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Modeling of the Pressure-Density Relationship in a Large Cubic Baler

S. Afzalinia[1*], and M. Roberge[2]

ABSTRACT

In the course of this study, empirical models were developed for the pressure-density relationship in a large cubic baler for baling alfalfa and barley straw. Least squares regression analysis was employed to develop the empirical model and estimate the model coefficients by minimizing the summation of the squared differences between data resulting from the developed empirical model and the corresponding experimental data for a certain distance from the plunger. The effect of the flake size and load setting on the plunger pressure (pressure exerted on the bale *via* the plunger) as well as bale density were also determined for bailing alfalfa and barley straw. Results showed that the developed empirical model for either one of alfalfa or barley straw was a combination of a quadratic and an exponential equation which exhibited a good correlation with the experimental data (R^2 of 0.89 for alfalfa and R^2 of 0.94 for barley straw). Results also revealed that load setting significantly affected the plunger pressure and as well the bale density so that plunger pressure and bale density increased with increase in load setting (up to 70% for alfalfa and 100% for barley straw) in both of the forage materials. Flake size (position of the pre-compression sensitivity lever) had also a slight effect on the plunger pressure and on the bale density.

Keywords: Bale density, Empirical model, Flake size, Large cubic baler, Load setting.

INTRODUCTION

A large portion of forage materials is baled by small cubic and as well by large round balers. Round bales are of low densities (100 to 170 kg m^{-3}), are difficult to handle, and impose high transportation costs (Hunt, 2001; Culpin, 1986; Jenkins *et al.,* 1985). Small cubic balers are of low field capacities producing low density bales in the range of 114 to 207 kg m^{-3} (Hunt, 2001). Use of a large cubic baler which produces large, high-density cubic bales could very well alleviate the aforementioned problems. To achieve precise data for the bale compression chamber design and for optimization of the compression chamber dimensions in a newly designed large cubic baler, it is necessary to study the relationship between the plunger pressure and the bale density and as well the effect of load setting and flake size on the bale density and plunger pressure (Afzalinia, 2005; Remoué, 2007).

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

[1] Department of Agricultural Engineering Research, Fars Research Center for Agriculture and Natural Resources, P. O. Box: 71555-617, Shiraz, Islamic Republic of Iran.
[*] Corresponding author: email: sja925@mail.usask.ca
[2] Digital Simulation and Analysis Group, CNH Global NV, Saskatoon, Saskatchewan, Canada. 1000, 71st Street East, S7K 3S5.

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, γ_0= Maximum, variable, and initial bulk densities (kg m^{-3}) respectively, *P*= Applied pressure (MPa), and *K*= Model coefficient which reflects the stiffness of the forage particles as stated by Bilanski *et al.* (1985).

This model is one of the most realistic models for the pressure-density relationship in forage materials since through this model it is possible to predict the initial density (γ_0) at zero pressure (through the other introduced models it is not possible to predict the non-zero initial density of the baled forage), implying 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 pressure:

$$\gamma = J\ln(P/L) \qquad (2)$$

Where, γ= Bulk density (kg m^{-3}), *P*= Applied pressure (MPa), and *J, L*= Model coefficients.

Bilanski *et al.* (1985) reported an exponential equation for the pressure-density relationship of the compressed straw as follows:

$$P = m\gamma^n \qquad (3)$$

Where, *P*= Applied pressure (MPa), γ= Bulk density (kg m^{-3}), and *m, n*= Model coefficients.

Equations (2) and (3) were developed using a low loading rate; therefore these models are not applicable to the compression processes at high loading rates. On the other hand, initial conditions ($P=0$ and $\gamma=\gamma_0$) were not defined for Equation (3). Therefore, these models can predict material density only for a certain range of applied pressures. O'Dogherty and Wheeler (1984) introduced the following equation for the applied pressure as a function of the material bulk density for compacted barley straw:

$$P = Ee^{F\gamma} \qquad (4)$$

Where, *P*= Applied pressure (MPa), γ= Bulk density (kg m^{-3}), and *E, F*= Model coefficients.

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

$$\gamma = \gamma_0 + (A+BP)(1-e^{-CP}) \qquad (5)$$

Where, γ= Bulk density (kg m^{-3}), γ_0 = Initial bulk density (kg m^{-3}), *P*= Applied pressure (MPa), and *A, B, C*= Model coefficients.

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

$$P_{max} = Q\log[1-R(\gamma-\gamma_0)] \qquad (6)$$

Where, P_{max}= Maximum applied pressure (MPa), γ, γ_0= Variable and initial bulk densities, respectively (kg m^{-3}), and *Q, R*= Coefficients 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 different levels of moisture contents and particle sizes. They introduced the following equation:

$$P = G + H\gamma + I\gamma^2 \qquad (7)$$

Where, *P*= Applied pressure (kPa), γ = Bulk density (kg m^{-3}), and *G, H, I*= Model coefficients.

Comprehensive knowledge of the pressure-density relationship in balers is necessary to design and optimize the bale compression chamber structure. Since all reported models for the pressure-density relationship in literature were based on the data of compressing forage materials and coir pith in a closed-end cylindrical die, these models cannot be directly extended to the pressure-density relationship in balers. Therefore, this study was conducted to achieve the following objectives:

Development and validation of an empirical model describing the relationship between plunger pressure and bale density in balers.

Evaluation of the flake size and load setting effects on the bale density and plunger pressure.

MATERIALS AND METHODS

Large Cubic Baler

In this research a New Holland BB960 large cubic baler (New Holland, 2001) was employed to bale alfalfa and barley straw. Through this baler bales of 1.2 m width, 0.9 m height, and an adjustable lengths of up to 2.5 m are produced. The bale density control system of the baler could be adjusted in three different modes, but the baler should normally work in automatic mode to produce bales with uniform bale densities close to the pre-set density by the operator. Therefore, the automatic bale density control mode was employed throughout the study. In this mode, the plunger force strain gage based sensor located on the plunger arm, 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 as based on the 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. When the measured load on the plunger is lower than the preset one, the electronic system will control the density hydraulic valve to increase the pressure on the density cylinders causing the bale chamber doors to close. In contrast, if the measured load on the plunger is higher than the preset one, the electronic system will control the density hydraulic valve to decrease pressure on the density cylinders and the bale chamber doors will open. The available load settings in the automatic bale density control mode are 10, 20, 30%, and so on, up to 100% of the maximum available plunger force. The maximum available plunger force differs from crop to crop (for instance it is about 500 kN for barley straw). 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 bale applies a resistance equal to the pre-set force to the plunger (New Holland, 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 a pre-adjusted pressure before entering the main chamber. A sensitivity lever of ten positions applies different pre-compression pressure levels to be baled materials. The position of this lever determines the thickness of the flakes charged to the main compression chamber (flake size).

Instrumentation

To measure the force on the plunger (force applied to the plunger from baled materials in the x-direction), a set of four strain gages (EA-06-500BL-350, Microsoft Measurements, Raleigh, North Carolina) were mounted one on each arm of the plunger (Figure 1). Two strain gages were mounted one on each side of the plunger arms vertically as well as horizontally to sense the maximum deformation and compensate for the temperature effect.

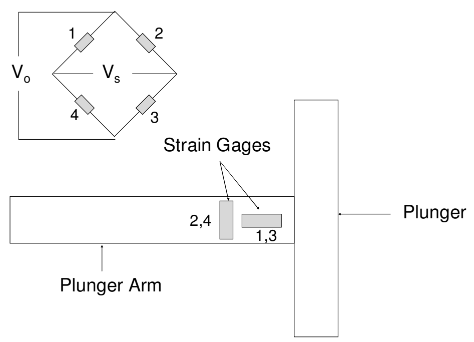

Figure 1. Arrangement of strain gages on the plunger arm and Wheatstone bridge (V_s and V_o represent the excitation and bridge output voltages, respectively).

Strain gages were employed 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 were utilized to record the output of the sensor at a frequency of 50 Hz. The actual bale bulk density was computed through a measurement of the bale dimensions and weight. Moisture content of the samples was determined using the ASAE standard S358.2 DEC 98 for forage materials (ASAE, 2001). A split plot experimental design 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 pressure and the bale density. SAS software (SAS Institute, Cary, NC) was employed to analyze the data resulting from this experiment, and as well the treatment means comparison was performed using Duncan's Multiple Range Tests.

Empirical Model

Developing an empirical model for the relationship between bale density and plunger pressure in a large cubic baler was one of the objectives of this study. In order to establish this model, baling data related to alfalfa and barley straw (plunger force and bale density) at different load settings were made use of. Various models had been introduced for the pressure-density relationship of forage materials in the close-end cylindrical die, some of which were tested with the data obtained in this experiment to find the most appropriate model for the pressure-density relationship in relation with the bale. Least squares regression analysis was employed to fit the models to the experimental data related to each crop. The most promising model for the purpose of this study was revealed to be the model suggested by Ferrero *et al.* (1990). This model was modified using the least squares method to show the best agreement with the experimental data of the relationship between alfalfa and barley straw bale densities *vs.* plunger pressure. So, the pressure-density relationship for the large cubic baler in the course of alfalfa *vs.* barley straw baling process was best expressed through the following model:

$$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP}) \quad (8)$$

Where, *P*= Compression pressure (MPa) and *A, B, C, D*= Model coefficients which are functions of bale chamber geometry and forage material properties.

Field Experiments

The baler was tested in two different provinces of Canada to collect the pertaining appropriate data (plunger force and bale density) for the pressure-density relationship. First, it was tested in Saskatchewan in late June and early July with alfalfa then it was shipped to Québec and tested with barley straw in late July and early August.

The farm in Saskatchewan was located in Clavet, a small town about 30 km South-East of Saskatoon. This field consisted of 64 ha of second year alfalfa. Alfalfa cutting was performed in late June and early July, completed in three days. The effects of flake size and the load settings on the plunger pressure and bale density were evaluated on this field. The baler was used to bale alfalfa at 12.4% (wb) moisture content. To determine the effects of flake size (thickness) and load setting on the required plunger pressure and the material bale density, three levels of flake sizes (three positions of the sensitivity lever for thin/thick flakes including 3, 6, and 9 out of 10) as well as three levels of load settings (50, 60, and 70% of the available maximum plunger force) were taken into account. Baling was performed at a constant speed of 8 km h^{-1}. In Québec, barley straw with 8.7% moisture content (wb) was baled on a 48 hectare farm. To determine the effect of flake size and the load setting on the plunger pressure and the material bale density, three levels of the flake size (three positions of the sensitivity lever including 3, 6, and 9 out of

10) and four levels of load settings (40, 60, 80, and 100% of the available maximum plunger force) were taken into consideration. Baling was performed at a constant speed of 15 km h^{-1}. Baling speeds were selected as based on forage canopy in the rows while load settings randomly selected. The forces on the plunger arms were recorded through the data acquisition system while bale density calculated through a measurement of bale dimensions as well as 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 in the formation of each bale. This plunger force was then converted to the plunger pressure by dividing the force by the plunger cross-sectional area.

RESULTS AND DISCUSSION

Validation of the 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, using the study's experimental data to find the most suitable model for the pressure-density relationship. Results of validation of these models using the experimental data of alfalfa (90 data points) are shown in Table 1. This table shows that the developed model for the pressure-density relationship in this study (first model in the table) is of the highest coefficient of determination (R^2= 0.89) while the lowest average error (2.55%) as compared with the other tested models including model derived by Ferrero *et al.* (1990). The experimental data and predicted densities for alfalfa as based on the developed empirical model (Equation (8)) versus plunger pressure are plotted in Figure 2.

The estimated values for the constant coefficients of models for alfalfa are presented in Table 2. Models expressing the 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 employed in the present study. The compression chamber of a baler is an open-end canal rather than a closed-end die, and for this reason, none of the previously proposed models could be applied to the data related to the pressure-density relationship of the large cubic baler.

Models proposed by Ferrero et al. (1990), Viswanathan and Gothandapani (1999),

Table 1. Summary of validation of different models of pressure-density relationship with the data related to the baling in alfalfa while using the large cubic baler.

Pressure-density model	R^2	*SD*	*SE*	*AE* (%)
$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP})$ (Developed model)	0.89	4.25 (kg m^{-3})	0.45 (kg m^{-3})	2.55
$\gamma = \gamma_0 + (A + BP)(1 - e^{-DP})$ (Ferrero *et al.*, 1990)	0.86	4.93 (kg m^{-3})	0.52 (kg m^{-3})	2.96
$(\gamma_{max} - \gamma)/(\gamma_{max} - \gamma_0) = e^{(-P/K)}$ (Bilanski *et al.*, 1985)	0.85	5.04 (kg m^{-3})	0.53 (kg m^{-3})	3.02
$\gamma = J \ln(P/L)$ (Butler and McColly, 1959)	0.83	0.34 (lb ft^{-3})	0.04 (lb ft^{-3})	3.27
$P = G + H\gamma + I\gamma^2$ (Viswanathan and Gothandapani, 1999)	0.87	17.04 (kPa)	1.8 (kPa)	5.91
$P = Q \log[1 - R(\gamma - \gamma_0)]$ (Watts and Bilanski, 1991)	0.86	0.02 (MPa)	0.002 (MPa)	6.09

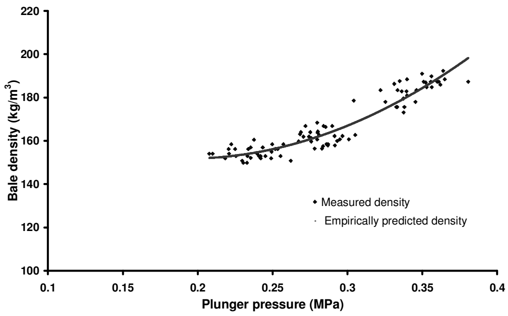

Figure 2. Experimental and predicted densities vs. plunger pressure in a large cubic baler for alfalfa at a moisture content of 12.4% wb.

Watts and Bilanski (1991), Butler and McColly (1959), and Bilanski et al. (1985) were also tested against the data related barley straw (12 data points) to find the most suitable model for the pressure-density relationship (Table 3). The developed model for the pressure-density relationship possessed the highest coefficient of determination (0.94) and the lowest average error (2.5%). Predicted bale density, based on the developed empirical model (Equation (8)) and the experimental data for barley straw, versus plunger pressure are plotted in Figure 3. The estimated values for the constant coefficients of models for barley straw are presented in Table 4.

Baling Alfalfa

Means comparison analysis using Duncan's Multiple Range Tests on alfalfa revealed that the difference between the plunger pressures and bale densities at all load settings was significant (P< 0.01). Plunger pressure and bale density increased with increasing load settings (Table 5) which was so expected; therefore, when the load was set at 70% of the available

Table 2. Constant coefficient values used to calculate the coefficient of determination and average error of models in baling alfalfa.

Developed model	Ferrero *et al.* (1990)	Bilanski *et al.* (1985)	Butler and McColly (1959)	Viswanathan and Gothandapani (1999)	Watts and Bilanski (1991)
γ_0 = 80.0	γ_0 = 81.0	γ_0 = 80.0	J= 4.7	G= -1294.7	γ_0 = 78.2
A= 119.9	A= 10.0	γ_{max} = 534.0	L= 4.6	H= 15.7	Q= 5.7
B= -501.5	B= 262.9	K= 1.36		I= -0.037	R= -0.0014
C= 1306.6	D= 70.9				
D= 71.3					

Table 3. Summary of validation different models of pressure-density relationship with the data of baling barley straw while using the large size cubic baler.

Pressure-density model	R^2	*SD*	*SE*	*AE* (%)
$\gamma = \gamma_0 + (A + BP + CP^2)(1 - e^{-DP})$ (Developed model)	0.94	3.22 (kg m^{-3})	0.93 (kg m^{-3})	2.50
$(\gamma_{max} - \gamma)/(\gamma_{max} - \gamma_0) = e^{(-P/K)}$ (Bilanski *et al.,* 1985)	0.94	3.26 (kg m^{-3})	0.94 (kg m^{-3})	2.52
$\gamma = J \ln(P/L)$ (Butler and McColly, 1959)	0.94	0.21 (lb ft^{-3})	0.06 (lb ft^{-3})	2.55
$\gamma = \gamma_0 + (A + BP)(1 - e^{-DP})$ (Ferrero *et al.,* 1990)	0.92	3.73 (kg m^{-3})	1.08 (kg m^{-3})	2.89
$P = G + H\gamma + I\gamma^2$ (Viswanathan and Gothandapani, 1999)	0.93	25.66 (kPa)	7.41 (kPa)	7.81
$P = Q \log[1 - R(\gamma - \gamma_0)]$ (Watts and Bilanski, 1991)	0.92	0.03 (MPa)	0.008 (MPa)	8.00

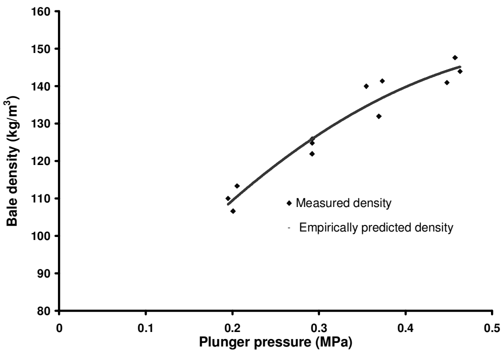

Figure 3. Experimental and predicted densities vs. plunger pressure in a large cubic baler for barley straw at a moisture content of 8.7% wb.

maximum load, the plunger pressure reached its highest value. Results also revealed that flake size setting exerted a slight effect on the alfalfa bale density while a significant effect on the plunger pressure. The means comparison analysis of the bale density at different flake sizes showed that the bale density at the flake size of 3/10 was slightly lower than the bale densities at other sizes (Table 5). The plunger pressure increased with increasing flake size (thickness); even though it was thought as to decrease with increasing flake size. This was probably due to higher material rebounding after each plunger stroke for the thicker flakes. The effect of interaction between load setting and flake size on the bale density was significant only at the load setting of 70%. Bale density at the flake size of 3/10 and at 70% load setting was significantly different from that at this load setting and at 6/10 as well as at 9/10 flake sizes (Table 6).

Baling Barley Straw

Analysis of baling barley straw data indicated that the plunger pressure and bale densities were drastically affected by the load settings. The plunger pressure and bale density increased with increasing load setting which was so expected (Table 7). Results also showed that the plunger pressure and bale density slightly increased with increasing flake size (Table 7) which followed a similar trend as compared to the effect of flake size on plunger pressure and bale density in baling alfalfa. The trends of bale density and plunger pressure changes with load setting and flake size were similar in the cases of alfalfa and barley straw; however the rate of change was slightly different due to different physical

Table 4. Constant coefficient values used to calculate the coefficient of determination and average error of models in baling barley straw.

Developed model	Ferrero *et al.* (1990)	Bilanski *et al.* (1985)	Butler and McColly (1959)	Viswanathan and Gothandapani (1999)	Watts and Bilanski (1991)
γ_0 = 50.0	γ_0 = 53.4	γ_0 = 50.0	*J*= 2.68	*G*= -9.42	γ_0 = 82.0
A= 9.1	*A*= 13.3	γ_{max} = 170.0	*L*= 2.26	*H*= -1.69	*Q*= 8.3
B = 301.7	*B*= 239.8	*K*= 0.29		*I*= -0.033	*R*= -0.002
C = -250.1	*D*= 71.2				
D = 71.2					

Table 5. Average plunger pressures and bale dry matter densities at different load settings and flake sizes for alfalfa.

Load setting (%)	Plunger pressure (MPa)	Bale density (kg m^{-3})	Flake size	Plunger pressure (MPa)	Bale density (kg m^{-3})
50	0.237 a	154.3 a	3/10	0.278 a	165.2 a
60	0.283 b	161.8 b	6/10	0.290 b	167.5 b
70	0.345 c	183.8 c	9/10	0.296 c	167.2 b

Each value of bale density and plunger pressure presented in this table is an average of 9 data points.

Table 6. The effect of interaction between load setting and flake size on the bale density for the case of alfalfa.

Load setting (%)	Flake size	Bale density* (kg m^{-3})
50	3/10	155.1 a
50	6/10	155.1 a
50	9/10	152.6 a
60	3/10	162.4 b
60	6/10	161.7 b
60	9/10	161.3 b
70	3/10	178.0 c
70	6/10	185.8 d
70	9/10	187.6 d

* Each value in the third column of this table is an average of 3 data points.

Table 7. Average plunger forces and bale dry matter densities at different load settings and flake sizes for baling barley straw.[a]

Load setting (%)	Plunger pressure (MPa)	Bale density (kg m^{-3})	Flake size	Plunger pressure (MPa)	Bale density (kg m^{-3})
40	0.200 a	109.9 a	3/10	0.329 ab	127.0 a
60	0.294 b	124.1 b	6/10	0.328 b	129.6 b
80	0.368 c	137.7 c	9/10	0.333 a	130.3 b
100	0.456 d	144.1 d			

[a] Each value in the second and third columns of this table is an average of 9 data points, while each value in the fifth and sixth columns is an average of 12 data points.

properties of these materials. The interaction between load setting and flake size had a significant effect on the plunger force at all load settings but 60%. Results showed that at the highest level of load setting (100%) the medium flake size required the maximum plunger force, while at the medium load settings (60 and 80%) the thickest and at the lowest load setting (40%) the thinnest flake size needed the maximum plunger force (Table 8).

CONCLUSIONS

Results of this study showed that the

Table 8. The effect of the interaction between load setting and flake size on the plunger force for the case of barley straw.

Load setting (%)	Flake size	Plunger force (kN)*
40	3/10	0.205 a
40	6/10	0.195 ab
40	9/10	0.201 b
60	3/10	0.292 c
60	6/10	0.294 c
60	9/10	0.296 c
80	3/10	0.369 d
80	6/10	0.359 e
80	9/10	0.375 d
100	3/10	0.447 f
100	6/10	0.463 g
100	9/10	0.457 g

*Each value in the third column of this table is an average of 3 data points.

plunger pressure and bale density were significantly affected by the load setting and flake size in a large cubic baler. An empirical model was developed for the pressure-density relationship of a large cubic baler for the cases of alfalfa and barley straw. Some of the specific conclusions that can be drawn from this research as based on the addressed objectives are outlined as follows: The empirical model was in good correlation with the experimental data (R^2 of 0.89 for alfalfa and 0.94 for barley straw).

The developed empirical model for both alfalfa and barley straw was concluded as a combination of a quadratic and an exponential equation.

Plunger pressure and bale densities increased with increasing load setting and flake size in the large cubic baler for the studied crops.

Recommendations

According to results and limitations of this study, the following recommendations can be presented to make the future studies more fruitful in this area: Since the field experiments in the present study were performed at one level of moisture content for each crop, evaluation of the effect of crop moisture content on the pressure-density relationship can be considered in the future research.

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مدل رابطه فشار-چگالی در بیلر مکعبی بزرگ

چکیده

در این تحقیق، مدلهای تحلیلی و تجربی برای رابطه فشار-چگالی در بسته بندی یونجه و کاه جو توسط بیلرهای مکعبی بزرگ ارائه گردید. مدل تحلیلی با استفاده از فرمولهای ساختاری موجود برای مواد کشسان خطی ایزوتروپیک و تغییرات حجم بسته علوفه استخراج گردید. برای استخراج مدل تجربی و تخمین پارامترهای آن، روش آنالیز رگرسیونی حداقل مربعات و حداقل کردن مربع اختلاف بین داده های واقعی و داده های تخمین زده شده مورد استفاده قرار گرفت .همچنین اثر ضخامت لایه های علوفه بسته بندی شده (میزان علوفه ای که در هر مرحله از محفظه پیش تراکم وارد محفظه تراکم اصلی می شود) و تنظیمات بار، بر فشار پیستون و چگالی بسته های یونجه و کاه جو مورد بررسی قرار گرفت. نتایج نشان داد که بر اساس مدل تحلیلی، چگالی بسته ابتدا با افزایش فاصله از پیستون کاهش می یابد و سپس تا انتهای محفظه تراکم ثابت می ماند. مدل تجربی ارائه شده برای یونجه و کاه جو، هردو ترکیبی از معادله درجه دوم و نمائی بود. مدل تجربی همخوانی خوبی با داده های تجربی نشان داد در حالی که مدل تحلیلی تخمین دقیقی از چگالی بسته به خصوص در فشار کم پیستون ارائه نداد .نتایج همچنین نشان داد که تنظیمات بار اثر معنی داری بر فشار پیستون و چگالی بسته داشت به طوری که فشار پیستون و چگالی بسته در هردو نوع علوفه با افزایش میزان بار، افزایش یافت. ضخامت لایه های علوفه بسته بندی شده نیز اثر کمی بر فشار پیستون و چگالی بسته داشت.