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EVALUATION OF PROPERTIES OF PELLETS MADE OF SWINE MANURE

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This paper deals with assessment of density, moisture content and mechanical properties of pellets made of dry swine manure utilizing pellet production line MGL 200. Pellets were subsequently subjected to compressive loading test. Furthermore, the values obtained were measured by means of device Andilog Stentor 1000 and compression diagrams were plotted. In terms of compressive strength, pellet type 1 showed value of 10.47 MPa; pellet type 2 showed value of 6.24 MPa. Considering the elasticity modulus, pellet type 1 showed value of 122.39 MPa; pellet type 2 showed value of 71.12 MPa. Other observed properties included force necessary for 10% compression strain; force in the first maximum of force-strain curve; force in the inflection point of the force-time curve. Results obtained from compressive loading test provide a basis for innovations in pellet production utilizing materials other than wood biomass.

Keywords: compressive loading; deformation; strength; modulus of elasticity

Utilization of biomass made of materials from agricultural production and waste biomass, the potential of which cannot be neglected, comes to the forefront and is very topical. Great attention is currently paid to utilization of wastes from agricultural production not only in the field of science and research (Bappah et al., 2019; Martínez-Guido et al., 2019; Purohit and Chaturvedi, 2018), but also in practice. Alternative pellet production represents one method for utilization of the aforementioned materials, not only in energy sector but also in agriculture. Their utilization is closely tied to the requirements for the pellet quality. Multiple scientists investigate the pellet quality in Slovakia, as well as abroad (Dumitrascu et al., 2018; Jiang et al., 2016; Lee et al., 2019; Spirchez et al., 2019; Zamorano et al., 2011), who evaluated the pellet quality on the basis of their composition, density, moisture content, durability, etc. Zafari and Kianmehr (2012) have dealt with the issue of effects of temperature, pressure and moisture on durability of cattle manure pellets.

Pellet mechanical properties assessment by compressive loading test began to receive increased attention in the last decade. Testing utilizes the experience achieved by other researchers, obtained from evaluation of other materials of biological origin (Kubík and Kažimírová, 2015; Oloso and Clarke, 1993; Vursavuş and Özgüven, 2004). Hardness (compression strength) is one of the significant properties of commercial pellets, which reflects the mechanical strength of single pellet during handling, transportation, and storage (Jiang et al., 2014). Compression strength is defined as the maximum compressive force that a pellet can withstand before breaking when exposed to a diametrical compressive force between two horizontal metal plates. In general, there are no limits for pellet hardness established

by standards. According to the literature, the hardness value of different biomass materials reached 25 kgf and the ideal value that ensures high-quality pellets was found to be 22 kgf (Carroll and Finnan, 2012; García-Maraver et al., 2015; Said et al., 2015). Assessment of such pellet values proved to play a significant role in terms of handling, storage and subsequent industrial and agricultural pellet exploitation.

Material and methods

The work aimed to conduct an analysis of the mechanical properties of pellets made of alternative materials based on pellet behaviour observation during compressive loading test by means of the Stentor Andilog 1000 device (Andilog Technologies, Vitrolles, France). Pellets were made of separated and dried swine manure (Fig. 1) from local pig farm. Pellets were produced by means of production line MGL 200 (Kovo Novak, Czech Republic) and their final form was achieved by employing the water as binding agent.

Fig. 1 Dried swine manure and swine manure pellet type 1

Swine manure pellet type 1 was produced from dried swine manure by adding 10% of water. Swine manure pellet type 2 was produced from dried swine manure by adding 20% of water.

Parameters and pellet density

Pellet density was measured in accordance with the STN EN ISO 18847 Solid biofuels – Determination of particle density of pellets and briquettes, which is aimed at evaluation of pellet density produced from wood as well as waste of agricultural production origins. It is necessary to let the pellets to stabilize. The diameter, length and weight of the pellet are continuously measured throughout the entire process. Only when the pellet weight changes by a maximum of 0.1% within 24 hours, it is possible to consider the pellets stabilized. In relation to determination of pellet density, the specimen diameter and length with an accuracy of ± 0.05 mm was determined according to the STN EN ISO 17829 Solid biofuels – Determination of length and diameter of pellets. Pellet weight was measured by means of laboratory scales Explorer Pro (Ohaus Corporation, USA) with an accuracy of ± 0.0001 mg. The final pellet weight was calculated on the basis of obtained data.

Pellet moisture content

In order to determine the pellet moisture content, gravimetric furnace Nabertherm L9/11/SW (Nabertherm GmbH, Germany) with digital scales Kern ew 420-3NM (with accuracy of ± 0.001 g) was used, since it allows heating of analysed samples up to $1,100$ °C while recording the weight of the samples.

Pellet moisture was determined in accordance with STN EN ISO 18134 Solid biofuels – Determination of moisture content. The sample is heated to 105 – 110 °C and is dried until the difference in sample mass between two consecutive measurements, conducted 30 minutes apart, is lower than 0.1% of the sample mass observed at the previous measuring.

Measurement of pellet mechanical properties

Pellet mechanical properties are assessed by means of a quasi-static compressive loading test. For the purposes of measurement, only undamaged pellet samples with modified contact surfaces – these must be straight – can be used. The pellet is placed on a solid plane in the axis of the testing device. Subsequently, the pellet is compressed between two planes, while the upper plane of testing device is of circular shape with 20 mm diameter; the lower plane is of rectangular shape. Movement speed of upper circular plane is set to $10 \text{ mm} \cdot \text{min}^{-1}$. The maximal loading force applied to sample is 500 N. The device records loading force values with accuracy of 0.05 N.

Measurement evaluation

The results of pellet compressive loading test include values of force F and movement of upper plane of measuring device ΔL_0 . In order to plot the compression diagram $F(\varepsilon)$, it is firstly necessary to calculate the pellet deformation according to the relation:

$$\varepsilon = \frac{\Delta L_0}{L_0} \quad (1)$$

where:

ε – deformation ($\text{mm} \cdot \text{mm}^{-1}$); L_0 – initial pellet length (mm); ΔL_0 – distance between the device planes (mm)

Furthermore, for the purposes of plotting the compression diagram, it is vital to determine the compressive stress on the basis of the following relation:

$$\sigma = \frac{F}{S} \quad (2)$$

where:

σ – compressive stress (MPa); F – force acting on the pellet (N); S – cross-sectional area of the pellet (mm^2)

The pellet elasticity modulus is determined using linear regression method, the result of which is as follows:

$$\sigma = E\varepsilon + m \quad (3)$$

where:

σ – compressive stress (MPa); E – elasticity modulus (MPa); ε – deformation ($\text{mm} \cdot \text{mm}^{-1}$); m – regression coefficient (MPa)

Subsequently, the force in the first maximum of the loading curve F_m and deformation in the first maximum are determined:

$$\varepsilon_m = \frac{v t_m}{L_0} \quad (4)$$

where:

ε_m – deformation at the first maximum of force ($\text{mm} \cdot \text{mm}^{-1}$); v – deformation rate ($\text{mm} \cdot \text{s}^{-1}$); t_m – time at the first maximum of force (s); L_0 – initial pellet length (mm)

Time t_m is determined on the basis of the first maximum of the loading curve $F(t)$. Deformation rate is calculated on the basis of values of movement course and rate of upper loading plane. Deformation ε_{mp} is subtracted from dependence $F(\varepsilon)$.

Compressive stress in the first maximum of loading curve is calculated as follows:

$$\sigma_m = \frac{4F_m}{\pi d^2} (1 - \varepsilon_m) \quad (5)$$

where:

σ_m – compressive stress in the first maximum (MPa); F_m – force at the first maximum (N); d – pellet diameter (mm); ε_m – deformation at the first maximum of force ($\text{mm} \cdot \text{mm}^{-1}$)

Compressive stress σ_{mp} is subtracted from dependence $\sigma(\varepsilon)$.

Initial pellet strength F_{10} is determined as force necessary for 10% compression strain. Value F_{10} is subtracted from dependence $F(\varepsilon)$.

Another evaluated pellet property is loading force in the inflection point F_{inf} , deformation in the inflection point ε_{inf} and compressive stress in the inflection point σ_{inf} . Inflection point lies between the beginning and the first maximum of the loading curve. Dependence gradient changes its increasing tendency to decreasing in the inflection point.

In order to obtain these properties, it is necessary to plot a cubic regression curve in compression diagram within the interval $(0, F_m)$. Following regression formula are the results:

$$F = a\varepsilon^3 + b\varepsilon^2 + c\varepsilon + d \quad (6a)$$

where:

F – compression force (N); ε – deformation ($\text{mm}\cdot\text{mm}^{-1}$); a – regression coefficient ($\text{N}\cdot(\text{mm}\cdot\text{mm}^{-1})^{-3}$); b – regression coefficient ($\text{N}\cdot(\text{mm}\cdot\text{mm}^{-1})^{-2}$); c – regression coefficient ($\text{N}\cdot(\text{mm}\cdot\text{mm}^{-1})^{-1}$); d – regression coefficient (N)

$$F = et^3 + ft^2 + gt + h \quad (6b)$$

where:

F – compression force (N); t – compression time (s); e – regression coefficient ($\text{N}\cdot\text{s}^{-3}$); f – regression coefficient ($\text{N}\cdot\text{s}^{-2}$); g – regression coefficient ($\text{N}\cdot\text{s}^{-1}$); h – regression coefficient (N)

Accuracy of the regression formula is expressed by determination coefficient R^2 .

Deformation in the inflection point of the compression diagram is calculated as follows:

$$\varepsilon_{inf} = \frac{vt_{inf}}{L_0} \quad (7)$$

where:

ε_{inf} – deformation in the inflection point ($\text{mm}\cdot\text{mm}^{-1}$); v – deformation rate ($\text{mm}\cdot\text{s}^{-1}$); t_{inf} – time in the inflection point (s); L_0 – original pellet length (mm)

Compressive stress in the inflection point can be calculated according to the following formula:

$$\sigma_{inf} = \frac{4F_{inf}}{\pi d^2} (1 - \varepsilon_{inf}) \quad (8)$$

where:

σ_{inf} – compressive stress in the inflection point (MPa); F_{inf} – force in the inflection point (N); d – pellet diameter (mm); ε_{inf} – deformation in the inflection point ($\text{mm}\cdot\text{mm}^{-1}$)

Time and force in the inflection point were subtracted from dependence $F(t)$.

Statistical indicators – arithmetic mean; standard deviation; variation coefficient – are utilized for the purposes of assessment of recorded and calculated values. In terms of pellet properties evaluation, correlation coefficient is also determined.

Results and discussion

Table 1 shows geometrical properties, density and moisture content of pellet types 1 and 2.

Table 1 Properties of pellet types 1 and 2

	Pellets	1	2
Diameter d (mm)	$\bar{x}$	6.21	5.82
	S	0.08	0.09
	s (%)	1.32	1.54
Length L_0 (mm)	$\bar{x}$	14.36	13.03
	S	1.51	1.02
	s (%)	10.52	7.8
Density ρ ($\text{kg}\cdot\text{m}^{-3}$)	$\bar{x}$	1,407.23	1,363.04
	S	9	10.88
	s (%)	0.64	0.8
Moisture W (%)	$\bar{x}$	8.46	8.46
	S	0.14	0.13
	s (%)	1.63	1.48

Mean density is $1,407.23 \text{ kg}\cdot\text{m}^{-3}$ for pellet type 1 and $1,363.04 \text{ kg}\cdot\text{m}^{-3}$ for pellet type 2. The standard deviation for density is low. Pampuro et al. (2013) reported that it is possible to increase the pellet density made of swine manure from an initial value of $<200 \text{ kg}\cdot\text{m}^{-3}$ to a final value $>1,000 \text{ kg}\cdot\text{m}^{-3}$ by compression of dry fraction. The density of the pellet type 2 is lower in contrast to pellet type 1, however, mean moisture contents of both types are identical – 8.46% – despite the fact that different amounts of water were used for their production. This does not influence the moisture content of stabilized pellets, what is also indicated by standard deviation, as well as low variation coefficient.

Fig. 2 illustrates the dependences $F(\varepsilon)$ and $F(t)$ obtained from compressive loading test of pellets made of swine manure 1. Behaviour of all pellets during compression process is very similar. Compression diagrams are largely almost linear. Pampuro et al. (2017) reported similar course of compressive loading test in their investigation of pellets made of swine manure.

Values of F_m ranged from 215.77 to 418.18 N. Deformation values are low, mere 10–15%, suggesting the low pellet compressibility. The time necessary for reaching the first maximum is relatively balanced and ranges from 8.6 to 12 s.

Fig. 3 illustrates the dependences $F(\varepsilon)$ and $F(t)$ obtained from compressive loading test of pellets made of swine manure 2. Similarly to pellet type 1, compression diagram of all pellets is largely linear. Furthermore, almost all curves show a steep gradient. Values of F_m ranges from 105.4 to 217.36 N; Zhai et al. (2018) – who investigated pellets made of hydrochar with molasses as a binder and subjected them to compressive loading test – observed similar values for F_m . The time, necessary for reaching the first maximum, ranges from 8.8 to 16.1 s.

Fig. 2 Compression diagrams of pellet type 1 – dependences $F(\varepsilon)$ and $F(t)$

Fig. 3 Compression diagrams of pellet type 2 – dependences $F(\varepsilon)$ and $F(t)$

Fig. 4 Linear parts of dependence $\sigma(\varepsilon)$

Course of compressive loading test indicates that majority of pellets of both types is fragile.

Pellet modulus of elasticity is determined from linear part of dependence $\sigma(\epsilon)$ (Fig. 4). Gradient of all curves obtained from testing of pellet type 1 is uniform. Values of modulus of elasticity of pellet type 1 ranges from 102.58 to 139.05 MPa. It is possible to divide the pellet type 2 into two groups on the basis of the gradient of curves. Values of modulus of elasticity of pellet type 2 ranges from 34.77 to 140.63 MPa.

Each determination coefficient R^2 shows value close to 1, indicating that their regressive curves showing the course of compressive loading test are almost identical with compression diagrams.

Table 2 shows the mechanical properties of the pellets made of swine manure (types 1 and 2). The results show that mechanical properties of these pellets are not the same. Values of F_m , σ_m , E , F_{10} , F_{inf} and σ_{inf} are higher in pellet type 1; ϵ_m shows higher values in pellet type 2 and values of ϵ_{inf} are the same for both pellet types. Values of F_m and F_{10} show the highest standard deviation.

The results indicate that addition of different amounts of water for the binding purposes in pellet production has an impact on the mechanical properties of the final products. Moreover, Jandačka et al. (2013) and Zhai et al. (2018) also confirmed that addition of liquid binder directly influences the final pellet mechanical properties.

Mean value of the elasticity modulus of pellet type 2 is 1.7 times lower in contrast to pellet type 1 that is made with addition of smaller amount of water. Furthermore, pellet type 1 showed mean strength of 10.47 MPa; pellet type 2 – produced with twice as much water as pellet type 1 – showed mean strength of 6.24 MPa. In addition to this, moisture content of final pellets after their stabilization was 8.46% for both types.

However, not only the final moisture content but also the amount of water or other liquid used during pellet production process for the binding purposes is of great significance, as confirmed by Huang et al. (2017). This means that the input material moisture influences the quality characteristics of the final products. Amount of added water is particularly important in cases when input resource contains water-soluble components, which subsequently form solid bridges that usually result in pellet strength enhancement after their drying. By adding more water than the optimal amount, the pellet material passes through the compression die holes more easily and compression level and density of pellets are lower. This fact is also confirmed by the results of assessment of mechanical properties of pellets made of swine manure.

Table 3 shows correlation coefficients of properties of pellet type 1 and Table 4 provides correlation coefficients for pellet type 2. Correlation coefficients with value exceeding 0.8 indicate significant linear dependence between properties and are highlighted in the tables. Mechanical pellet properties do not show significant dependence on geometric parameters.

Table 2 Mechanical properties of pellets

	Pellets	1	2
F_m (N)	$\bar{x}$	309.65	164.69
	S	70.54	34.32
	s (%)	22.78	20.84
ϵ_{mp} (mm·mm ⁻¹)	$\bar{x}$	0.12	0.15
	S	0.02	0.04
	s (%)	15.44	23.32
σ_{mp} (MPa)	$\bar{x}$	10.22	6.21
	S	2.27	1.36
	s (%)	22.24	21.92
ϵ_m (mm·mm ⁻¹)	$\bar{x}$	0.12	0.16
	S	0.02	0.03
	s (%)	15.24	21.31
σ_m (MPa)	$\bar{x}$	8.98	4.1
	S	1.91	0.88
	s (%)	21.24	21.45
E (MPa)	$\bar{x}$	122.39	71.12
	S	13.35	27.34
	s (%)	10.91	38.44
F_{10} (N)	$\bar{x}$	253.91	116.43
	S	57.76	37.82
	s (%)	22.75	32.48
F_{inf} (N)	$\bar{x}$	165.37	71.65
	S	34.48	27.34
	s (%)	20.85	38.16
ϵ_{inf} (mm·mm ⁻¹)	$\bar{x}$	0.07	0.07
	S	0.02	0.03
	s (%)	23.9	34.09
σ_{inf} (MPa)	$\bar{x}$	5.07	2.49
	S	1.01	0.95
	s (%)	19.9	38.15
σ_p (MPa)	$\bar{x}$	10.47	6.24
	S	2.19	1.38
	s (%)	20.93	22.15

Table 3 Correlation coefficients of properties of pellet type 1

	<i>d</i>	<i>L</i> ₀	<i>F</i> ₁₀	<i>F</i> _{<i>m</i>}	ε_{mp}	σ_{mp}	ε_m	σ_m	<i>E</i>	<i>F</i> _{inf}	ε_{inf}	σ_{inf}
<i>d</i>	1											
<i>L</i> ₀	0.01	1										
<i>F</i> ₁₀	0.27	-0.2	1									
<i>F</i> _{<i>m</i>}	0.33	-0.57	0.69	1								
ε_{mp}	0.06	-0.53	-0.32	0.46	1							
σ_{mp}	0.23	-0.6	0.69	0.99	0.46	1						
ε_m	0.09	-0.54	-0.32	0.44	0.99	0.44	1					
σ_m	0.23	-0.56	0.75	0.99	0.38	1	0.36	1				
<i>E</i>	0.27	0.06	0.83	0.48	-0.45	0.47	-0.49	0.53	1			
<i>F</i> _{inf}	0.34	-0.37	0.58	0.94	0.53	0.93	0.49	0.92	0.37	1		
ε_{inf}	0.03	-0.03	-0.56	0.1	0.83	0.09	0.81	0.02	-0.59	0.33	1	
σ_{inf}	0.23	-0.38	0.63	0.94	0.47	0.94	0.43	0.94	0.41	0.99	0.26	1

Table 4 Correlation coefficients of properties of pellet type 2

	<i>d</i>	<i>L</i> ₀	<i>F</i> ₁₀	<i>F</i> _{<i>m</i>}	ε_{mp}	σ_{mp}	ε_m	σ_m	<i>E</i>	<i>F</i> _{inf}	ε_{inf}	σ_{inf}
<i>d</i>	1											
<i>L</i> ₀	-0.25	1										
<i>F</i> ₁₀	-0.5	0.6	1									
<i>F</i> _{<i>m</i>}	-0.42	0.14	0.48	1								
ε_{mp}	0.24	-0.65	-0.74	0.18	1							
σ_{mp}	-0.53	0.17	0.53	0.99	0.12	1						
ε_m	0.05	-0.7	-0.63	0.27	0.96	0.24	1					
σ_m	-0.57	0.31	0.67	0.96	-0.08	0.98	0.04	1				
<i>E</i>	-0.51	0.48	0.89	0.48	-0.7	0.53	-0.59	0.68	1			
<i>F</i> _{inf}	0.03	0.35	0.23	0.53	-0.03	0.49	-0.15	0.53	0.43	1		
ε_{inf}	0.48	-0.15	-0.64	0.01	0.54	-0.07	0.36	-0.16	-0.41	0.57	1	
σ_{inf}	-0.07	0.4	0.33	0.55	-0.13	0.52	-0.24	0.58	0.52	0.99	0.47	1

Conclusion

The presented research was aimed at evaluation of the selected properties of alternative pellets made from dried swine manure, i.e. density, moisture, and mechanical properties.

The density values of the two observed pellet types are 1,407.23 kg·m⁻³ and 1,363.04 kg·m⁻³, respectively. It can be concluded that, from the density standpoint, the observed pellets are comparable to pellets commonly used for heat production by direct combustion.

Mean moisture value of both pellet types is 8.46%, satisfying the standards for solid biofuels.

Static compressive loading test was used for evaluation of the pellet mechanical properties. Results show that the observed pellets do not differ from each other significantly in this regard. Additionally, the observed values are comparable to those of pellets made from other types of biomass. In pellet type 1, which used 10% vol. water as a binder, compressive strength was higher than in type 2. The same is true for other

observed properties, with the exception of deformation properties, which were lower than in type 2.

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