position sensor was subtracted from the initial distance measured to determine the instantaneous height of the sample.

Hay samples were hand packed into the compression cell. A sample size of 300 g was packed uniformly into the cell. The samples were cut to 127 mm lengths and layered into the cell in a crisscross fashion. The experiments were designed with two factors: hay quality and hay moisture content. Two levels of hay quality and four levels of moisture content were used in the tests. The hay samples were compressed to 6 different loads, starting at 90 kN and increasing at intervals of 30 kN to 240 kN. These loads translate into maximum applied pressures of 5.58 MPa, 7.44 MPa, 9.30 MPa, 11.16 MPa, 13.02 MPa and 14.88 MPa. After each desired load was reached, the compression machine crosshead was stopped and its position was held constant until a total elapsed time of 200 s had passed. During this time, the relaxation in the material was observed, where the force with respect to relaxation time were recorded. After each test, the sample was removed, weighed and sealed in a bag for post-experiment moisture content determination. One test was conducted for each treatment. The data recorded by the computer was used to determine the instantaneous velocity of the Baldwin machine crosshead speed, the density of hay, and pressure with respect to time.

2.3 Data analysis

The experimental data was analyzed by using several models which have previously been used to describe experimental compression and relaxation data. The models were fitted to the experimental data using both SAS (Statistical Analysis System, Cary, NC) and Microsoft Excel (Microsoft Corp., Redmond, WA) programs. The SAS program was used in the analysis of Cooper-Eaton model. The rest of the models were analyzed using the Excel program. For the Microsoft Excel analysis, the raw data was analyzed with both the solver function and non-linear regression. The constants that were determined from the models were related to the experimental variables. The mean square error and the coefficient of determination were used to determine the acceptability of the correlation between the model constants and the experimental variables.

The compressibility of powders has been analyzed on numerous occasions by many researchers. The models proposed by these researchers were assessed on their applicability to the compression of timothy hay. Walker[8] described the volume ratio in terms of applied pressure for non-metallic powders, and particles of sulfur, ammonium and sodium chloride, and trinitrotoluene (Equation (1)).

$$\frac{V}{V_s} = m \cdot \ln P + b \quad (1)$$

Where, V = volume of compacted hay, m^3; V_s = void-free solid volume, m^3; P = applied pressure, MPa; m, b = constants.

Jones[9] indicated that the relationship between pressure and density of industrial metal powders could be represented by a straight line when plotted on log-log scales (Equation (2)).

$$\ln \rho = m' \cdot \ln P + b' \quad (2)$$

Where, ρ=compact bulk density, kg/m^3; m', b'= constants.

Kawakita and Lüdde[10] related pressure to volume reduction of metallic powders, Equation (3).

$$\frac{P}{C} = \frac{1}{a_1 b_1} + \frac{P}{a_1} \quad (3)$$

$$C = \frac{V_0 - V}{V_0} \quad (4)$$

Where, C = volume ratio; V_0 = initial volume at zero pressure, m^3; a_1, b_1 = constants.

The last model for compression of powders that was used to describe the hay compression data was by Cooper and Eaton[11]. Equation (5) was created to numerically depict the compression of ceramic powders through two independent probabilistic processes. The first of which was the filling of large voids through material sliding past one another and slight fractures. The second process included the filling of small voids through plastic flow and fragmentation.

$$\frac{V_0 - V}{V_0 - V_s} = a_2 e^{\frac{-k_1}{P}} + a_3 e^{\frac{-k_2}{P}} \quad (5)$$

Where, a_2, a_3, k_1, k_2 = constants.

The compression characteristics of straw were analyzed by both Pitt and Gebremedhin[6], and Faborode and O'Callaghan[12]. Faborode and O'Callaghan's[12] model (Equation (6)) was assessed to determine its applicability to timothy hay compression. Pitt and Gebremedhin[6] provided a model (Equation (7)) that was a slight modification of Faborode and O'Callaghan's model. Both are exponential models that express pressure in terms of compressed straw density. The compression of straw can be modeled by these equations up to a density of 500 kg/m^3, after which the equations become inaccurate.

$$P = \frac{A\rho_0}{b_2}[e^{b_2(\frac{\rho}{\rho_0}-1)} - 1] \quad (6)$$

$$P = h[e^{f(\beta-\beta_0)} - 1] \quad (7)$$

Where, ρ_0 = initial bulk density, kg/m^3; β = dry matter density, kg/m^3; β_0 = compact dry matter density, kg/m^3; A, b_2, f, h = constants.

A model to describe the relaxation characteristics of solid foods was developed by Peleg and Moreyra[13]. Relaxation curves at different deformation levels were normalized and fitted to the model (Equation (8)). The constants in the model give the shape characteristics of different types of material and can be used to compare different materials.

$$\frac{F_0 \cdot t}{F_0 - F(t)} = k_3 + k_4 \cdot t \quad (8)$$

Where, F_0= initial relaxation force, kN; $F(t)$= relaxation force at time t, kN; t =time, s; k_3, k_4 = constants.

Moreyra and Peleg[14] (1980) modified Peleg and Moreyra's[13] model and indicated that the slope should be greater than one (Equation (9)). The slope can be used as an index which gives an indication of the solidity of the compressed material. The slope can also be used in determining the asymptotic modulus of food powders and solid foods[15]. The asymptotic modulus is the residual stress in the Peleg's relaxation model and can be defined as the ability of the compressed material to sustain un-relaxed stresses.

$$E_A = \frac{F_0}{A_a \varepsilon}\left(1 - \frac{1}{k_4}\right) \quad (9)$$

Where, E_A = asymptotic modulus, MPa; ε = strain; A_a = cross-sectional area, m^2.

The percent average relaxation was calculated by using the initial force at the beginning of the relaxation phase and the final force after an elapsed time of 200 s. The equation for calculating the percent average relaxation is given in Equation (10) as follows:

$$\text{Percent average relaxation} = \frac{100 \times (F_0 - F_e)}{F_0} \quad (10)$$

Where, F_e = final relaxation force, kN.

3 Results and discussion

3.1 Moisture content

The moisture content values of timothy hay measured before and after testing showed that all of the samples except for those adjusted to 6%, lost moisture during storage and testing (Table 1). The variation in the moisture contents before and after testing could be attributed to the variable moisture distribution in the hay during conditioning and storage. Also, relative humidities are approximately 30% or lower in the storage, making samples to lose moisture during storage.

Table 1 Moisture content of hay samples before and after each test

Sample ID	Moisture content /% w.b.	
	Before test	After test
LP-18*	21.39 (1.17)	18.94 (1.37)
LP-15	16.36 (0.29)	16.24 (0.39)
LP-10	10.76 (0.06)	8.76 (0.62)
LP-06	6.21 (0.14)	6.38 (0.26)
HP-18**	18.11 (0.30)	16.42 (0.57)
HP-15	13.55 (0.06)	12.97 (0.27)
HP-10	10.55 (0.31)	10.17 (0.24)
HP-06	6.57 (1.98)	7.44 (0.88)

Note: * LP-## stands for low quality hay, followed by its expected moisture content in % wet basis.

** HP-## stands for high quality hay, followed by its expected moisture content in % wet basis.

Values in brackets represent standard deviation, n = 3.

3.2 Hay density

Table 2 shows the effects of applied pressures and moisture content on the compact density of the timothy hay samples. The compact density of the hay samples increased with increasing moisture content. Comparing the compact density of the hay samples at almost similar moisture contents of 16.24% for low quality and 16.42% for high quality, it is observed that there were marginal differences in their compact densities. Hay quality did not appear to influence the compact density of the hay samples. The density of the high quality hay at 7.44% moisture content was slightly higher than the low quality hay at 8.76% for applied pressures of 13.02 MPa and 14.88 MPa. The density of the samples increased with the increasing applied pressures for a particular moisture content. Watts and Bilanski[16] reported that an increase in moisture content increased the compact density of alfalfa samples, and that the maximum applied pressure also increased the compact density. They indicated that an increase in moisture content significantly reduced the maximum applied pressure required to achieve the same compact density. The same trend reported by Watts and Bilanski[16] was also observed in this investigation. During the relaxation portion of the test, the densities remained constant. Figure 1 shows a typical compression curve of the timothy hay samples at different levels of preset compression pressures.

Table 2 Density of compressed hay (kg/m^3) at different maximum applied pressures and moisture contents

Moisture content /% w.b.	Applied pressure /MPa					
	5.58	7.44	9.30	11.16	13.02	14.88
High quality timothy hay						
7.44	752.9	799.4	812.9	860.1	925.3	978.7
10.17	804.3	826.7	947.7	992.7	1 075.2	1 130.8
12.97	883.7	930.8	966.8	995.0	1 283.8	1 314.7
16.42	921.7	1 037.6	1 122.5	1 204.2	1 277.7	1 308.4
Low quality timothy hay						
6.38	625.7	671.2	716.1	773.8	822.7	913.2
8.67	804.7	829.8	852.0	879.6	902.4	924.2
16.24	997.9	1 035.0	1 076.1	1 189.1	1 197.7	1 333.6
18.94	1 124.5	1 151.2	1 229.0	1 375.9	1 414.8	1 466.0

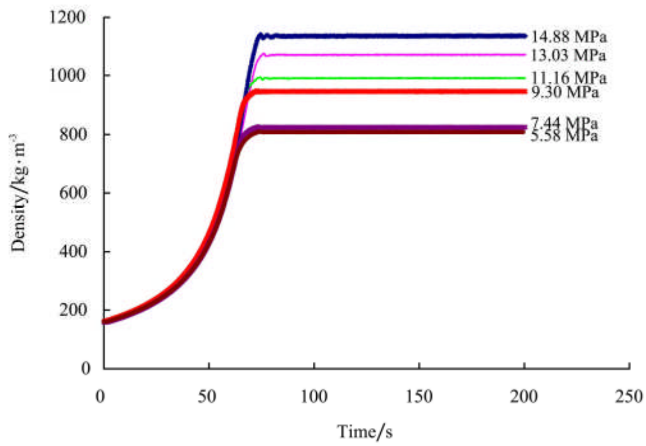

Figure 1 Typical curves of hay density as a function of compression and relaxation time at different preset levels of compression pressures for high quality hay at a moisture content of 10.17% w.b.

As the pressure increased, the rate of density change decreased. This is a result of the hay displacing and depleting the amount of air gaps and voids contained within the sample cell. Narayan and Bilanski[17] also observed the same trend in their studies of uniaxial compression of wheat straw. They indicated that at low pressure, particle reorientation dominated the load response; whereas at high pressure, individual particle deformation affected the load behavior. The horizontal sections of the curves are when the compression of the hay samples ends and relaxation begins. During relaxation, the density remains constant at constant strain and the pressure decreases with time.

3.3 Compression models

The relationship between pressure, volume, and density of the timothy hay during the compression portion of the tests were fitted to models that have been developed for powders. The first of which was Walker's model[8]. This model yields values of volume ratio which decrease linearly as the pressure increases. The graph shows that the volume ratio of compressed hay was high at low hay moisture content. In other words, low moisture content hay samples produced compressed samples of higher volume ratios which indicate that low moisture samples require more energy to compress than high moisture samples. Walker's model produced an average coefficient of determination value of 90% (R^2 = 0.90). Figure 2 shows the relationship between the volume ratio and the natural logarithm of applied pressure.

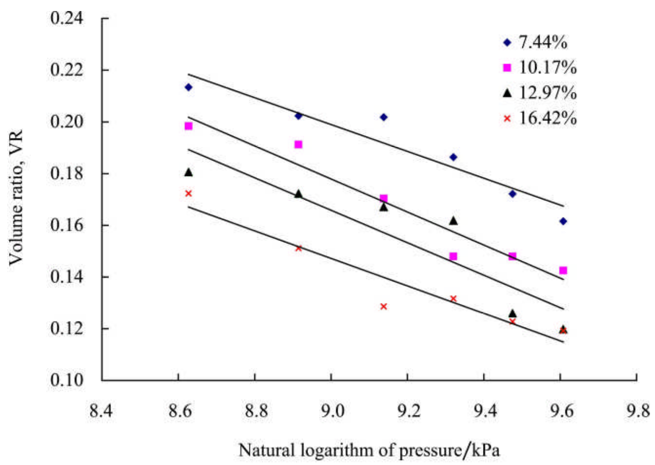

Figure 2 Fitting of Walker's model to the experimental compression data for high quality timothy hay

The value of compressibility constant, "*m*", the slope, is relatively consistent, and is seen to stay more constant in the high quality hay samples. For high quality samples "*m*" had an average value of -0.05688 with a standard deviation of 0.00573. While the low quality samples "*m*" had an average value of -0.03547 with a standard deviation of 0.004957 (14%). The high quality hay showed a higher slope (absolute value) indicating higher compressibility than the low quality hay. The differences could probably be attributed to the make up of the hays. The low quality hay consisted of more leafy material compared to the high quality hay which had more stalks. The leafy material in the low quality hay resulted in its low compressibility. The slope m, slightly decreased with increasing moisture content. A relationship was established between the hay moisture content and the slope "*m*". The value of "*b*" peaked between a moisture content of 10%-15%, before and after which, the value of "*b*" decreased. A relationship was observed between the moisture content of the samples and the constant "*b*". These relationships varied slightly between the two hay qualities and are shown in Equations (11) to (14). The R^2 of the model constants of high quality hay were higher compared to the low quality hay.

High quality hay:

$$m = 0.136 - 0.087\sqrt{M_c} + 0.002\sqrt{M_c^3}$$

$$[R^2 = 0.999,\ \text{Standard error} = 0.0036] \quad (11)$$

$$b = -0.918 + 0.741\sqrt{M_c} - 0.022\sqrt{M_c^3}$$

$$[R^2 = 1.000,\ \text{Standard error} = 0.0017] \quad (12)$$

Low quality hay:

$$m = -0.429 + 0.169\sqrt{M_c} - 0.004\sqrt{M_c^3}$$

$$[R^2 = 0.783,\ \text{Standard error} = 0.0165] \quad (13)$$

$$b = 4.315 - 1.621\sqrt{M_c} + 0.040\sqrt{M_c^3}$$

$$[R^2 = 0.826,\ \text{Standard error} = 0.1561] \quad (14)$$

Where, M_c = hay moisture content, % w.b.

Jones[9] model was not successful in modeling the compression characteristics of timothy hay. No consistent relationship was determined between the model constants and the experimental variable.

R^2 values obtained from Kawakita and Lüdde[10] model ranged between 0.997 and 1.000. However, no correlation was found between the model constants in this equation and the experimental variables. The values of a_1 and b_1 increased with moisture content, but no suitable trend could be established.

Cooper and Eaton's[11] model elucidates the two mechanisms that exist during the compression of powders.

The mechanisms include the filling of large pores through particle rearrangement and the filling of smaller pores through fragmentation and plastic flow. These two processes are represented by the constant a_2 and a_3, respectively, in the Cooper-Eaton model. The model analysis yielded values for a_2 ranging from 0.63 to 0.99, while the values of a_3 ranged from values of 0.00 to 0.26 (Table 3). This suggests that majority of the compression occurs by filling the large pores through particle rearrangement. There is a slight indication of compression through plastic flow and fragmentation, which is most likely due to the presence of finer particles distributed throughout the majority large particles. The values of k_1 and k_2 showed a lot of variations and no trend was observed between them and the experimental variables. The R^2 between the experimental and calculated values of the volume ratio were all higher than 0.72 with majority of them near 0.90.

Table 3 Cooper-Eaton model (Equation (5)) constants for both hay qualities

Sample ID	a_2	a_3	k_1	k_2	R^2
LP- 6*	0.626	0.260	0.495	0.496	0.91
LP-10	0.913	0.000	-0.338	-0.338	0.92
LP-15	0.871	0.100	1.504	1.503	0.86
LP-18	0.967	0.077	-3.199	1 146.900	0.90
HP- 6**	0.988	0.000	53.331	-2 483.100	0.84
HP-10	0.881	0.076	-8.484	678.000	0.92
HP-15	0.949	0.000	0.790	-208.900	0.72
HP-18	0.933	0.040	0.122	0.122	1.00

Note: * LP-## stands for low quality hay, followed by its expected moisture content in % w.b.

** HP-## stands for high quality hay, followed by its expected moisture content in % w.b.

Faborode and O'Callaghan's[12] model (Equation (6)) was able to predict accurately the relationship between pressure and compact density for compact densities less than 500 kg/m^3. The R^2 were always equal to 1.0. Unlike Pitt and Gebremedhin's[6] model (Equation (7)), the values of the model constants determined by using Faborode-O'Callaghan's model could be predicted using the experimental variables. It was determined that the constant "b_2" (Equation (6)) did not correlate well with the hay moisture content. The average and standard deviation of "b_2" for all the hay samples were 1.02 and 0.16. The values of "A" could be related to the wet basis moisture content, M_c, by the following relationship:

$$A = -95M_c + 2100 \tag{15}$$

Therefore, the new form of Faborode-O'Callaghan model for compressing timothy hay at densities of less than 500 kg/m^3 can be written as follows.

$$P = \frac{(2100 - 95M_c)\rho_0}{1.02}[e^{1.02(\frac{\rho}{\rho_0}-1)} - 1] \tag{16}$$

The R^2 values between the experimental and calculated "A" values for the high quality and low quality hay were 0.844 and 0.910, respectively. The mean square error for these same data points were 16 446.16 and 32 007.25 for high quality and low quality hay, respectively.

Pitt and Gebremedhin[6] model accurately described the relationship between pressure and density with R^2 values equal to 1.0. However, the values of the model constants did not have any relationship with the experimental variables. Therefore, this equation was not useful for modelling the correlation between the model constants and the experimental variables.

It was determined that a simple power law model of the following form:

$$P = B_2(\rho^{B_1}) \tag{17}$$

could accurately relate the applied pressure to the hay sample compact density above 500 kg/m^3. Where, B_1, B_2 = constants.

The average value of constant B_1 was determined to be 3.36 with a standard deviation of 0.17 for both hay qualities. Van Pelt[18] obtained average B_1 values of 0.29, 0.24, 0.24 and 0.23 for dry corn stalks, soybean straw, wet corn and dry alfafa hay, respectively. The value of "B_2" varied with moisture content. A relationship between the constant B_2 and moisture content was established for both hay qualities. The relationship between B_2 and moisture content was different for the two hay qualities used in this experiment. Equation (18) shows the power law model for both hay qualities at densities above 500 kg/m^3.

$$P = B_2(\rho^{3.36}) \tag{18}$$

where, for high quality timothy hay:

$$B_2 = \exp^{\left[-21.369+(\frac{17.643}{M_c})\right]} \tag{19}$$

and for low quality hay:

$$B_2 = 1.2\times10^{-8} - 6.0\times10^{-10} M_c \qquad (20)$$

The R^2 values for the calculated versus experimental values were 0.834 and 0.832 for high and low quality hays, respectively. When comparing the calculated values of pressure versus the experimental values, the coefficient of determination for all the samples was 1.0. This shows that a simple power law model can successfully predict the relationship between pressure and density during the compression of timothy hay above densities of 500 kg/m^3.

3.4 Relaxation characteristics

The hay samples experienced a relatively uniform increase in compression pressure as the loads were applied. After the desired pressures were reached, the relaxation characteristics of the compressed samples were observed. The initial loading of the samples followed the same curve pattern, while the relaxation curves were almost equally spaced and followed the same pressure decaying pattern. The slight fluctuations in the curves may be due to the relaxation characteristics of the hay samples. The relaxation curves were affected by the initial maximum applied load. The higher the applied pressure, the higher is the residual stress that is left in the sample. Typical compression-relaxation curves for the hay samples are presented in Figure 3. Tabil and Sokhansanj[19] observed similar compression-relaxation characteristics during the compaction of alfalfa grinds.

The compression-relaxation characteristics of the hay samples show that the relaxation behavior of timothy hay is time-dependent. Hay samples exhibited both elastic and viscous characteristics, a behavior exhibited by most agricultural materials. This shows that timothy hay is a viscoelastic material. Since large strain stresses were applied and all the strains were not recovered, timothy hay samples might have exhibited nonlinear viscoelastic behavior. Zoerb and Hall[20] determined that agricultural products such as pea bean exhibited viscoelastic behavior. Negi et al.[21] similarly reported that silages exhibited nonlinear viscoelastic behavior.

As the moisture contents of the timothy hay samples were increased, the percent relaxation also increased for both hay qualities (Table 4). The moisture content of the samples had an evident effect on the percent relaxation. The high quality hay illustrates this trend more than the low quality hay. The effect of applied load on the percent relaxation of hay was random. The hay qualities did not seem to affect the percent relaxation, as no major trend was observed. The percent relaxation values ranged from 27.40% to 53.35% for the high quality hay, and for the low quality hay the values varied from 28.80% to 53.70%.

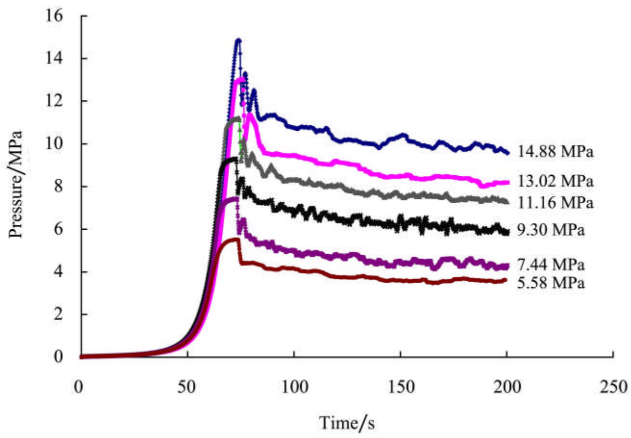

Figure 3 Typical pressure vs. time curves for varying maximum applied pressures during compression and relaxation for high quality timothy hay at 10.17%

Table 4 Effects of applied pressure and moisture content on percent relaxation of high quality and low quality hay

Applied pressure /MPa	High quality hay percent average relaxation /%				Low quality hay percent average relaxation /%			
	*MC** = 7.44%	*MC* = 10.17%	*MC* = 12.97%	*MC* = 16.42%	*MC* = 6.38%	*MC* = 8.76%	*MC* = 16.24%	*MC* = 18.94%
5.58	27.4	34.4	44.1	46.6	28.8	48.0	46.8	43.2
7.44	38.1	42.0	40.6	52.5	34.0	38.5	42.5	44.0
9.30	37.5	36.4	53.3	50.6	38.7	49.0	42.1	53.7
11.16	35.5	35.1	39.5	43.4	40.5	44.0	47.1	44.9
13.02	34.8	37.2	43.1	38.2	34.1	42.7	49.2	38.1
14.88	35.6	35.6	37.6	35.6	32.2	39.7	47.9	41.4

Note: **MC* = moisture content of the hay before testing or after testing.

The internal pressure of the compressed hay samples declined towards an asymptotic value during the relaxation period. It was observed that the slope (k_4) of Equation (8) decreased with increasing moisture content and was relatively unaffected by the maximum load or pressure. This suggests that timothy hay is less rigid with increasing moisture contents. Moreyra and Peleg[14] and Peleg and Moreyra[13] reported that the slopes (k_4 values) of wet materials were lower than dry materials. Peleg and Moreyra[13] suggested that this phenomenon could be attributed to the internal flow of liquid in the sample and rearrangement of liquid bridges.

The values of E_A can be thought of as a measure of the sample rigidity, the less rigid a sample is, the smaller its asymptotic modulus. Similar to the values of k_4, the values of E_A decreased with increasing moisture content. Furthermore, the values of E_A increased with increasing maximum load or pressure. The applied load affected E_A in this manner because a higher applied load could cause a higher density or solid-like properties. Table 5 shows the asymptotic modulus of all samples tested. The increase in E_A values with respect to increasing applied pressures have been reported by other researchers[19,23] as well.

Table 5 Asymptotic modulus (E_A) of timothy hay as a function of hay quality, maximum pressure, and moisture content

Hay quality	Moisture content/%	Maximum applied pressure /MPa					
		5.58	7.44	9.30	11.16	13.02	14.88
		Asymptotic modulus /MPa					
Low	6.38	4.87	6.01	7.49	8.37	10.76	11.81
Low	8.76	3.47	5.17	5.61	7.36	8.83	10.51
Low	16.24	3.26	4.82	6.25	6.60	6.34	7.62
Low	18.94	3.91	4.72	4.65	6.52	8.82	10.33
High	7.44	4.90	5.60	7.04	8.64	10.10	11.43
High	10.17	4.27	5.24	6.94	8.52	9.27	11.17
High	12.97	3.44	5.28	5.38	7.69	7.74	10.32
High	16.42	3.48	3.71	5.17	7.29	9.03	10.50

The manner in which the E_A values varied with respect to the moisture content and the maximum applied pressure were analyzed. It was determined that a linear relationship existed as indicated by Equation (21). The relationship can be applied to both hay qualities. The R^2 values between experimental and calculated E_A was determined to be 0.90, and the mean square error was 0.63. Tabil and Sokhansanj[19] reported a power law relationship between the maximum applied pressures and the E_A values. Mani et al.[23] presented a linear relationship between the E_A values and the applied pressures. In this study, E_A was a linear function of both the maximum applied pressure and moisture content of the hay sample.

$$E_A = 0.787P_M - 0.093M_c \quad (21)$$

Where, P_M = maximum applied pressure, MPa.

4 Conclusions

The compression and relaxation characteristics of timothy hay samples were investigated and the following conclusions can be drawn:

1) The compact density of the hay samples increased with increasing moisture content and maximum applied pressure. Less maximum applied pressure was required to achieve the same compact density with increasing moisture content.

2) Models were fitted to the applied pressure-compact density data. Relationships were developed between the model constants and the experimental variables.

3) The use of Faborode-O'Callaghan model for bale densities less than 500 kg/m^3 and a simple power law model for bale densities greater than 500 kg/m^3 appropriately expressed the relationship between pressure and hay density during the compression of timothy hay.

4) The percent relaxation of the hay samples were affected by the maximum applied pressure and the moisture content of hay. Hay samples with higher moisture contents had higher percent relaxation than low moisture content samples. The percent relaxation values ranged from 27.4% to 53.35% for the high quality hay, and from 28.8% to 53.7% for the low quality hay.

5) The asymptotic values (E_A) were influenced by the maximum applied pressure and hay moisture content. A linear relationship was developed between the asymptotic modulus, maximum applied pressure and moisture content.

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