IMPACT OF PRESSURE ON THE PARAMETERS OF PEA STRAW COMPACTION

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ARTICLE INFO	ABSTRACT
	This paper presents the results of pea straw compaction efficiency tests. The compliance of the tested material to pressure agglomeration was assessed depending on the compaction pressure used (45-113 MPa). The compaction was carried out using a Zwick testing machine, type Z020/TN2S, and a closed die pressing unit. It was found that, along with the pressure increase, the material density in the chamber increased (from 1.255 to 1.76 g·cm⁻³), as well as the agglomerate's density (from 0.739 to 1.05 g·cm⁻³) and the product's mechanical resistance (from 0.31 to 0.69 MPa). Increasing the compaction pressure in the analyzed range increased the unit value of compaction work, from 17.16 to 34.27 J·g⁻¹.

Introduction

The constantly growing role of renewable energy in the energy balance increases the economic use of waste from agri-food production (Danish and Wang, 2019; Mao et al., 2018, Zdanowska et al. 2019). In this context, straw is of great importance (Kwaśniewski and Kuboń, 2016; Lisowski et al., 2018). As a raw material for the production of solid biofuels, straw of virtually all types of arable crops, including legumes, can be used. This is important because in the case of plants such as peas, the straw is usually left unused and plowed down.

Straw, in combination with other commonly used energy carriers, is a fuel quite cumbersome to use. Unlike conventional sources, it is a heterogeneous material with a lower energy value, especially per unit of volume (Adamczyk et al., 2005, 2006). This state of affairs requires changing its original form into agglomerates obtained in the process of pressure compaction (Hejft, 2002). In consequence, it allows to significantly reduce the costs associated with the distribution and use of plant biomass for energy purposes.

Many studies demonstrate that in the production process of molded solid biofuels, the value of the applied compaction pressure (i.e. unit piston pressure) (Li and Liu, 2000; Mani et al., 2006) and the moisture content of the raw material (Relova et al., 2009; Kulig and Skonecki, 2011) is of great importance. The value of these parameters impacts both the

course of the process and the quality of the finished product (Whittaker and Shield, 2017). Application of too low a pressure results in agglomerates with insufficient mechanical durability. However, an uncontrolled increase of the pressure can lead to an unnecessary increase in energy consumption and wear of the working elements of production equipment.

Earlier studies of the author presented the results of research on the impact of the above parameter on the efficiency of pressure compaction of biomass of various origins (Kulig et al. 2013, 2014). This work is a continuation of research in this area. Therefore, the purpose of the work was to determine the impact of a piston pressure unit on the parameters of the compaction process of crushed pea straw.

Material and methods

The research material was pea straw, collected during the 2019 harvest. The raw material was cut into 20 mm chaff. Then the thus prepared material was crushed using a beater shredder (type ML-500) equipped with a sieve with a hole diameter of ϕ4 mm. The compaction was carried out for raw material with 10 and 20% humidity. The bulk density of the raw material – determined in accordance with PN-ISO 7971-2: 1998 – was respectively: 0.151 g·cm^{-3} for 10% humidity, and 0.162 g·cm^{-3} for 20% humidity.

A ZWICK strength testing machine, type Z020/TN25, and a closed die pressing unit were used in compaction tests. The research was carried out in accordance with the methodology presented by Laskowski and Skonecki (2001). A matrix with a chamber diameter $d = 15$ mm was used, in which a 2 g mass was compacted. The temperature of the cylinder (and of compacted material) was 20ºC, and piston speed was 10 mm·min^{-1}. The 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, 79, 96 and 113 MPa. Each process was carried out in a triplicate.

The effect of the measurement was the compaction characteristics curve, demonstrating the dependence of compaction force on piston shifts (Fig. 1). The maximum material density in the chamber was determined based on the curve ρ_c and total compaction work L_c. Material susceptibility to compaction k_c ($k_c = L_c'\cdot(\rho_c - \rho_n)^{-1}$ was calculated, where: $L_c' = L_c \cdot m^{-1}$ – unit value of compaction work, m – the mass of the material sample, ρ_n – bulk density of the raw material. After 48 hours of storage, the agglomerate density ρ_a was determined for the obtained briquette. The agglomerate compaction degree S_{za} was also determined, based on the formula: $S_{za} = \rho_a \cdot \rho_n^{-1}$.
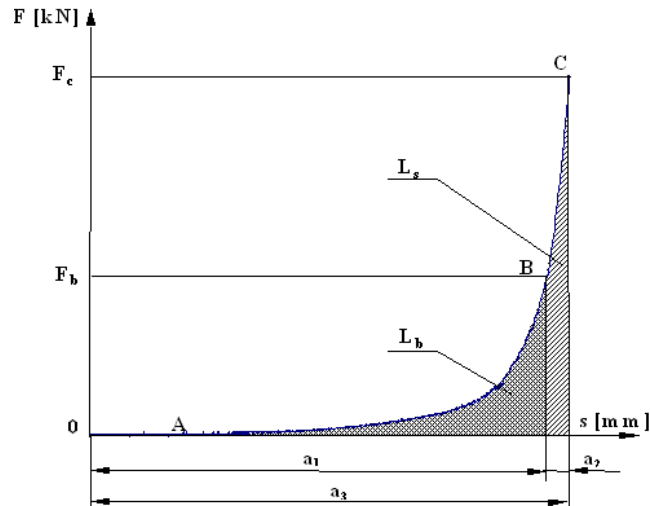
Figure 1. Compaction characteristics: a_1 – proper compaction, a_2 – compression, a_3 – extrusion (Laskowski and Skonecki, 2001)

Next, the agglomerate quality was determined, in terms of mechanical durability. Mechanical resistance of the agglomerate was determined by the so-called Brazilian test, using the ZWICK Z020/TN2S testing machine. Mechanical resistance σ_n (MPa) was calculated from the formula (Ruiz et al., 2000):

$$\sigma_n = \frac{2F_n}{\pi\, dl} \qquad \text{(MPa)} \tag{1}$$

where:
- d − agglomerate diameter, (mm)
- l − agglomerate length, (mm)
- F_n − agglomerate destructive force, (N)

Results and discussion

Regression equations that describe the dependence of the examined process parameters on the compaction pressure are presented in Tab. 1. Figures 2-5 show that the impact of pressure on the course of the compaction process and the properties of the obtained agglomerate (for each raw material moisture content tested) can be described by linear and logarithmic models ($\alpha_a = 0.01$).

The relationships shown in Fig. 2 indicate that with the increase of the compaction pressure, the maximum raw material density in the chamber ρ_c increased, as did the density of the agglomerate ρ_a. The range of density variability ρ_c for the examined raw materials ranged from 1.255 to 1.76 g·cm^{-3}. Higher values of this parameter were obtained for the raw material with 20% humidity. It should be assumed that the wetter raw material must have increased its plasticity, which led to an increase in particle packing. Similar comments were also made

by Mani et al. (2006). In contrast, the density of the agglomerate after storage ρ_a was higher for the raw material with 10% humidity (the range varied from 0.949 to 1.05 g·cm^{-3}). For the raw material with 20% humidity, the values of this parameter ranged from 0.739 to 0.96 g·cm^{-3}. A significant increase in density ρ_a occurred in the pressure range of 45-96 MPa. However, a further increase in pressure practically did not contribute to increasing the density of the obtained agglomerate. With reference to pressures 96 and 113 MPa, the obtained differences in parameter values ρ_a, were not statistically significant (p> 0.01).

Table 1.

Regression equations describing the dependence of density ρ_c, ρ_a, the density of the agglomerate S_{za}, mechanical resistance δ_m. work $L_c{}'$ and the coefficient k_c on the compaction pressure P and the value of the determination coefficient R^2

Process parameter	Raw material moisture	Regression equation	R^2
Density of the material in the chamber, (ρ_c)	10%	$\rho_c = 0.1P + 1.725$	0.918
	20%	$\rho_c = 0.09P + 1.319$	0.989
Density of the agglomerate after 48 hours, (ρ_a)	10%	$\rho_a = 0.125 \ln P + 0.468$	0.918
	20%	$\rho_a = 0.253 \ln P - 0.234$	0.972
Degree of agglomerate compaction, (S_{za})	10%	$S_{za} = 0.835 \ln P + 3.12$	0.929
	20%	$S_{za} = 1.581 \ln P + 1.465$	0.972
Mechanical resistance of the agglomerate, (δ_m)	10%	$\delta_m = 0.173 \ln P + 0.168$	0.971
	20%	$\delta_m = 0.309 \ln P + 0.903$	0.984
Compaction work, $(L_c{}')$	10%	$L_c{}' = 0.165P + 13.98$	0.980
	20%	$L_c{}' = 0.194P + 8.66$	0.971
Coefficient of material compaction compliance, (k_c)	10%	$k_c = 0.034P + 17.613$	0.959
	20%	$k_c = 0.075P + 10.56$	0.972

Changes in agglomerate density S_{za}, dependent on the compaction pressure, were illustrated in Fig. 3. The values obtained characterize the scope of agglomerate density change after its removal from the die and expansion within 48 hours of storage, as compared to the initial density of the material. As the unit pressure of the piston increases, the degree of agglomerate density S_{za} increased, ranging from 4.618 to 6.993. Higher values of S_{za} obtained for the raw material with 10% moisture demonstrate that its agglomerate freely expanded to a lesser degree than the product obtained from the raw material with 20% moisture. As a result, it achieved higher density values. In this case, the density of the agglomerate after storage was greater than the initial density of the raw material by approx. 6 to 7 times. As in the case of density changes ρ_a, the largest increase in parameter value S_{za} for both tested material moistures occurred in the pressure range of 45-96 MPa.
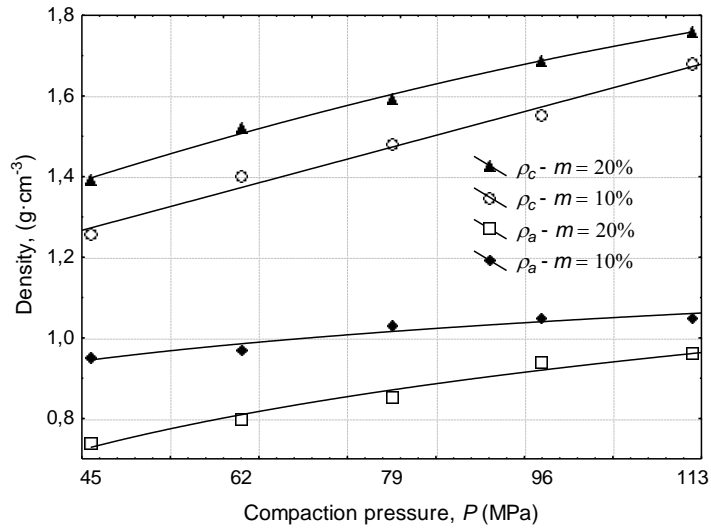
Figure 2. The relationship between the density of the material in the compaction chamber (ρ_c) and the density of the agglomerate (ρ_a), and the compaction pressure (P) for various raw material moistures (m)
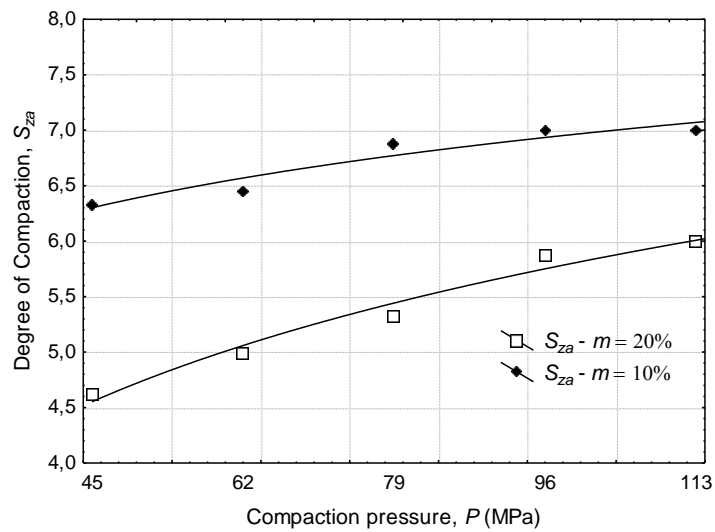

Figure 3. The relationship between the degree of agglomerate density (S_{za}) and the compaction pressure (P) for different raw material moistures (m)

The higher density of the agglomerate, obtained as a result of increasing the compaction pressure, had a positive effect on the mechanical strength of the obtained products. The results of the mechanical strength tests showed that as the compaction pressure increased, so

did the agglomerate's mechanical strength, irrespective of its humidity (Fig. 4). The highest value of the analyzed parameter (0.69 MPa) characterized the 10% humidity agglomerate, obtained when using 113 MPa pressure. By contrast, the lowest value of σ_n (0.31 MPa) was obtained for the 20% humidity raw material product, compacted at 45 MPa.

Compared to the tests carried out on other plant raw materials (Mani et al., 2006; Relova et al., 2009; Skonecki and Kulig, 2011), the performed pea straw agglomeration tests confirmed the tendencies of the agglomerate to change its density and mechanical strength, depending on the pressure applied, and moisture content.
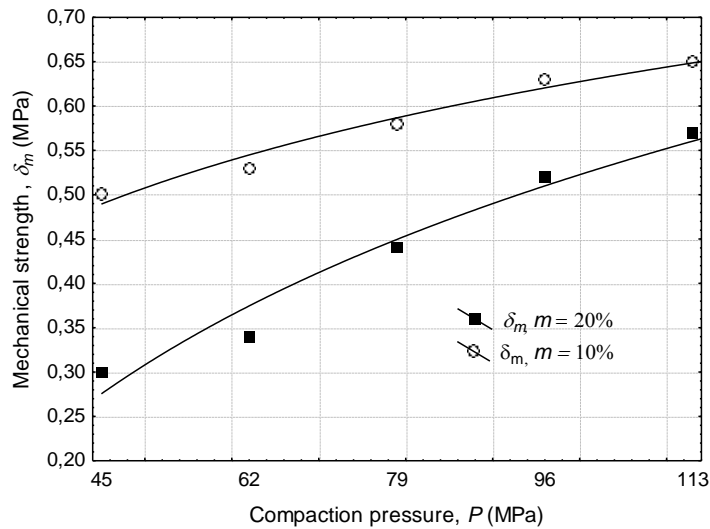

Figure 4. Relationship between mechanical resistance (δ_m) of the agglomerate and the compaction pressure (P) for different raw material moistures (m)

The test results presented in Fig. 5 indicate that the increase in compaction pressure caused an increase of the unit value of compaction work for each tested raw material. Thus, obtaining agglomerates with the highest density and mechanical resistance was associated with higher energy expenditures each time. The value of work $L_c{}'$ ranged from 17.16 J·g^{-1} for the pressure of 45 MPa (raw material with 20% humidity) to 34.27 J·g^{-1} for a pressure of 113 MPa (raw material with 10% humidity). Compaction of the raw material with 20% humidity was characterized by lower energy consumption in the entire tested range of pressure variability. Also in this case, increasing the humidity (m) probably caused the compacted material to become more plastic and its compaction compliance to increase, as evidenced by the lower value of the compaction compliance coefficient k_c (Fig. 5). The minimum value of k_c for m = 20% (P = 45 MPa) was 13.68 J·cm^3·g^{-2}, and the maximum was 18.63 J·cm^3·g^{-2} (P=113 MPa). However, for humidity m=10%, coefficient k_c increased from 17.2 J·cm^3·g^{-2} to 21.45 J·cm^3·g^{-2} along with the increasing compaction pressure, from 45 to 113 MPa. The obtained results for coefficient k_c confirm its tendency to change along with the increasing agglomeration pressure, as for the compaction of other raw materials (Kulig et al. 2013, 2014).
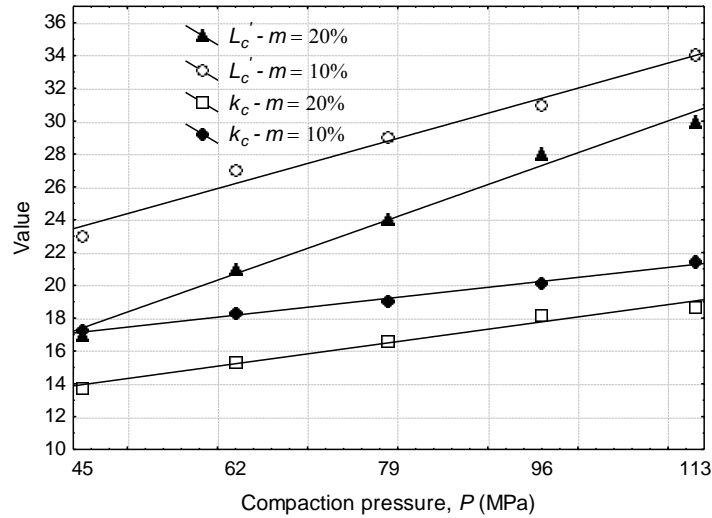
Figure 5. Relationship between a unit value of compaction work (L_c) and the material compaction compliance coefficient (k_c) and compaction pressure (P) for various raw material moistures (m)

Conclusions

Based on the results of the research, the following conclusions can be made:
1. The increase in unit piston pressure from 45 to 113 MPa increases the maximum density of the raw material in the chamber (ρ_c) by 26.5% on average.
2. It has been demonstrated that increasing the compaction pressure in the range of 45-96 MPa causes an increase in the agglomerate's density ρ_a (by 29.7% on average), and in the agglomerate's density values S_{za} (by 33% on average). However, further increase in the value of the unit piston pressure brings no statistically significant changes in the values of the parameters considered.
3. Mechanical strength σ_n of the obtained agglomerates increased along with the increase in compaction pressure, by 78.8% on average. Higher values σ_n (on average by 32%) has been shown for agglomerate obtained from raw material with 10% moisture content.
4. It was found that increasing the compaction pressure in the examined ranges caused an increase in the unit value of compaction work L_c' and the material efficient on compaction k_c. In the first case, the average increase in value was 66.3%, and in the second case, 31.42%.

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WPŁYW CIŚNIENIA NA PARAMETRY PROCESU ZAGĘSZCZANIA SŁOMY GROCHOWEJ

Streszczenie. Przedstawiono wyniki badań efektywności zagęszczania słomy grochowej. Oceniono podatność badanego materiału na proces aglomerowania ciśnieniowego w zależności od stosowanego ciśnienia zagęszczania (od 45 do 113 MPa). Zagęszczanie przeprowadzano przy wykorzystaniu maszyny wytrzymałościowej Zwick typ Z020/TN2S i zespołu prasującego z matrycą zamkniętą. Stwierdzono, że wraz ze wzrostem ciśnienia rosła gęstość materiału w komorze (w zakresie od 1,255 do 1,76 g·cm^{-3}) i gęstość aglomeratu (w zakresie od 0,739 do 1,05 g·cm^{-3}) oraz zwiększała się odporność mechaniczna produktu (w przedziale od 0,31 do 0,69 MPa). Zwiększanie ciśnienia zagęszczania w analizowanym przedziale powodowało wzrost wartości jednostkowej pracy zagęszczania w zakresie od 17,16 do 34,27 J·g^{-1}.

Słowa kluczowe: słoma grochowa, aglomerowanie, energochłonność zagęszczania ciśnieniowego, jakość aglomeratów