PRESSURE-DENSITY RELATIONSHIP IN A LARGE SQUARE BALER

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ABSTRACT

Analytical and empirical models were developed for the pressure-density relationship of a large square baler for baling alfalfa and barley straw. The effect of flake size and load setting on the plunger force and bale density was also determined for baling alfalfa and barley straw. Results showed that according to the analytical model, bale density initially decreased with distance from the plunger, and then remained almost constant up to end of the compression chamber. The developed empirical model for both alfalfa and barley straw was a combination of a quadratic and an exponential equation. Results also revealed that load setting had a significant effect on the plunger force and bale density, while flake size had a slight effect on the plunger force and bale density.

INTRODUCTION

A large portion of forage materials is baled by small rectangular and large round balers. Round bales have a low density, are difficult to handle, and have a high transportation cost. Small rectangular balers have low field capacity and produce low density bales. Using a large square baler which produces large, high-density rectangular bales could very well eliminate the aforementioned problems. To achieve accurate data for the bale compression chamber design and optimization in a baler, it is necessary to study the relationship between the plunger pressure and the bale density, and the effect of machine settings on the bale density and plunger force. There is a direct relationship between the applied pressure and the forage material bulk density during the compaction process. Bilanski et al. (1985) studied the mechanical behavior of alfalfa under compression in a closed-end cylindrical die. They developed an analytical model to express the relationship between the applied axial pressure and the material bulk density. The analytical model is given below:

$$(\gamma_{\max} - \gamma)/(\gamma_{\max} - \gamma_0) = e^{(-P/K)}, \qquad (1)$$

where; γ_{max}, γ, and γ_0 are maximum, variable, and initial densities, respectively (kg/m^3), P is applied axial pressure (MPa), and K is forage particle stiffness (MPa).

This model is one of the most realistic models for the pressure-density relationship in forage materials. This model properly predicts the initial density (γ_0) at zero pressure, and implies that the material density will not increase infinitely with increased applied pressure. Butler and McColly (1959) introduced the following model to represent the compressed straw final density as a function of the applied axial pressure:

$$\gamma = k_1 \ln(P / k_2), \quad (2)$$

where; γ is material final bulk density (lb/ft^3), P is applied axial pressure (psi), and k_1, k_2 are model parameters.

Ferrero et al. (1990) studied the density-pressure relationship of compressed straw. They compressed chopped wheat and barley straw with the maximum length of 40 mm and moisture contents ranging from 7 to 23 and 10 to 20%, respectively. They applied the following empirical model to the experimental data:

$$\gamma = \gamma_0 + (A + BP)(1 - e^{-CP}), \quad (3)$$

where; γ is compressed density (kg/m^3), γ_0 is initial bulk density (kg/m^3), P is compression pressure (MPa), and A, B, C are model constants.

Watts and Bilanski (1991) reported that the maximum stress in alfalfa wafers for a certain deformation was a function of material density in the form of:

$$P = K_1 \log[1 - K_2(\gamma - \gamma_0)], \quad (4)$$

where; *P* is the maximum pressure in the wafer (MPa), γ and γ_0 are variable and initial densities, respectively (kg/m^3), K_1 and K_2 are variables that are linear functions of material moisture content, loading rate, and leaf content.

Viswanathan and Gothandapani (1999) studied the pressure-density relationship of compressed coir pith with the different levels of moisture contents and the particle sizes. They introduced the following equation for this relationship:

$$P = A + B\gamma + C\gamma^2, \quad (5)$$

where; P is plunger pressure (kPa), γ is material bulk density (kg/m^3), and A, B, C are model coefficients.

Most of the developed models for pressure-density relationships are generally either exponential or power law relationships. In most cases, the shortcomings of these models appear at the initial and boundary conditions where they fail to predict the density at these conditions. This study was conducted in the field using a New Holland BB960 large square baler to develop analytical and empirical models for the pressure-density relationship and evaluate the effect of flake size and load setting on the bale density and plunger force for baling alfalfa and barley straw.

MATERIALS AND METHODS

Large square baler

In this project a newly designed New Holland BB960 large square baler was used to bale alfalfa and barley straw. This baler produces bales with 1.2 m width, 0.9 m height, and an adjustable length of up to 2.5

m. The automatic bale density control mode was used in this study. In this mode, the plunger force sensor senses the force applied to the bale via the plunger, and a processor sets the pressure in the bale density controlling system to adjust the bale density based on plunger force. A density level is selected in this mode by the operator from the tractor cab based on the crop type and moisture content. The available load settings in the automatic bale density control mode are 10, 20, 30, up to 100% of the maximum available plunger force. By changing the load setting the side hydraulic cylinders adjust the applied forces to the top and side walls in such a way that the baler applies a resistance equal to the requested force to the plunger (New Holland BB960 manual 2001). There is also a pre-compression chamber that is located prior to the main compression chamber so that the forage materials are compressed at an adjustable pressure before entering the main chamber. A lever with ten positions applies different pre-compression pressure levels to the materials which is called stuffer trip sensitivity lever. The position of this leaver determines the size of the flake charged to the main compression chamber (flake sizes).

Instrumentation

To measure the forces on the plunger, a set of four strain gages (EA-06-500BL-350, Microsoft Measurements, Raleigh, North Carolina) were mounted on each arm of the plunger. Strain gages were used in a Wheatstone bridge form, and a data acquisition system including a data logger (PPIO-AI8), a signal conditioner (EXP16), a power supply, and a laptop was used to record the output of the sensor at the frequency of 50 Hz. The actual bale bulk density was calculated by measuring the bale dimensions and weight. A split plot experimental design with three replications was established in the field to evaluate the effect of the main factor (load setting) and the sub factor (flake size) on the plunger force and the bale density.

Analytical model

In order to simplify the problem in this study, it was assumed that forage material behaves as an isotropic linear elastic material. With this assumption, analytical model for the pressure-density relationship of a large square baler was developed using the theory of elasticity. In general, the constitutive relationship for an isotropic linear elastic material (Fig. 1) is characterized by modulus of elasticity (E) and Poisson’s ratio (ν). The general form of the constitutive relationship for an isotropic linear elastic material is as follows:

$$\varepsilon_{ij} = \frac{1+\nu}{E}\sigma_{ij} - \frac{\nu}{E}\delta_{ij}\sigma_{kk}, \quad (6)$$

where; i is x, y, or z and j is x, y, or z.

Considering normal stresses only and using the relationships between the stresses and strains in an isotropic linear elastic element and an element of the bale inside the compression chamber of the baler (Fig. 2), the following equations can be developed between stress and strain of an element of bale in different directions:

$$-\varepsilon_x = -\frac{1}{E}\left[P_x - \nu\left(P_y + P_z\right)\right] \qquad \text{in } x\text{-direction,} \qquad (7)$$

$$-\varepsilon_y = -\frac{1}{E}\left[P_y - \nu\left(P_x + P_z\right)\right] \qquad \text{in } y\text{-direction and} \qquad (8)$$

$$-\varepsilon_z = -\frac{1}{E}\left[P_z - \nu\left(P_x + P_y\right)\right] \qquad \text{in } z\text{-direction.} \qquad (9)$$

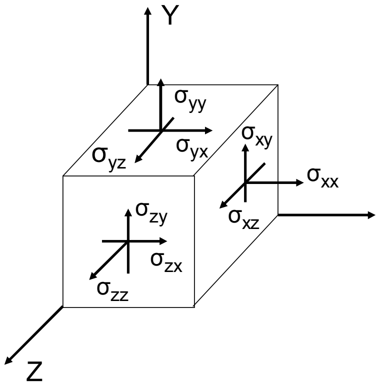

Figure 1 Stress tensor on an element of an isotropic linear elastic material.

From Eqs. 7, 8, and 9, P_y and P_z can be calculated in terms of P_x, ε_y, and ε_z as follows:

$$P_y = \frac{\nu}{1-\nu}P_x + \frac{E}{(1-\nu^2)}\left(\varepsilon_Y + \nu\varepsilon_Z\right) \quad \text{and} \quad (10)$$

$$P_z = \frac{\nu}{1-\nu}P_x + \frac{E}{(1-\nu^2)}\left(\nu\varepsilon_Y + \varepsilon_Z\right). \quad (11)$$

Bale density changes during the baling process along the bale length because of changing bale volume. Volume change of element is also stated in terms of either strains or pressures using the following equation:

$$\frac{\Delta V}{V} \cong \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{1-2\nu}{E}\left(P_x + P_y + P_z\right). \quad (12)$$

An analytical model can be derived by plugging P_y and P_z from Eqs. 10 and 11 into Eq. 12 as follows:

$$\frac{\Delta V}{V} = \frac{1-2\nu}{E}\left(P_x + \frac{2\nu}{1-\nu}P_x + \frac{E}{1-\nu}\left(\varepsilon_y + \varepsilon_z\right)\right). \quad (13)$$

On the other hand, the relationship between volume change and density is expressed by:

$$\frac{\Delta V}{V} = 1 - \frac{V_x}{V_0} = 1 - \frac{\gamma_0}{\gamma}. \quad (14)$$

Furthermore, according to the geometry of the compression chamber, the following assumptions can be made:

$$\varepsilon_y = \frac{\alpha x}{a} = \varepsilon_y(x) \text{ and} \quad (15)$$

$$\varepsilon_z = \frac{2\beta x}{b} = \varepsilon_z(x)\,. \quad (16)$$

where; a is starting height of compression chamber (cm), b is starting width of compression chamber (cm), x is distance from the full extension point of the plunger (cm), α is angle of top wall of compression chamber with respect to x-axis and β is angle of side wall of compression chamber with respect to x-axis.

By equating the right hand sides of Eqs. 13 and 14, and using Eqs. 3.15 and 3.16, the following equation can be obtained:

$$1-\frac{\gamma_0}{\gamma} = \frac{P_x(1-2\nu)(1+\nu)}{E(1-\nu)} + \frac{1-2\nu}{1-\nu}\left(\frac{b\alpha+2a\beta}{ab}\right)x\,. \quad (17)$$

After simplifying Eq. 17, the following model can be developed for the bale density as a function of pressure, crop properties, and bale chamber dimensions:

$$\gamma = \frac{\gamma_0 Eab(1-\nu)}{Eab(1-\nu)-(1-2\nu)\left[abP_x(1+\nu)+E(b\alpha+2a\beta)x\right]}\,. \quad (18)$$

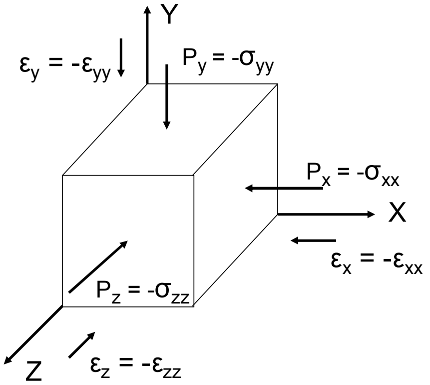

Figure 2 Normal stresses applied to an element of bale inside the compression chamber.

Empirical model

Developing an empirical model for the relationship between bale density and plunger pressure in a large square baler was one of the objectives of this study. In order to establish this model, the data of harvesting alfalfa and barley straw at different load settings were used. Different models had been introduced for the pressure-density relationship of forage materials, where some of them were tested with the data of this experiment to find the best model for the pressure-density relationship. The most promising model for the purpose of this study revealed to be the model suggested by Ferrero et al. (1990). Therefore, this model was modified to show the best agreement with the experimental data of the relationship between alfalfa and barley straw bale density and plunger pressure. So, the pressure-density relationship for the large square baler during alfalfa and barley straw baling process was best expressed with the following model:

$$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP}), \qquad (20)$$

where; γ is compressed bulk density (kg/m^3), γ_0 is initial bulk density (kg/m^3), P is compression pressure (MPa), and A, B, C, D are model constants.

Field experiments

The baler was tested in two different provinces of Canada including Saskatchewan and Québec in 2001. The farm considered in Saskatchewan consisted of a quarter section (64 ha) of second year pure alfalfa. The first cut was done in late June and early July, completed in three days. The effect of flake size and the load settings on the plunger force and bale density was evaluated on this field. The equipped large square baler was used to bale alfalfa at 12.4% moisture content. To determine the effect of flake size and load setting on the required plunger force and the material bale density, three levels of flake sizes (three positions of the sensitivity lever such as 3, 6, and 9 out of 10) and three levels of load settings (50, 60, and 70% of the available maximum plunger force) were considered. Baling was performed at the constant speed of 8 km/h. The forces on the plunger arms were recorded by the data acquisition system and bale density was calculated by measuring bale dimensions and weight. The average of the peak forces resulting from the sum of the forces on the two plunger arms was considered as the plunger force for each bale formation. In Québec, barley straw with 8.7% moisture content was baled in a 48 hectare farm. To determine the effect of flake size and the load setting on the plunger force and the material bale density, three levels of flake sizes (three positions of the sensitivity lever such as 3, 6, and 9 out of 10) and four levels of load settings (40, 60, 80, and 100% of the available maximum plunger load) were considered. Baling was performed at the constant speed of 15 km/h. The forces on the plunger arms were recorded by the data acquisition system and bale density was calculated by measuring bale dimensions and weight.

RESULTS AND DISCUSSION

Analytical model for pressure-density

Alfalfa bale density versus distance from the full extension point of the plunger along the compression chamber was plotted based on analytical model of pressure-density (Eq. 18). This graph showed that bale density decreased with distance of up to 50.0 cm, and then remained almost constant up to the end of the compression chamber (Fig. 3), while in reality bale density should remain almost constant along the compression chamber. This analytical model failed to accurately predict the bale density along the compression chamber length due to the assumptions made in the model development. This model was developed by assuming elastic behavior for forage materials, while these materials were not elastic in reality. Therefore, the unloading process in forage materials was not reversible. Figure 4 compares the pressure-density relationship based on the analytical model with the possible pressure-density relationship in reality. Point "A" is on the plunger; therefore the pressure and density at this point are the maximum pressure and density in the baling process. Point "B" is assumed to be a point at a distance *x* from the full extension point of the plunger. According to the analytical model (Eq. 18), point "B" should be on the pressure-density curve. Thus, the density at this point (γ_B) is much smaller than the maximum density (γ_{max}). In practice, point "B" will be probably somewhere at "C" instead of being at "B" due to the inelastic property of forage materials. Point "C" has a density close to the maximum density; therefore in reality density remains almost constant along the compression chamber length. Unfortunately, no experimental data of the variation of bale density along the compression chamber were available to validate this analytical model. Figure 3 showed the bale density variation with distance from the plunger when the bale was inside the bale chamber, so it cannot be extended to the variation of the bale density after coming out of the compression chamber. When the bale is out of the compression chamber, the tied twines keep a constant pressure on the bale. This constant pressure can balance the bale density along the bale length by densifying the looser parts and loosening the denser parts. Therefore, the bale final density will have a value which is approximately an average of the maximum and minimum densities of the bale in the compression chamber.

Empirical model for pressure-density relationship

Different models have been proposed for the pressure-density relationship of forage materials in the literature. Some of these models including those proposed by Ferrero et al. (1990), Viswanathan and Gothandapani (1999), Watts and Bilanski (1991), Butler and McColly (1959), and Bilanski et al. (1985) were tested with the data of the experimental tests to find the best model for the pressure-density relationship. Results of validation of these models using the experimental data of alfalfa are shown in Table 1. This table showed that the developed model for the pressure-density relationship in this study (first model in the table) had the highest coefficient of determination and lowest average error.

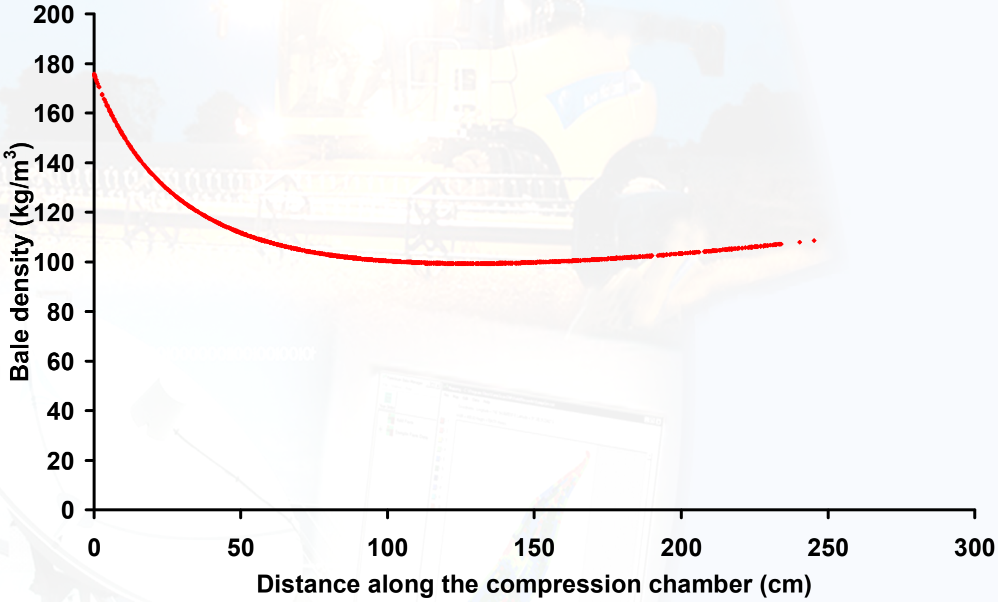

Figure 3 Variation of bale density along the compression chamber length for alfalfa at a moisture content of 12.4% wb based on the analytical model of pressure-density (zero on the *x*-axis is the full extension point of plunger).

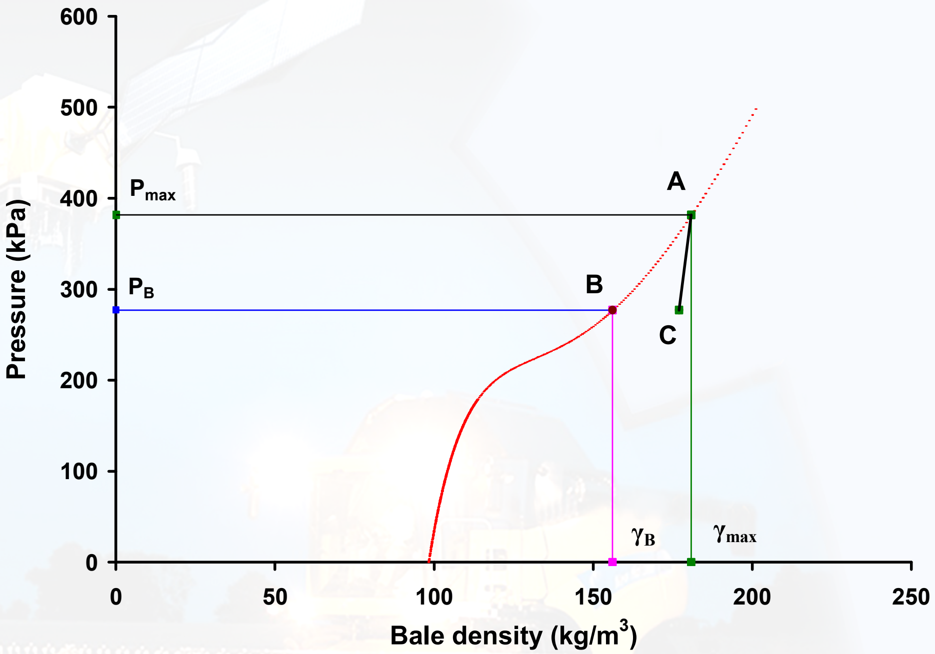

Figure 4 Comparing the pressure-density relationship based on the analytical model with the possible pressure-density relationship in reality.

The coefficient of determination and average error for this model were 0.89 and 2.55%, respectively. This model was a modified version of model proposed by Ferrero et al. (1990). Experimental data and predicted density for alfalfa based on the proposed model (Eq. 20) versus plunger pressure are plotted in Figure 5. The standard error and the coefficient of determination of the model of equation 20 were 4.25 kg/m^3 and 0.89, respectively.

Models expressing pressure-density relationship in the literature were the results of compressing forage materials in a closed-end die which differed from the baler compression chamber used in the present study. Basically, the compression chamber of a baler is an open-end canal rather than a closed-end die. For this reason, none of the previously proposed models could be applied to the data of the pressure-density relation of the large square baler.

Table 1 Summary of validating of different models of pressure-density relationship with the data of baling alfalfa in the large square baler.

Pressure-density model		R^2	Average error (%)
$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP})$		0.89	2.55
$\gamma = \gamma_0 + (A + BP)(1 - e^{-DP})$	(Ferrero et al. 1990)	0.86	2.96
$(\gamma_{\max} - \gamma)/(\gamma_{\max} - \gamma_0) = e^{(-P/K)}$	(Bilanski et al. 1985)	0.85	3.02
$\gamma = k_1 \ln(P/k_2)$	(Butler and McColly1959)	0.83	3.27
$P = A + B\gamma + C\gamma^2$	(Viswanathan 1999)	0.87	5.91
$P = K_1 \log[1 - K_2(\gamma - \gamma_0)]$	(Watts and Bilanski1991)	0.86	6.09

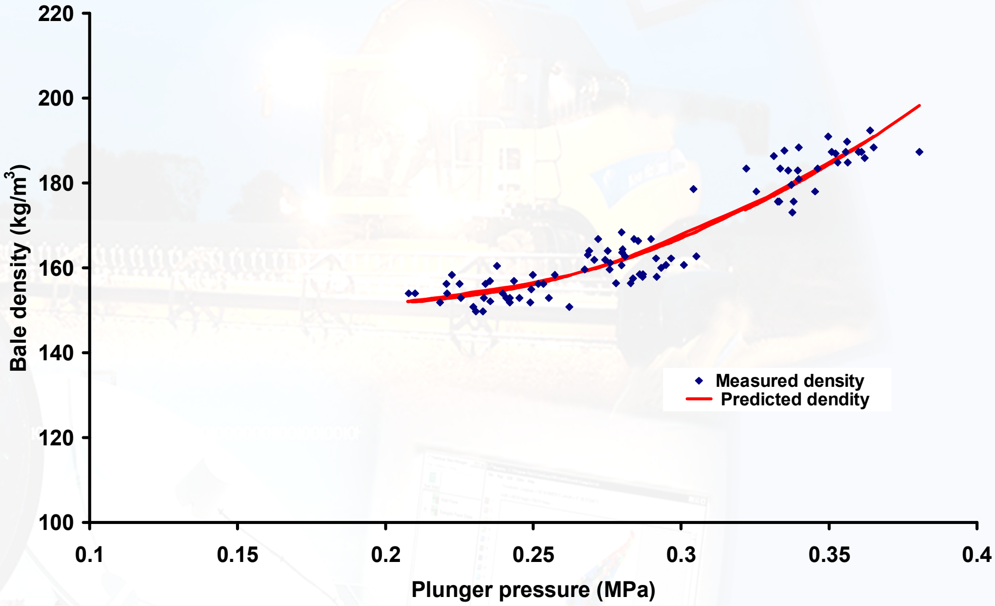

Figure 5 Experimental and the predicted densities vs. plunger pressure in a large square baler for alfalfa at a moisture content of 12.4% w.b.

Models proposed by Ferrero et al. (1990), Viswanathan and Gothandapani (1999), Watts and Bilanski (1991), Butler and McColly (1959), and Bilanski et al. (1985) were also tested with the data of barley straw to find the best model for the pressure-density relationship. Results of validation of these models using the experimental data of barley straw are shown in Table 2. This table showed that the developed model for pressure-density relationship in this study (first model in the table) had the highest coefficient of determination and lowest average error. The coefficient of determination and average error for this model were 0.94 and 2.50%, respectively. Experimental data and predicted density for barley straw based on the developed model (Eq. 20) versus plunger pressure are plotted in Figure 6. The standard error and the coefficient of determination of this model were 3.21 kg/m^3 and 0.94, respectively.

Table 2 Summary of validating different models of pressure-density relationship with the data of baling barley straw in the large square baler.

Pressure-density model	R^2	Average error (%)

$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP})$		0.94	2.50
$(\gamma_{\max} - \gamma)/(\gamma_{\max} - \gamma_0) = e^{(-P/K)}$	(Bilanski et al. 1985)	0.94	2.52
$\gamma = k_1 \ln(P/k_2)$	(Butler and McColly1959)	0.94	2.55
$\gamma = \gamma_0 + (A + BP)(1 - e^{-DP})$	(Ferrero et al. 1990)	0.92	2.89
$P = A + B\gamma + C\gamma^2$	(Viswanathan 1999)	0.93	7.81
$P = K_1 \log[1 - K_2(\gamma - \gamma_0)]$	(Watts and Bilanski1991)	0.92	8.00

Baling alfalfa

Results of this study showed that load setting had a significant effect ($p<0.01$) on the plunger force and bale density of alfalfa. Means comparison analysis using Duncan’s multiple range tests revealed that the difference between the plunger forces and bale densities at the all load settings was significant (Table 4). Plunger force and bale density increased with increasing load setting. Increased plunger force with increasing load setting was expected; therefore, when the load was set at 70% of the available maximum load, the plunger force reached its highest value. Results also revealed that flake size setting had a significant effect on the alfalfa bale density and plunger force. The difference between all mean values of plunger forces at different flake sizes was significant (Table 5). The mean comparison analysis of the bale density at different flake sizes showed that the bale density at the flake size of 3/10 was significantly different from the bale densities at other flake sizes. The bale density and plunger force increased with increasing flake size (Table 5). Although, the plunger force was supposed to decrease with increasing flake size, results showed that the plunger force increased with increased flake size. This was probably due to the increased flake size which increased the material rebounding after each plunger stroke.

Baling barley straw

Results of analyzing data of baling barley straw showed that the plunger force was drastically affected by the load setting. Based on the mean comparison analysis, the difference between plunger loads at all load settings was significant (Table 6). The plunger force and bale density increased with increasing load setting; however, sufficient data were not available for bale density to perform a complete statistical analysis. Results also showed that the difference between plunger forces at flake sizes of 6/10 and 9/10 was significant. The plunger force and bale density slightly increased with increasing flake size (Table 7).

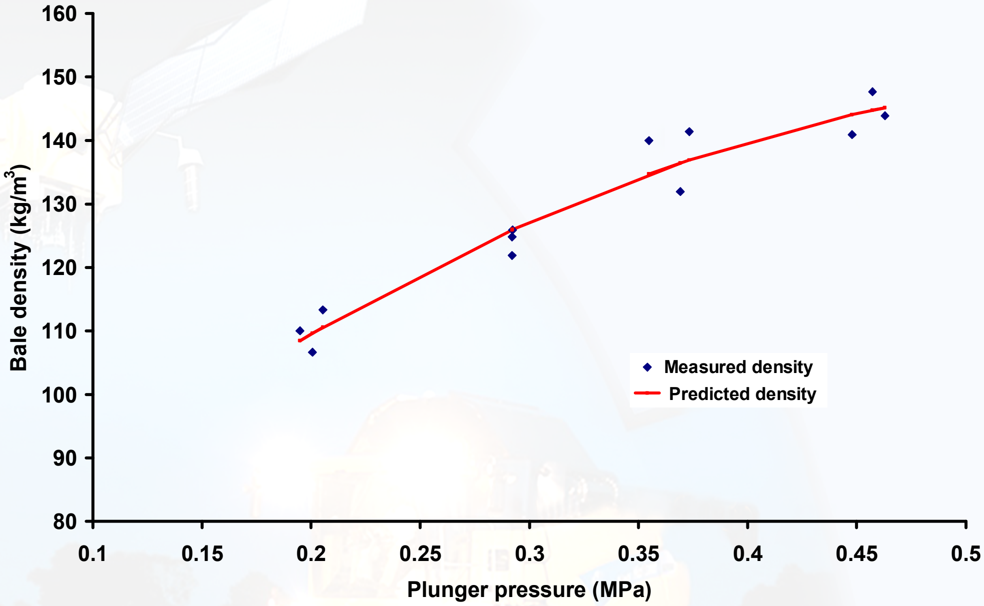

Figure 6 Experimental and the predicted densities vs. plunger pressure in a large square baler for barley straw at a moisture content of 8.7% w.b.

Table 4 Average plunger forces and bale densities at different load settings for alfalfa.

Load setting (as percentage of the available maximum load)	Plunger force (kN)	Bale density (kg/m^3)
50	255.6 a	154.3 a
60	305.5 b	161.8 b
70	372.3 c	183.8 c

Table 5 Average plunger forces and bale densities at different flake sizes for alfalfa.

Flake size	Plunger force (kN)	Bale density (kg/m^3)
3/10	299.7 a	165.2 a
6/10	313.6 b	167.5 b
9/10	320.1 c	167.2 b

Table 6 Average plunger forces and bale densities at different load settings for baling barley straw.

Bale density setting (percent of available maximum density)	Plunger force (kN)	Bale density (kg/m^3)
40	216.4 a	109.9
60	317.7 b	124.1
80	397.8 c	137.7
100	492.4 d	144.1

Table 7 Average plunger forces at different plunger/stuffer ratio settings for the baled barley straw

Flake size	Plunger force (kN)	Bale density (kg/m^3)
3/10	354.9 ab	127.0
6/10	354.0 b	129.6
9/10	359.3 a	130.3

CONCLUSIONS

Analytical and empirical models were developed for the pressure-density relationship of the baler for baling alfalfa and barley straw. Based on the analytical model, the bale density decreased with increasing distance from the plunger up to 50 cm, and then remained almost constant up to end of compression chamber. The developed empirical model for both alfalfa and barley straw was a combination of a quadratic and an exponential equation. Load setting had a significant effect on the plunger force and bale density, while flake size had a slight effect on the plunger force and bale density. The plunger force and bale density significantly increased with increasing load setting, while they slightly increased with increasing flake size.

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چکیده

دراین تحقیق، مدلهای تحلیلی و تجربی برای رابطه بین فشار اعمال شده از طریق پیستون و جرم مخصوص علوفه بسته بندی شده برای علوفه هایی مانند یونجه و کاه جودر محفظه تراکم بیلرنیوهلند BB960 ارایه شد. براساس مدل تحلیلی جرم مخصوص بسته ابتدا با افزایش فاصله از پیستون کاهش یافت و پس ازآن تا انتهای طول محفظه تراکم ثابت ماند. مدل تجربی ارایه شده برای رابطه بین فشار و جرم مخصوص در هر دو نوع علوفه ترکیبی از معادله درجه دوم ونمائی بود. برای ارزیابی مدلهای ارایه شده برای رابطه بین فشار و جرم مخصوص آزمایشات مزرعه ای با تنضیمات مختلف نیروی پیستون و ضخامت علوفه ای که درهرضربه پیستون وارد محفظه تراکم می شود، صورت گرفت و نیروهای وارده به بازوهای پیستون اندازه گیری گردید. همچنین جرم مخصوص بسته ها از طریق اندازه گیری ابعاد و جرم بسته ها محاسبه شد. نتایج این آزمایشات نشان دادند که هردو این تنضیمات اثر معنی داری روی نیروی اعمال شده از طرف پیستون به بسته علوفه وجرم مخصوص بسته دارند به طوری که نیروی اعمال شده وجرم مخصوص بسته با افزایش ضخامت علوفه و نیروی تنظیم شده افزایش یافت.