Compression of fractionated sun-cured and dehydrated alfalfa chops into cubes: Pressure and density models

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Adapa, P., Schoenau, G., Tabil, L., Sokhansanj, S. and Singh, A. 2005. **Compression of fractionated sun-cured and dehydrated alfalfa chops into cubes: Pressure and density models.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 3.33-3.39. The compression of fractionated sun-cured and dehydrated alfalfa chops was studied by fitting the compression data to five pressure density equations. The cubes were made from different mixtures of leaves and stems from either sun-cured alfalfa or artificially dried alfalfa. In general, the Cooper-Eaton model had the best fit for the data. However, the coefficient of multiple determination (R^2 values) obtained were very low. Therefore, new statistical cube compaction models for sun-cured and dehydrated alfalfa were developed. Multiple linear regression analysis was performed, where density was considered as the dependent variable while pressure, holding time, and leaf content were considered as independent variables. The new models had better R^2 values compared to the five current models. **Keywords**: fractionation, alfalfa chops, cube, linear regression, sun-cured and dehydrated alfalfa.

La compression de mélanges de luzerne hachée séchée au soleil et déshydratée a été étudiée en soumettant les données de compression à cinq équations de prédiction de la densité en fonction de la pression appliquée. Les cubes ont été faits à partir de différents mélanges de feuilles et de tiges de luzerne séchée au soleil ou séchée artificiellement. De manière générale, le modèle Cooper-Eaton a offert la meilleure prédiction de la densité par rapport aux données expérimentales bien que les valeurs du coefficient de détermination multiple (valeurs de R^2) obtenues aient été très faibles. Par conséquent de nouveaux modèles statistiques pour la compaction de cubes ont été développés pour la luzerne séchée au soleil ou déshydratée. Une analyse de régression multiple linéaire a été réalisée en considérant la densité comme variable dépendante et le temps de compression et le contenu en feuilles comme variables indépendantes. Les nouveaux modèles avaient de meilleures valeurs de corrélation R^2 comparativement aux cinq modèles courants. **Mots clés**: fractionnement, hachures de luzerne, cube, régression linéaire, luzerne séchée au soleil et déshydratée.

INTRODUCTION

Fractionation of alfalfa is an important concept, wherein, the plant is separated into two or more component parts (usually leaves and stems). Alfalfa leaf fraction is high in protein and carotenoids, low in fiber and is useful to feed monogastric animals such as poultry and swine or as a protein supplement in the pharmaceutical industry for human consumption. Alfalfa stem fraction is high in fiber and can be used for ruminant feed, paper and hardboard, and energy production (biofuel/ethanol).

Alfalfa forage crop is cut, chopped, dried, and densified to make cubes typically 30x 30 mm in cross-section. The densified cubes result in lower handling, transportation, and storage costs, especially for export. Alfalfa chops exhibit distinct behavior under various pressures and holding time during cubing. To a great extent, the quality of a manufactured cube depends on the physical forces that bond alfalfa chops together (Tabil and Sokhansanj 1996a).

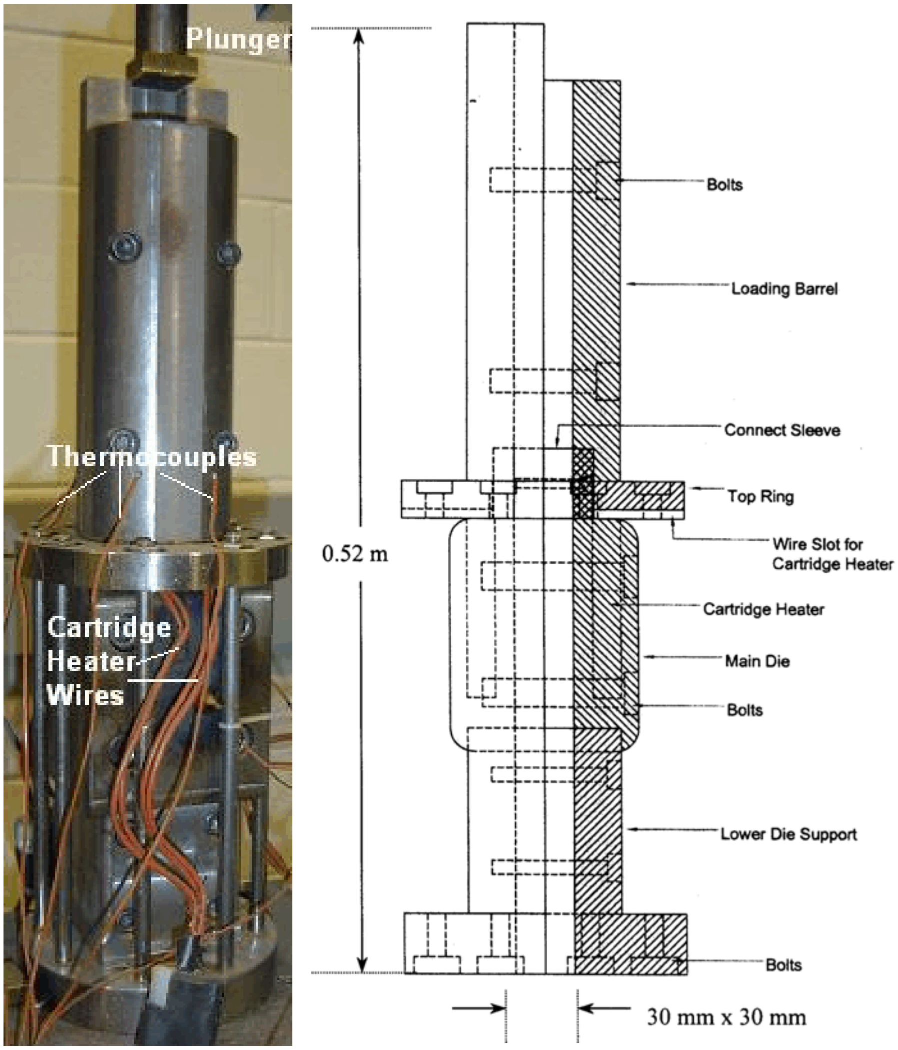
Therefore, it is important to study the compression characteristics of fractionated sun-cured and dehydrated alfalfa chops, when subjected to different pressures and holding times. A close fit plunger die assembly was used to make a cube in a single stroke of the plunger. Cubes are formed by subjecting alfalfa chops to high pressure, forcing the particles to agglomerate. Compaction of chops is usually achieved in three stages. In the first stage, particles rearrange themselves under low pressure to form close packing. In the second stage, elastic and plastic deformation of particles take place allowing them to flow into smaller void spaces increasing inter-particle surface contact area. Finally, in the third stage, under high pressure, the second stage of compaction continues until the true density of particles is reached. During this phase, starch gelatinization, and protein de-saturation, and cross-linking in alfalfa may occur forming very strong solid bridges (Tabil and Sokhansanj 1996b; Hasting and Higgs 1978).

Particles (metallic or non-metallic) behave in a different manner under different pressures and holding times. Therefore, it is important to study the change in compact density and volume as a function of pressure and holding time. Five compaction models were studied using the pressure-volume and pressure-density data obtained during compression tests of alfalfa chops, namely Heckel (1961), Walker (1923), Jones (1960), Cooper and Eaton 1962), and Panelli and Filho (2001). For details on these five models and their concepts, see Adapa et al. (2002). It was deemed appropriate to develop new cube compaction models for sun-cured and dehydrated alfalfa chops because the already existing models are unable to define the compaction behavior of alfalfa chops.

MATERIALS and METHODS

Material preparation

Fractionated sun-cured and dehydrated alfalfa chops were used to make cubes. Sun-cured chops were obtained from a forage



(a) (b)

Fig. 1. Photograph (a) and right-sectioned view (b) of the cube die assembly used to study the compression behavior of dehydrated and sun-cured alfalfa chops.

processing plant at Broderick, Saskatchewan. Dehydrated chops were acquired from an alfalfa dehydrating plant in Tisdale, Saskatchewan. The moisture contents of sun-cured and dehydrated chops were 7 and 6% (wb), respectively. The moisture content was determined using ASAE Standard S358 (ASAE 2000) and the oven drying was carried out at 103°C for 24 h. Separation of alfalfa into leaf and stem fractions was achieved using ANSI/ASAE Standard S424.1 (ASAE 2003) sieve. The device consists of a stack of five perforated trays with square holes and varying plate thickness. A stack of two sieves (instead of five) was used along with a pan to achieve leaf and stem separation. The nominal opening sizes of the two square-hole sieves were 3.96 and 1.17 mm, respectively. The overs on the 3.96 mm sieve were called stems and the material in the pan was called leaves. Leaves could have also contained fine broken stems. The overs on the 1.17 mm sieve were discarded. Each fractionated component was kept in black polyethylene bags for further analysis.

Leaf and stem fractions were combined on a mass basis to get five different samples each for sun-cured and dehydrated alfalfa with leaf content ranging from 0 to 100% in increments of 25%. Prior to each compression test, the mixture was remoistened to 10% (wb) and was preheated to 75°C. Sample moisture content of 10% was obtained by spraying a predetermined amount of water on the sample chops prior to cubing. Preheating of chops was done using a microwave oven. A 25 g sample was weighed in a plastic container and placed in the microwave oven. A lid was replaced on top of the container to protect moisture from escaping because of the heat. A small hole was made at the center of the lid to insert a thermocouple wire once the sample was removed from the oven. Preheating was required to achieve a uniform elevated chop temperature before feeding them into the cubing die and to form better cubes. In industrial cubing operations, chops come from the dryer where chop temperature ranges from 70 to 90°C.

Evaluation of physical properties

Bulk and particle density of fractionated sun-cured and dehydrated alfalfa chops were determined. Particle density was measured using a gas pycnometer (QuantaChrome, Boynton Beach, FL). A 15-g sample of alfalfa chop was placed in the pycnometer cell and the volume determined. Bulk density was determined by carefully filling a standard 0.5-L cylindrical container (SWA951, Superior Scale Co. Ltd., Winnipeg, MB) with a sample. After filling every third portion of the container volume with alfalfa chops, it was tapped on a wooden table for approximately 10 times to allow the material to settle down. After completely filling the container, excess material at the top was removed using a straight edge. The mass of fractionated chops contained in the cylinder was measured. Three replicates for each sample were performed.

Chop length or particle size of sun-cured and dehydrated alfalfa chops were measured using ANSI/ASAE Standard S424.1 (ASAE 2003). Three replicates for each test were performed.

Cuber

A single cubing unit (Fig. 1) with a square opening of 30 x 30 mm and a length of 0.52 m was designed and constructed. The die consists of five parts: loading barrel, connecting sleeve, top ring, main die, and lower die support. The main die is constructed from stainless steel while the other parts use carbon steel. Four cartridge heaters were used to heat the main die surface to the desired temperature. The die core temperature was measured using four type-T thermocouples inserted into the main die through a connect sleeve. A temperature controller was connected to one of the thermocouples to regulate heat supplied by the cartridge heaters. The die was mounted on a stainless

Table 1. Bulk and particle densities of fractionated sun-cured and dehydrated alfalfa chops at 10% (wb) moisture content.

Leaf content (%)	Density (kg/m^3)			
	Sun-cured alfalfa		Dehydrated alfalfa	
	Bulk	Particle	Bulk	Particle
0	56 ± 2†	1237 ± 4	128 ± 3	990 ± 3
25	109 ± 3	216 ± 4	114 ± 1	1043 ± 1
50	162 ± 2	269 ± 6	161 ± 6	1102 ± 1
75	991 ± 1	1345 ± 1	177 ± 6	1152 ± 2
100	1127 ± 1	1389 ± 3	194 ± 8	1283 ± 1

Number of replicates, n = 3
† ± 95% confidence interval

steel base with a hole matching the outer diameter of the bottom of lower die support. This gave stability and allowed the plunger to move vertically against a lower stationary piston with no lateral movement. Square headpieces of 29 x 29 mm cross-section were attached to the plunger and lower piston to push and compress material inside the die.

Compression test

A hydraulic press with a pressure limit of 14.0 MPa, was used to compress fractionated sun-cured and dehydrated alfalfa chops. Three preset pressures of 9.0, 12.0, and 14.0 MPa were used. The hydraulic press was capable of making a single cube in one stroke of the plunger. The cube die was maintained at a temperature of 90±5°C, in order to simulate the frictional heating of alfalfa chops during industrial cubing operation. The mass of chops used for making each cube varied between 22 and 25 g. After compression, the piston was held in place (holding time) for either 10 or 30 s before the cube was ejected from the die. Fifteen cubes were made at each combination of pressure (9, 12, or 14 MPa), holding time (10 or 30 s), leaf content (0, 25, 50, 75, and 100%) and for two sources of alfalfa (dehydrated or sun-cured). The mass, length, and cross-section of each cube was measured to determine volume and density.

RESULTS and DISCUSSION

Physical properties and compression test

Table 1 shows the bulk and particle densities of fractionated sun-cured and dehydrated alfalfa chops at a moisture content of 10% (wb). The bulk and particle densities of sun-cured and dehydrated alfalfa increased with an increase in leaf content. The particle density of sun-cured alfalfa was higher than dehydrated alfalfa for all leaf contents, which may be because the sun-cured alfalfa came from bales. For bales, the material has been previously compressed, whereas for the dehydrated alfalfa the chops were dried without prior compaction. Also, the difference in drying methods used during processing of sun-cured and dehydrated alfalfa could have some effect. Sun-cured samples are dried in the field using solar radiation; whereas dehydrated alfalfa is dried in rotary drum dryers using temperatures of 500 to 900°C. The sun-cured and dehydrated leaves were mostly in powdered form after fractionation. The particle density analysis showed that sun-cured alfalfa had smaller particle size compared to dehydrated alfalfa, resulting in higher bulk densities for sun-cured alfalfa at 75 and 100% leaf content.

Table 2. Chop length or particle size for sun-cured and dehydrated alfalfa.

Leaf content (%)	Length (mm)	
	Sun-cured alfalfa	*Dehydrated alfalfa
0	+62.7 ± 6.6	28.9 ± 7.2 †
100	*0.89 ±0.15	0.82 ± 0.23

+ Number of replicates, n = 15 (manually measured using vernier caliper)
* Number of replicates, n = 3 (ASAE Standard S424, 1999)
† ± 95% confidence interval

Table 2 shows the chop length or particle size for sun-cured and dehydrated alfalfa. For sun-cured alfalfa stems, the amount of stems retained on the top screen exceeded 1% of the total sample mass, therefore, 15 sub-samples/stems were hand picked and measured manually using a vernier caliper.

Tables 3a and 3b show the cube mass, length, cross-sectional area, volume, and density values for various combinations of applied pressure, holding time, and leaf content for fractionated dehydrated and sun-cured alfalfa. The applied compressive pressures recorded by the data logger were slightly different than the preset pressure values. This is due to the limitations of the hydraulic press control valves and the inertia of the piston/crosshead.

In general, the density of dehydrated and sun-cured cubes increased with an increase in pressure, holding time, and leaf content (Tables 3a, 3b). An increase in leaf content resulted in smaller particle size, an increase in particle surface contact area, and higher protein content. In the presence of high temperature and pressure, starch gelatinization, protein de-saturation, and crosslinking in alfalfa may occur, facilitating bonding between particles. Also, more material was accommodated in a smaller volume, resulting in an increased cube density.

The Duncan Multiple Range Test (DMRT) was performed on the data (raw data in Tables 3a, 3b) to determine whether the variation in sample holding time and leaf content had any effect on the experimental results (Gomez and Gomez 1984). DMRT involves the computation of the difference between any two treatment means as significant or non-significant. DMRT values were calculated at the 5% level of significance. Two DMRT analyses were performed on the collected data. In the first DMRT analysis, treatment means for various leaf content at the same pressure, holding time, and forage type (sun-cured or dehydrated) were compared and the differences were shown by designations of the lower case letters a, b, c, d, and e. The second DMRT analysis was performed to study the difference in treatment means for the two holding times (10 and 30 s) at the same pressure, leaf content, and forage type with the upper case letters F, G, H, I, J, K, L, M, N, and O used to show the difference.

The DMRT showed that a significant difference in density was generally observed, particularly for dehydrated alfalfa, with

Table 3a. Cube mass, length, cross-sectional area, volume, and density values at various combinations of applied pressure, holding time, and leaf content for dehydrated alfalfa.

P_{preset} (MPa)	P_{actual} (MPa)	Holding time (s)	Leaf (%)	Mass (g)	Length (mm)	Area (mm^2)	Volume (mm^3)	Density* (kg/m^3)
9.0	9.18 ± 0.06	10	0	23.34 ± 0.18	27.10 ± 0.38	1078 ± 13	29193 ± 505	†800 ± 10 aF
	9.35± 0.07		25	23.50 ± 0.10	26.20 ± 0.25	1041 ± 08	27327 ± 340	860 ± 10 bG
	9.33± 0.08		50	23.78 ± 0.10	27.60 ± 0.24	1033 ± 07	28479 ± 371	836 ± 12 cI
	9.40 ± 0.08		75	24.02 ± 0.09	24.40 ± 0.22	1026 ± 04	25045 ± 196	959 ± 08 dK
	9.43± 0.10		100	24.18 ± 0.09	23.60 ± 0.15	1024 ± 00	24178 ± 155	1000 ± 05 eM
	9.32 ± 0.07	30	0	23.78 ± 0.10	27.39 ± 0.42	1074 ± 11	29405 ± 500	810 ± 14 aF
	9.34 ± 0.06		25	23.66 ± 0.09	26.53 ± 0.39	1069 ± 10	28363 ± 397	835 ± 11 bH
	9.39 ± 0.08		50	23.84 ± 0.08	27.10 ± 0.43	1028 ± 06	27872 ± 492	856 ± 14 cJ
	9.45 ± 0.08		75	24.12 ± 0.05	23.45 ± 0.15	1024 ± 00	24009 ± 158	1005 ± 06 dL
	9.32± 0.09		100	24.56 ± 0.08	23.52 ± 0.22	1024 ± 00	24080 ± 224	1020 ± 09 dN
12.0	12.11 ± 0.23	10	0	23.43 ± 0.13	25.20 ± 0.28	1071 ± 11	27012 ± 390	868 ± 11 aF
	12.20 ± 0.08		25	23.47 ± 0.14	24.50 ± 0.29	1063 ± 14	26060 ± 518	902 ± 16 bH
	12.20 ± 0.08		50	23.88 ± 0.08	25.60 ± 0.29	1026 ± 04	26274 ± 373	910 ± 12 bJ
	12.21 ± 0.10		75	24.01 ± 0.07	23.30 ± 0.17	1024 ± 00	23816 ± 169	1008 ± 08 cK
	12.33 ± 0.12		100	24.65 ± 0.04	23.00 ± 0.12	1024 ± 00	23528 ± 118	1048 ± 05 dM
	12.29 ± 0.08	30	0	23.75 ± 0.08	25.03 ± 0.22	1059 ± 15	26495 ± 386	897 ± 12 aG
	12.22 ± 0.08		25	23.76 ± 0.07	24.55 ± 0.34	1037 ± 10	25459 ± 443	934 ± 16 bI
	12.23 ± 0.07		50	24.01 ± 0.08	24.43 ± 0.23	1037 ± 10	26366 ± 379	911 ± 12 cJ
	12.23 ± 0.06		75	24.08 ± 0.06	22.81 ± 0.25	1024 ± 00	23361 ± 251	1031 ± 16 dL
	12.21 ± 0.07		100	24.16 ± 0.27	22.04 ± 0.19	1024 ± 00	22568 ± 197	1071 ± 12 eN
14.0	14.11 ± 0.24	10	0	23.50 ± 0.12	24.13 ± 0.41	1063 ± 09	25640 ± 433	917 ± 10 aF
	14.20 ± 0.07		25	23.69 ± 0.09	23.66 ± 0.19	1065 ± 13	25197 ± 329	941 ± 09 bG
	14.21 ± 0.08		50	23.94 ± 0.09	24.80 ± 0.30	1026 ± 04	25462 ± 387	941 ± 13 bI
	14.21 ± 0.11		75	23.82 ± 0.06	22.40 ± 0.21	1028 ± 06	23054 ± 238	1034 ± 10 cK
	14.36 ± 0.13		100	24.52 ± 0.04	22.20 ± 0.14	1024 ± 00	22755 ± 140	1078 ± 07 dL
	14.30 ± 0.08	30	0	23.77 ± 0.11	24.00 ± 0.20	1065 ± 12	25586 ± 327	930 ± 14 aF
	14.25 ± 0.09		25	24.00 ± 0.08	23.50 ± 0.26	1039 ± 08	24418 ± 338	984 ± 13 bH
	14.21 ± 0.07		50	23.77 ± 0.09	24.10 ± 0.21	1026 ± 04	24719 ± 272	962 ± 12 cJ
	14.32 ± 0.06		75	24.10 ± 0.04	22.40 ± 0.19	1030 ± 09	23031 ± 219	1047 ± 09 dK
	14.19 ± 0.09		100	24.64 ± 0.05	22.10 ± 0.15	1024 ± 00	22673 ± 156	1087 ± 08 eL

*15 replicates; † ± 95% confidence interval; Duncan Multiple Range Test at 5% level of significance for same sample lot at various leaf to stem ratios (a, b, c, d and e); for holding time at same leaf to stem ratio and pressure (F, G, H, I, J, K, L, M, N, and O).

a change in leaf content at any pressure and holding time, except for some cases (at 9.0 MPa, 30 s for 75 and 100% leaf content; at 12.0 MPa, 10 s for 25 and 50% leaf content; and at 14.0 MPa, 10 s for 25 and 50% leaf content). In most cases for sun-cured alfalfa, a significant difference in density values was observed with change in leaf content, except for some cases (at 9.0 MPa, 30 s for 25 and 50% leaf content; at 14.0 MPa, 10 s for 0 and 75% leaf content; and at 14.0 MPa, 30 s for 0 and 75% leaf content). The digression of data from a trend for sun-cured and dehydrated alfalfa cubes could be attributed to the randomization error during the cubing process.

An increase in holding time at the same pressure and leaf content, generally increased cube density, except for some cases of dehydrated alfalfa (at 9.0 MPa, 0% leaf content; at 12.0 MPa, 50% leaf content; and at 14.0 MPa, 0, 75, and 100% leaf contents). This digression of data from a trend for sun-cured and dehydrated alfalfa cubes could also be attributed to randomization error. All density values for sun-cured alfalfa showed a significant difference between the two holding times.

Fitting compression models to pressure, density, and volume data

Five compression models, Heckel (1961), Walker (1923), Jones (1960), Cooper and Eaton (1962), and Panelli and Filho (2001) were fitted to the pressure, density, and volume data for dehydrated and sun-cured alfalfa cubes (Tables 3a, 3b). Among the five models, the Cooper-Eaton, Eq.1, had the best fit for the experimental data obtained from dehydrated alfalfa samples at holding times of 10 and 30 s for all leaf contents. The Cooper-Eaton model also had the best fit for sun-cured alfalfa at holding times of 10 and 30 s for various leaf contents, except at holding time of 10 s for a leaf content of 0% (Walker model had the best fit) and at holding time of 30 s for leaf contents of 0% (Jones model had the best fit) and 75% (Walker model had the best fit).

$$\frac{V_0 - V}{V_0 - V_s} = a_1 \exp\left(-k_1 / P\right) + a_2 \exp\left(-k_2 / P\right) \qquad (1)$$

Table 3b. Cube mass, length, cross-sectional area, volume, and density values at various combinations of applied pressure, holding time, and leaf content for suncured alfalfa.

P_{preset} (MPa)	P_{actual} (MPa)	Holding time (s)	Leaf (%)	Mass (g)	Length (mm)	Area (mm^2)	Volume (mm^3)	Density* (kg/m^3)
9.0	9.21 ± 0.04	10	0	22.82 ± 0.17	27.00 ± 0.35	1113 ± 14	30108 ± 579	759 ± 13 aG
	9.23 ± 0.04		25	22.64 ± 0.19	26.10 ± 0.47	1100 ± 10	28724 ± 741	790 ± 16 bI
	9.13 ± 0.03		50	22.82 ± 0.14	27.10 ± 0.40	1102 ± 08	29885 ± 553	765 ± 14 cK
	9.19 ± 0.03		75	22.51 ± 0.13	24.30 ± 0.27	1076 ± 08	26135 ± 325	862 ± 11 dM
	9.25 ± 0.03		100	23.09 ± 0.21	24.80 ± 0.35	1026 ± 04	25458 ± 357	908 ± 15 eO
	9.15 ± 0.05	30	0	23.31 ± 0.10	26.14 ± 0.28	1096 ± 09	28639 ± 396	815 ± 10 aH
	9.15 ± 0.04		25	23.36 ± 0.11	25.32 ± 0.22	1089 ± 06	27568 ± 281	847 ± 07 bJ
	9.09 ± 0.06		50	23.36 ± 0.09	25.90 ± 0.74	1067 ± 08	27635 ± 851	848 ± 26 bL
	9.13 ± 0.04		75	23.20 ± 0.09	24.09 ± 0.30	1067 ± 12	25705 ± 429	904 ± 17 cN
	9.21 ± 0.05		100	23.44 ± 0.21	23.58 ± 0.47	1024 ± 00	24149 ± 484	972 ± 22 dP
12.0	12.04 ± 0.07	10	0	22.72 ± 0.15	24.90 ± 0.56	1100 ± 08	27373 ± 726	832 ± 20 aG
	11.92 ± 0.05		25	22.53 ± 0.64	25.40 ± 0.70	1107 ± 11	28138 ± 923	801 ± 14 bI
	12.05 ± 0.06		50	22.63 ± 0.24	25.90 ± 0.36	1098 ± 10	28385 ± 496	798 ± 13 cK
	12.05 ± 0.12		75	23.07 ± 0.18	24.30 ± 0.29	1087 ± 08	26409 ± 418	874 ± 13 dM
	12.08 ± 0.07		100	23.40 ± 0.16	24.70 ± 0.46	1028 ± 06	25387 ± 506	923 ± 19 eO
	12.41 ± 0.07	30	0	23.71 ± 0.10	23.83 ± 0.21	1093 ± 06	26055 ± 292	910 ± 10 aH
	11.86 ± 0.08		25	23.38 ± 0.09	24.08 ± 0.25	1091 ± 04	26279 ± 326	890 ± 08 bJ
	11.92 ± 0.07		50	22.99 ± 0.14	25.93 ± 0.32	1082 ± 07	28064 ± 376	820 ± 11 cL
	12.07 ± 0.09		75	23.23 ± 0.11	23.13 ± 0.20	1067 ± 08	24678 ± 337	942 ± 12 dN
	12.13 ± 0.09		100	23.33 ± 0.24	22.87 ± 0.38	1030 ± 09	23571 ± 531	991 ± 16 eP
14.0	13.33 ± 0.16	10	0	22.17 ± 0.33	23.50 ± 0.78	1093 ± 09	25097 ± 988	911 ± 23 aG
	13.71 ± 0.19		25	22.97 ± 0.13	25.20 ± 0.32	1104 ± 09	27789 ± 453	827 ± 13 bI
	13.95 ± 0.15		50	22.56 ± 0.21	25.50 ± 0.62	1091 ± 04	27790 ± 695	813 ± 15 cK
	13.67 ± 0.16		75	22.88 ± 0.17	23.80 ± 0.36	1091 ± 04	25944 ± 404	882 ± 11 aM
	13.85 ± 0.15		100	23.30 ± 0.16	23.90 ± 0.39	1046 ± 13	24992 ± 438	933 ± 17 dO
	14.31 ± 0.09	30	0	23.59 ± 0.08	23.20 ± 0.21	1089 ± 00	25294 ± 228	933 ± 08 abH
	13.95 ± 0.09		25	23.20 ± 0.16	23.30 ± 0.26	1089 ± 00	25346 ± 283	916 ± 06 bJ
	13.71 ± 0.13		50	23.00 ± 0.18	24.10 ± 0.27	1085 ± 11	26160 ± 449	880 ± 17 cL
	13.76 ± 0.17		75	22.99 ± 0.18	22.30 ± 0.30	1080 ± 10	24099 ± 444	955 ± 15 aN
	13.83 ± 0.17		100	23.60 ± 0.15	23.20 ± 0.49	1028 ± 06	23886 ± 566	990 ± 24 dP

*15 replicates; † ± 95% confidence interval; Duncan Multiple Range Test at 5% level of significance for same sample lot at various leaf to stem ratios (a, b, c, d and e); for holding time at same leaf to stem ratio and pressure (F, G, H, I, J, K, L, M, N, and O).

where:

a_1, a_2 = constants,
k_1, k_2 = constants (MPa),
P = applied pressure (MPa)
V = volume of compact at pressure P (m^3),
V_0 = volume of compact at zero pressure (m^3), and
V_s = void free solid material volume (m^3).

Although Cooper-Eaton had the best fit for most cases, the regression values (R^2 values) were generally low, especially for sun-cured alfalfa (Table 4). Therefore, new statistical models were developed to predict the compression characteristics of sun-cured and dehydrated alfalfa using multiple regression analysis.

For multiple linear regression analysis, density (ρ) was the dependent variable while pressure (P), holding time (t) and leaf content (x) were independent variables. Separate analyses were conducted for the sun-cured and dehydrated chops to determine individual equations for each material. The data (raw data from Tables 3a, 3b) were analyzed using procedures Proc Reg, Proc Corr, Proc Univariate, Proc Plot in SAS version 8.2 (SAS Institute 1999). A type I error rate of 5% was set for all analyses. Analysis of residuals was conducted to test the assumptions for regression analyses. Also, potential outliers in the data were tested, and if identified were removed from subsequent analyses. Multiple linear regression was conducted using Proc Reg in SAS and the highest coefficients of determination (R^2) were used to select among the possible regression models. The regression model was:

$$\rho = \beta_0 + \beta_1 t + \beta_2 P + \beta_3 x \tag{2}$$

where:

ρ = bulk density of compact powder mixture (kg/m^3),
t = holding time (s),
x = leaf content (%), and
$\beta_0, \beta_1, \beta_2, \beta_3$, = constants.

Table 4. Constants determined for Cooper-Eaton model (Eq. 1) for dehydrated and sun-cured alfalfa.

Holding time (s)	Leaf content (%)	Constants				R^2 values	*SSE
		a_1	a_2	k_1	k_2		
			Dehydrated alfalfa				
10	0	0.5857	0.5000	5.1340	-2.1321	0.8406	0.0008
	25	0.5881	0.5000	6.0749	-2.5867	0.6418	0.0012
	50	0.5183	0.5002	0.6682	0.6682	0.7771	0.0015
	75	0.5172	0.5000	2.0940	-0.9177	0.7772	0.0006
	100	0.5249	0.5000	3.7221	-1.6808	0.8996	0.0002
30	0	0.5339	0.5011	0.6112	0.6116	0.7953	0.0011
	25	0.5473	0.5001	0.7852	0.7854	0.8603	0.0012
	50	0.6236	0.5000	7.3853	-2.7185	0.7523	0.0015
	75	0.5099	0.5000	2.3291	-1.3324	0.5269	0.0005
	100	0.4940	0.5000	0.3658	0.3656	0.7413	0.0005
			Sun-cured alfalfa				
10	0	0.5211	0.4983	0.5779	0.5775	0.5266	0.0035
	25	0.5769	0.5000	7.3733	-2.9516	0.2383	0.0024
	50	0.4652	0.5037	0.4340	0.4339	0.3839	0.0033
	75	0.4528	0.5080	0.2380	0.2376	0.1356	0.0039
	100	0.4401	0.5132	0.2963	0.2961	0.1011	0.0084
30	0	0.5336	0.5001	0.5755	0.5754	0.7985	0.0010
	25	0.5266	0.5000	3.1938	-1.5485	0.8158	0.0004
	50	0.9570	0.5000	17.4401	-4.3325	0.2774	0.0048
	75	0.4923	0.5000	0.4180	0.4179	0.3335	0.0039
	100	0.4636	0.5002	0.2279	0.2278	0.0608	0.0089

* Sum of Square of Errors

A linear relationship was observed between dependent and independent variables. Analysis of residuals indicated that assumptions for regression regarding the experimental errors (experimental errors are random and independently distributed about a mean of zero and a common variance) were not violated. Test of residuals indicated that the distribution did not follow a normal distribution for the complete group of residuals for dehydrated ($P < 0.05$), but was normally distributed for sun-cured ($P > 0.05$) alfalfa. At 5% significant level, three outliers were identified using Lund's critical value (3.40) for the dehydrated alfalfa experiment and were removed from subsequent analysis (Lund 1975). No outliers were detected for the sun-cured alfalfa experiment. Non-normality of residuals is not very critical and would not have a marked effect on the models, therefore regression analyses were performed on the full data minus three outliers (Sokal and Rohlf 1994). No collinearity was detected for the independent variables using variance inflation factor and condition index (data not shown).

Regression analysis on the full model indicated that the model with all three variables was significant for both sun-cured and dehydrated experiment ($P < 0.0001$). Also, all the independent variables were significantly different than zero ($P < 0.0001$). Based on R^2 value, the full model with all three independent variables was accepted as the best predictor model for both experiments. The regression equations obtained were:

a) Dehydrated model ($R^2 = 0.85$):

$$\rho = 609.27 + 0.91t + 19.29P + 1.84x \tag{3}$$

b) Sun-cured model ($R^2 = 0.59$):

$$\rho = 622.32 + 3.23t + 11.65P + 1.34x \tag{4}$$

Table 5. Summary of stepwise regression analysis performed on data obtained from dehydrated and sun-cured alfalfa cubing experiments with leaf content, pressure, and holding time as independent variables and cube density as the dependent variable.

Variable entered	Number of variables in	Partial R^2	Model R^2	C_p	F value	P value
			Dehydrated alfalfa cubes			
Leaf percent	1	0.618	0.618	656.03	721.11	<0.0001
Pressure	2	0.216	0.834	36.18	578.61	<0.0001
Residence time	3	0.012	0.846	4.00	34.18	<0.0001
			Sun-cured alfalfa cubes			
Leaf percent	1	0.273	0.273	349.12	168.36	<0.0001
Pressure	2	0.217	0.490	113.97	189.98	<0.0001
Residence time	3	0.102	0.592	4.00	111.97	<0.0001

New R^2 values of 0.85 and 0.59 were obtained for dehydrated and sun-cured alfalfa, respectively (Table 5). The R^2 values of new equations showed that the new statistical models are a better fit to the experimental data as compared to R^2 values obtained by Cooper-Eaton model (Table 4). However, the R^2 value obtained from the new regression model for sun-cured alfalfa was low (0.59). The reason for the variation in cube density could be due to the non-uniform mixing of leaf and stem fractions during cubing trials. Also, the sun-cured alfalfa had been previously compressed into round bales before tub grinding. The pressure range for round balers, especially the hard core balers, is 3.45 to 13.8 MPa. The amount of pressure by the baler applied does not usually affect the bulk density of the round bale (Personal communication: M. Roberge, Assistant Professor, Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, SK). Therefore, it might have affected its compression characteristics. The observed difference in R^2 values between sun-cured and dehydrated alfalfa could be due to the difference in chop size. The average chop size for dehydrated alfalfa (~30 mm) was less than average chop size for sun-cured alfalfa (~60 mm). More uniform mixing of leaf and stem fractions is expected for dehydrated alfalfa relative to sun-cured alfalfa, henceforth, leading to a better fit or R^2 values.

CONCLUSIONS

The density of cubes increased by more than 5% when the holding time increased from 10 to 30 s. The Cooper-Eaton model had the best fit for the experimental data among the five different models studied, however the R^2 values obtained were low. Therefore, new statistical models were developed using multiple regression analysis for sun-cured and dehydrated alfalfa. The C_p statistic and R^2 from dehydrated and sun-cured experiment indicated that the full model was a better predictor than the reduced model and did not violate the assumptions of regression analysis. This study was conducted on alfalfa cubes with three levels of pressure (9, 12, and 14 MPa), two levels of holding time (10 and 30 s) and various leaf contents (0, 25, 50, 75, and 100%), therefore the equations that are proposed could be used in predicting the density of alfalfa cubes that have been manufactured from either dehydrated or sun-cured alfalfa with similar levels of independent variables used.

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REFERENCES

Adapa, P.K., L.G. Tabil, G.J. Schoenau, B. Crerar and S. Sokhansanj. 2002. Compression characteristics of fractionated alfalfa grinds. *Powder Handling and Processing - The International Journal of Storing, Handling, and Processing Powder* 14(4): 252-259.

ASAE. 2000. ASAE S358.2 - Moisture measurement - forages. In *ASAE Standards 2000*, 565. St. Joseph, MI: ASAE.

ASAE. 2003. ANSI/ASAE S424.1 - Method of expressing particle size of chopped forage materials by screeening. In *ASAE Standards 2003*, 606-608. St. Joseph, MI: ASAE.

Cooper, A.R. and L.E. Eaton. 1962. Compaction behavior of several ceramic powders. *Journal of the American Ceramic Society* 45(3): 97-101.

Gomez, K.A. and A.A. Gomez. 1984. *Statistical Procedures for Agricultural Research*, 2nd edition. New York, NY: John Wiley and Sons, Inc.

Hasting, W.H. and D. Higgs. 1978. Feed milling processes. In *Fish Feed Technology*, Chapter 18. FAO Publication ADCP/REP/80/11. Rome, Italy: FAO. http://www.fao.org/docrep/X5738E/x5738e0j.htm#4.%20pelleting (2004/12/09)

Heckel, R.W. 1961. Analysis of powder compaction phenomenon. *Transactions of the Metallurgical Society of AIME* 221: 1001-1008.

Jones, W.D. 1960. *Fundamental Principles of Powder Metallurgy*. London, UK: Edward Arnold Publishers Ltd.

Lund, R.E. 1975. Tables for an approximate test for outliers in linear models. *Technometrics* 17: 473-476.

Mallows, C.L. 1973. Some comments on C_p. *Technometrics* 15: 661-675.

Panelli, R. and F.A. Filho. 2001. A study of a new phenomenological compacting equation. *Powder Technology* 114: 255-261.

Sokal, R.R. and F.J. Rohlf. 1994. *Biometry: The Principles and Practice of Statistics in Biological Research*, 3rd edition. San Francisco, CA: W.H. Freeman and Company.

SAS Institute. 1999. *User's Guide: Statistics*, Version 8.2. Cary, NC: Statistical Analysis System, Inc.

Tabil, L.G. and S. Sokhansanj. 1996a. Process conditions affecting the physical quality of alfalfa pellets. *Journal of Applied Engineering in Agriculture* 12(3): 345-350.

Tabil, L.G. and S. Sokhansanj. 1996b. Compression and compaction behavior of alfalfa grinds - I. Compression behavior. *Powder Handling and Processing - The International Journal of Storing, Handling, and Processing Powder* 8(1):17-23.

Walker, E.E. 1923. The properties of powders. Part VI: The compressibility of powders. *Transactions of the Faraday Society* 19(1): 73-82.