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The Effect of Pressure on Compaction Process Parameters of Milk Thistle Straw With Binder

Ryszard Kulig[a] * (https://orcid.org/0000-0003-0994-8140)

[a] University of Life Sciences in Lublin, Department of Food Engineering and Machines, Lublin, Poland

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The results of research on determining the influence of pressure (from 45 to 113 MPa) on the compaction parameters of milk thistle straw (*Sylibum marianum*) are presented. Raw biomass and biomass containing the addition of a binder in the form of calcium lignosulfonate were investigated. Compaction was carried out using a Z020/TN2S Zwick universal testing machine and a pressing unit with a closed die. It was found that with increasing pressure, the density of material in the chamber and the density of the briquette rises (on average by 33.8%), and the mechanical strength of the finished product grows almost 3.5 times. Increasing the compaction pressure augments the compaction energy demand by an average of 84%. It was shown that the addition of binder increases the density of the briquette (by 22% on average) and raises the mechanical strength by 150% on average.

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1. Introduction

The unrelenting demand for solid biofuels favors the use of various types of by-products and residues from the agri-food industry [1-3]. Post-harvest biomass enjoys particular recognition in the context of the production of compact biofuels [4, 5].

In the literature on the subject, there is no unequivocal assessment of susceptibility of milk thistle biomass to pressure compaction. It should be emphasized that Poland is one of the leading producers of milk thistle in Europe [6], and the main purpose of cultivation is to obtain valuable seeds. Milk thistle straw, on the other hand, is a by-product that can be used to produce solid biofuels. In the coming years, in connection with the new EU CAP for 2023-2027, these plants will also be able to be included in the crops under eco-scheme-areas with melliferous plants. The biomass collected from such fields can also be used as a raw material in the pressure agglomeration process, as a component of fodder or compacted solid biofuels.

Plant biomass, due to its low density – making it difficult to transport, store and dose to boilers, in addition to its low calorific value (relative to the unit of volume), is difficult to distribute in its natural form. Therefore, in order to improve its suitability for energy purposes, first of all its density should be increased [7, 8]. This is achieved by the pressure compaction of loose raw material into briquettes or pellets [9-11].

* Corresponding author: ryszard.kulig@up.lublin.pl

In the context of the course of the process and the quality of the obtained product, the value of the applied compaction pressure is of exceptional importance [12-16], apart from the moisture content of the material [17-20]. The use of an inappropriate value of this parameter may, on the one hand, lead to excess energy consumption, and on the other hand, result in obtaining a briquette with inadequate strength properties.

A partial solution to the above problem may be the use of lignin binders, e.g. in the form of calcium lignosulfonate. These compounds bind individual components of the mixture, increasing the stability and quality of briquettes [17, 21, 22]. As a consequence, the obtained briquette is characterized by greater density and mechanical strength. This in turn reduces the total production costs and has a beneficial effect on reducing the volumes intended for storage or transport of the finished product.

Considering the above, the aim of this work is to determine the effect of the compaction pressure on the parameters of the pressure compaction process of the post-harvest biomass of milk thistle with various additions of calcium lignosulfonate.

2. Materials and methods

Milk thistle straw collected in August 2022 was used for the study. The obtained straw was crushed in a hammer mill equipped with sieves with a diameter of 3 mm. The research material was subjected to convection drying in order to obtain the assumed degree of humidity, i.e. 12%. The required moisture of the raw material was determined on the basis of the formula for mass variation over time, according to the following relationship:

$$m_1 = m_0 (\frac{100 - w_0}{100 - w_1} \quad \text{(g)} \tag{1}$$

where:
m_0 – initial mass of material, g;
m_1 – mass of material after drying, g;
w_0 – initial moisture content of material, %;
w_1 – moisture content of material after drying, %.

Then a weighed portion of the binder (calcium lignosulfonate) was added to the prepared raw material in an amount corresponding to the addition of 1 and 2 wt% (the maximum amount of the additive was adopted in accordance with PN-EN ISO 17225-1:2014. The control sample was the raw material without the addition of binder.

In the compaction studies, the Zwick Z020/TN2S universal testing machine was equipped with a pressing unit and a closed die with a cylinder (compaction chamber) diameter of 15 mm. The test parameters were as follows - mass of material sample: 2 g, cylinder (compacted material) temperature: 20 ˚C, piston speed: 10 mm·min^{-1}. Compaction was carried out for five values of the maximum compaction force, i.e. 8, 11, 14, 17 and 20 kN, which corresponded to the following compaction pressure values: 45, 62, 80, 96 and 113 MPa. The densification was carried out in three repetitions each time.

During the study, the curve of the so-called compaction characteristics (dependence of the compaction force on the displacement of the piston), from which the process parameters were determined [15, 23]. The values of maximum material density in the compaction chamber ρ_c and compaction work L_c were determined based on the characteristic points of the compaction curve. The coefficient of material susceptibility to compaction k_c was calculated:

$$k_c = \frac{L_c}{(\rho_c - \rho_n)} \quad ((\text{J·g-1})/(\text{g·cm}^{-3})) \tag{2}$$

where:
ρ_n – initial material density in the compaction chamber, g·cm^{-3};
L_c – compaction work, J·g^{-1}.

The density of the resulting briquettes was determined after 48 hours of storage ρ_a.

The degree of compaction of the analyzed material in the chamber S_{zm} and the compaction of the resulting briquette S_{za} were determined as the quotient of density ρ_c and ρ_a, and initial density in the compaction chamber ρ_n ($S_{zm} = \rho_c \cdot \rho_n^{-1}$, $S_{za} = \rho_a \cdot \rho_n^{-1}$).

The mechanical strength of a briquette δ_m was determined in the Brazilian compaction test using the Zwick Z020/TN2S universal testing machine (with the piston speed of 10 mm·min^{-1}). A briquette with diameter d and length l was compacted transversely to the axis until the breaking point, and maximum breaking force F_n was determined. Mechanical strength δ_m (MPa) was calculated using the following formula [24]:

$$\sigma_n = \frac{2 \cdot F_n}{\pi \cdot d \cdot l} \tag{3}$$

The analysis of the relationship between the compaction pressure and the parameters of the compaction process (for different binder contents in the raw material) was performed using statistical procedures included in the STATISICA program, each time assuming the significance level $α_i$ = 0.01. The form of the equations was selected by reverse stepwise regression. The significance of the regression coefficients was determined by Student's t-test. Model adequacy was verified using Fisher's test.

3. Results and discussion

The regression equations describing the dependence of the investigated parameters of the agglomeration process on the densification pressure and the binder content in the raw material are summarized in Table 1. Regression analysis showed that the obtained dependencies can be described by linear equations or logarithmic equations ($α_i$=0.01). These relationships are shown in Figures 1-4.

Table 1. Regression equations describing correlations between density ρ_c, ρ_a, compaction work L_c, coefficient k_c, degree of compaction S_{zm}, S_{za}, and mechanical strength δ_m and compaction pressure *P* and binder content Z_l, and values of determination coefficient R^2

Parameter	Binder content	Regression equation	R^2
Density of material in the chamber, ρ_c	Z_l = 0 wt%	$\rho_c = 0.007P + 0.738$	0.967
	Z_l = 1 wt%	$\rho_c = 0.0089P + 0.549$	0.985
	Z_l = 2 wt%	$\rho_c = 0.0091P + 0.523$	0.974
Density of briquette after 48 h., ρ_a	Z_l = 0 wt%	$\rho_a = 0.173 \ln P - 0.0059$	0.968
	Z_l = 1 wt%	$\rho_a = 0.248 \ln P - 0.232$	0.993
	Z_l = 2 wt%	$\rho_a = 0.341 \ln P - 0.539$	0.937
Compaction work, L_c	Z_l = 0 wt%	$L_c = 0.333P + 8.669$	0.972
	Z_l = 1 wt%	$L_c = 0.317P + 11.86$	0.990
	Z_l = 2 wt%	$L_c = 0.386P + 9.732$	0.993
Coefficient of susceptibility to compaction, k_c	Z_l = 0 wt%	$k_c = 0.118P+4.878$	0.997
	Z_l = 1 wt%	$k_c = 0.162P + 3.694$	0.978
	Z_l = 2 wt%	$k_c = 0.128P + 8.96$	0.983
Degree of compaction of material, S_{zm}	Z_l = 0 wt%	$S_{zm} = 0.048P + 7.564$	0.934
	Z_l = 1 wt%	$S_{zm} = 0.053P + 7.196$	0.952
	Z_l = 2 wt%	$S_{zm} = 0.056P + 6.765$	0.969
Degree of compaction of briquette, S_{za}	Z_l = 0 wt%	$S_{za} = 1.921 \ln P – 2.403$	0.906
	Z_l = 1 wt%	$S_{za} = 1.804 \ln P – 0.837$	0.913
	Z_l = 2 wt%	$S_{za} = 1.861 \ln P – 0.784$	0.905
Mechanical strength of briquette, δ_m	Z_l = 0 wt%	$\delta_m = 0.385 \ln P – 1.366$	0.989
	Z_l = 1 wt%	$\delta_m = 0.81 \ln P – 2.901$	0.956
	Z_l = 2 wt%	$\delta_m = 0.923 \ln P – 2.979$	0.970

3.1 Density of material in chamber and briquette

The analysis of the research results presented in Fig. 1 shows that for each binder content in the raw material z_l, the density of the material in the chamber ρ_c grew with increasing pressure. On the other hand, in the case of briquette density ρ_a the greatest rise occurred in the pressure range of 45-80 MPa. It should be assumed that increasing the value of the unit piston pressure caused an increment in the intensity of plastic deformations in the compacted material, which led to an increase in particle packing. Similar comments were also made by Li et al. [11] and Demirel et al. [14].

Each time, the highest values of the analyzed parameters were obtained for the material with the maximum binder content, and the lowest for the material without the addition of binder. For the material with the binder content of 2 wt% the range of density variation in the pressure range of 45-113 MPa was for ρ_c from 0.9 g·cm^{-3} to 1.54 g·cm^{-3}, and for ρ_a from 0.771 g·cm^{-3} to 1.069 g·cm^{-3}. It is worth noting that in the case of the density of the material in the compaction chamber, the effect of the binder on the value of this parameter had little effect. It was most noticeable in the pressure range from 45 to 96 MPa.

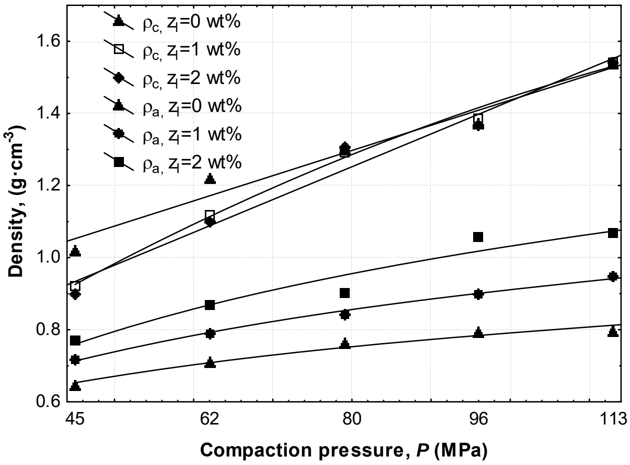

Fig. 1. Correlation between material density in chamber (ρ_c), briquette density (ρ_a) and compaction pressure (P) at various binder content levels (z_l)

3.2 Degree of compaction

The results of the studies of the degree of compaction of the material in the chamber and of the briquette after storage show that the value of the parameters rose with the increase in the compaction pressure (Fig. 2). The maximum density of the material in the chamber ρ_c, obtained as a result of applying the pressure of 113 MPa, was on average 12.5 times higher than the initial density of the material ρ_n, regardless of the binder content in the material. At the same time, it can be noticed that the impact of the binder in relation to the increase in the value of the analyzed parameter concerned primarily the compaction pressure in the range from 45 to 96 MPa.

The highest density of the degree S_{za} was characteristic for the material with the 2 wt% binder content, compacted in the pressure range of 80 - 113 MPa. In this case, the density of the briquette was about 7.2 times higher than the initial density of the material. For all the researched materials, as in the case of changes in density ρ_a, the greatest increase in the degree of compaction occurred in the pressure range of 45-80 MPa.

The studies of the compaction of milk thistle straw, compared to investigations carried out on other plant materials [16-18] confirmed the tendencies to change the density (Fig. 2) and mechanical strength of the briquette depending on the compaction pressure (Fig. 4).

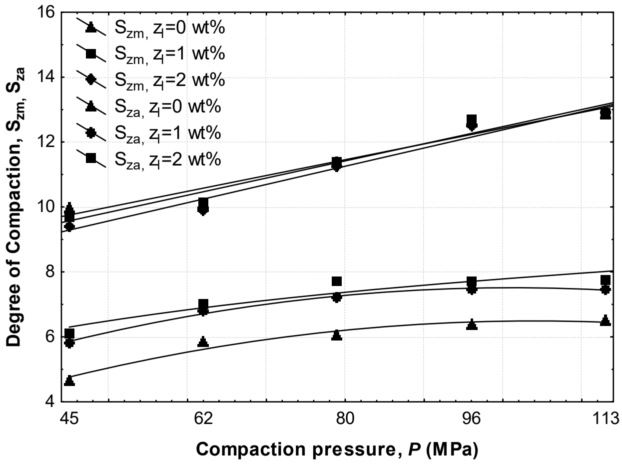

Fig. 2. Correlation between degree of compaction (S_{zm}), degree of briquette compaction (S_{za}) and compaction pressure (P) at various binder content levels (z_l)

3.3 Work of compaction and susceptibility of material to compaction

The relationships between the unit of compaction work L_c and the material coefficient for compaction and compaction pressure *P* are shown in Fig. 3. Throughout the research range, the value of the analyzed parameters grew with increasing compaction pressure. This regularity was observed for all the examined materials. The value of parameter L_c ranged from 24.2 to 53.94 $J \cdot g^{-1}$, and parameter k_c from 10.1 to 23.45 $(J \cdot g^{-1}) \cdot ((g. \cdot cm^{-3}))^{-1}$. The highest values of the analyzed parameters were recorded each time for the maximum compaction pressure (113 MPa) and the highest binder content (2 wt%). It can be assumed that increasing the binder addition to the raw material augmented the coefficient of friction of the material particles against each other and against the walls of the compaction chamber. As a consequence, this led to a rise in the compaction work value as well as a decrease in the susceptibility of the material to compaction (Fig. 3). Thus, the obtained results of the units of energy consumption for compaction L_c confirm the tendencies of its change with increasing compaction pressure as was shown in the case of the compaction of other raw materials [18, 21].

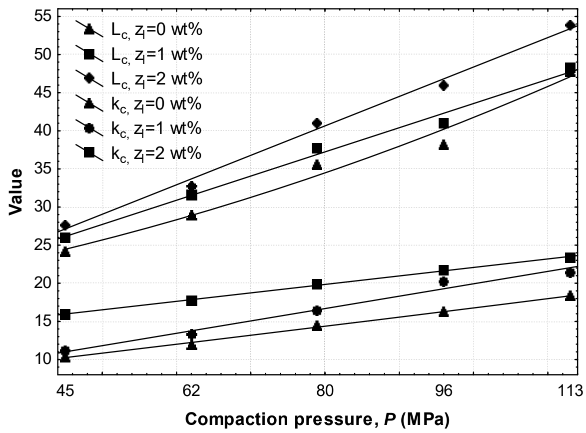

Fig. 3. Correlation between compaction work (L_c), coefficient of susceptibility to compaction (k_c) and compaction pressure (P) at various binder content levels (z_l)

3.4 Mechanical strength of briquette

The results of the mechanical resistance tests σ_n showed that for each type of material, the strength of the briquette grew with increasing compaction pressure. The mechanical resistance value ranged from 0.11 to 1.35 MPa. The highest values were for the briquette obtained during the compaction of the material with the 2 wt% binder addition using the pressure of 113 MPa.

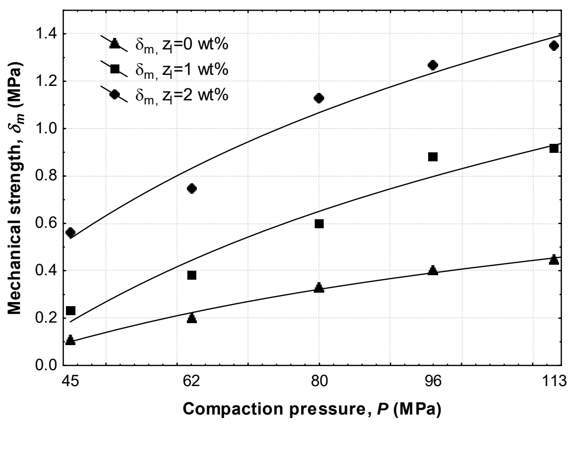

Fig. 4. Correlation between mechanical strength of briquette (δ_m) and compaction pressure (P) at various binder content levels (z_l)

It should also be noted that with increasing pressure, the differences in the σ_n values (resulting from the different binder content in the raw materials) widened. At the compaction pressure values of 96 and 113 MPa (for the material containing 2 wt% binder), the mechanical resistance was more than 3 times higher than the value obtained for the control material.

Conclusions

Based on the conducted research, the following conclusions can be drawn:

1. It was found that the density of the material in the compaction chamber – both for the material without the addition of a binder and with its participation – rises with increasing compaction pressure by an average of 50.6%. An increase in compaction pressure in the investigated range also causes an increment in the density of the briquette by an average of 35.2%. In the case of the ρ_a parameter, the impact of the binder addition also becomes important; the average increase in the briquette density value (resulting from this) is 22.6%.
2. The degree of material compaction in the chamber grows on average by 27.5% in the entire studied range of pressure. In turn, the degree of briquette density increases only in the pressure range of 45-96 MPa by an average of 26.4%.
3. The specific work of compaction and the ratio of material to compaction grow with increasing compaction pressure. The average changes in the first case are 73%, and in the second 45.3%. At the same time, it was shown that the increment in the binder addition reduces the susceptibility of the material to compaction.
4. Increasing the compaction pressure in the tested range contributes to the rise in the mechanical strength of the obtained briquette – on average by 348%. On the other hand, the 2 wt% binder addition to the raw material increases the value of σ_n by 266% on average.

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