SPRUCE PELLETS IN COMPRESSION LOADING SMREKINI PELETI PRI PRITISNOM OPTEREĆENJU

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ABSTRACT

Compression loading of sawdust pellets could be useful for studying the mechanical and structural properties of materials. Mechanical properties such as the failure stress and strain, the modulus of elasticity, the bulk modulus, the compressibility and the deformation energy can be used to evaluate the behaviour of pellets under static loading. The deformation energy as the apparent energy density was determined by integrating loading stress-strain curves between the initial point and the point of strength failure. A testing machine Andilog Stentor 1000 was employed for compression testing. The pellet samples were tested at a constant speed of 10 mm.min⁻¹. The true stresses and the Hencky's strain were determined in compression loading. The Cauchy's strain gives the relative deformation with regard to the initial sample height. The Hencky's strain derives from the integration of the infinitesimal strain. The true stress is evaluated using the instantaneous cross section of the sample. The loading curves of the dependence of the stress on the strain were realized, and the moduli of elasticity and the bulk moduli were determined from the compression diagrams respectively.

Keywords: spruce pellets, compression loading, modulus of elasticity, compressibility

REZIME

Pritisno opterećivanje peleta od piljevine može biti korisno za proučavanje mehaničkih i strukturnih osobina materijala. Mehanička svojstva kao što su zavisnost napon - deformacija, modul elastičnosti, zapreminski modul elastičnosti, kompresibilnost i energija deformacije mogu se koristiti za procenu ponašanja peleta pod statičkim opterećenjem.

Energija deformacije kao prividna gustina energije određena je integracijom krivih napon - deformacija između početne tačke i tačke prestanka otpora deformisanju (razaranje). Aparatura zatestiranje Andilog Stentor 1000 upotrebljena za testiranje pritiskom. Uzorci peleta su testirani konstantnom brzinom od 10 mm.min⁻¹. Stvarni naponi i Hencki-eva deformacija određeni su pri pritiskom opterećenju. Kaučijeva deformacija daje relativnu deformaciju u odnosu na početnu visinu uzorka. Henkijeva deformacija potiče od integracije infinitezimalnih deformacija. Stvarni napon se procenjuje pomoću trenutnog preseka uzorka. Utvrđene su krive opterećenja zavisnosti napon - deformacija, a moduli elastičnosti i zapreminski moduli elastičnosti određeni su sa dijagrama kompresije respektivno.

Keywords: peleti od smreke, pritisno opterećenje, modul elastičnosti, kompresibilnost

INTRODUCTION

Determining the geometric, compressive and heating parameters of fuel pellets forms a basis for the evaluation of their quality. In their study, Babić *et al.* (2013) focused on the stress-strain uniaxial compression test, which shows the response of biomaterials to an externally applied force that deforms the body of the material, causing changes in its dimension, shape or volume. This test provides important information about the elastic and plastic behaviour of materials. Babić *et al.* (2012) described the stress strain diagrams, which are graphical representations of the simultaneous force and head displacement values recorded during testing. The bioyield point force of certain biomaterials such as sunflower fruits was determined. Liu *et al.* (2014) described the mechanical strength of the pellet using an Instron Universal Tester (USA). The cylindrical pellet was horizontally placed between two anvils and compressive force was applied to the side of the pellet. The tester was run at a compression rate of 1 mm.min⁻¹ and stopped after the pellet was fractured or broken. The tensile strength was calculated. Mišljenović *et al.* (2016) studied the strength of pellets, which was evaluated using the three-point bending test. The three-point bending test was selected from a number of typically used diametric compression tests for its ability to precisely determine the length of pellets, and thus correctly interpret the results. A pellet was placed on a specially designed holder attached to a Lloyd LR 5K texture analyzer. The pellet was loaded at a speed of 1 mm.min⁻¹ until breakage and the force was recorded. Stasiak *et al.* (2017) determined the strength of

pellets using diametric compression between flat plates, and measured the heat of combustion and ash content in keeping with the international standards ISO 9831: 2005 and ISO 18122: 2016, respectively. The results obtained reveal that the mechanical and combustion parameters are proportion-dependent. Pellet strength decreased with the addition of ground straw. They observed a decrease in the pellet strength with an increase in the moisture content, whereas an increase in the pellet strength led to increased compaction pressure. Mišljenović *et al.* (2015) studied the strength of pellets, as well as sawdust compressibility, which was reduced when adding oil. The oil caused lower friction on the pellet – die wall contact area. Kažimírová *et al.* (2014) dealt with the quantification of moisture, combustible matter content, ash content and higher heating value of the selected types of biomass used for the heat production by direct combustion. The main contribution of this study is the acquisition of values usable in subsequent theoretical and practical efforts to increase the efficiency of the heat production by direct combustion of biomass. Božiková and Hlaváč (2013) examined the dependency of material resistance on the probe rotation, using a viscometer Anton Paar DV-3P for rheological measurements. The dependencies between the dynamic viscosity and temperature of two bio-oils (Plahyd N and Plahyd S) were determined, indicating an exponentially decreasing trend. Hlaváčová *et al.* (2018) confirmed that rheological data are important for product quality evaluation, engineering calculations and process design. The knowledge and understanding of material behaviour is crucially important for determining the size and energy requirements of the material.

Rheological models built upon experimental measurements can prove useful in material engineering with regard to energy and mass balances.

The purpose of this paper is to examine the behaviour of spruce sawdust cylindrical pellets in compression loading. The Hencky's strain (known as the true strain) and the true stress were used for describing the compression of the pellets. The following properties of spruce sawdust cylindrical pellets were determined and correlated: failure strength, failure strain, elastic modulus, bulk modulus, compressibility, Poisson's ratio, heating capacity and apparent energy density.

MATERIAL AND METHOD

The samples were made of quality spruce sawdust with the commercial signature BIOPEL EN plus A1, (BIOPEL, 2018). The pellets were of cylindrical shape with a diameter of 6 mm, a moisture content of 10 % and an ash content of up to 0.7 %. Twelve samples were used for the compressive measurement and nine samples were selected for processing. The pellet moisture content was measured using a moisture analyzer RADWAG MAC 210/WH (RADWAG Balances & Scales, Poland). The sample moisture content was measured as a change in the sample mass at a constant temperature of 105 °C during 28 min. The absolute moisture of the samples was 8.45 %. The heating capacity was measured using IKA calorimeter 5000 (IKA®-Werke GmbH & Co. KG, Staufen, Germany) on the 10 samples.

Static compressive loading in the uniaxial direction was used for the spruce sample testing. A testing machine Andilog Stentor 1000 (Andilog Technologies, Vitrolles, France) was employed for the compression tests conducted. The compression of spruce pellets samples between two parallel plates was carried out (Fig. 1).

Fig. 1 Compression test of the cylindrical spruce sawdust pellet sample using parallel plates – uniaxial loading

The experiments involved a total of nine samples of spruce pellets tested at a speed of 10 mm.min⁻¹. The force F (N) and the compression D (m) were measured using the acquisition software RSIC ver. 4.06. The material stress and strain were

calculated as the true stress and the Hencky's strain of the cylindrical pellet samples in compression loading (Nedomová et al., 2017). The loading curves of the dependence of the stress on the strain were made. The Cauchy's strain ε_c gives the relative deformation relative to the initial sample height l_0 :

$$\varepsilon_c = \frac{\Delta l}{l_0} \quad (1)$$

The Hencky's strain ε_H derives from the infinitesimal strain integration $-\frac{dl}{l}$:

$$\varepsilon_H = -\ln \left(\frac{l_0 - \Delta l}{l_0} \right) = -\ln(1 - \varepsilon_c) \quad (2)$$

The ultimate stress σ_u is given as the force F divided by the original cross section A_0 of the sample:

$$\sigma_u = \frac{F}{A_0} \quad (3)$$

The true stress σ_c is evaluated using the instantaneous cross section A of the sample (Casiraghi et al., 1985):

$$A = A_0 \frac{l_0}{l - \Delta l} \quad (4)$$

Then the true stress is expressed by the following equation:

$$\sigma_c = \frac{F}{A} = \frac{F}{A_0} \frac{l_0 - \Delta l}{l_0} = \sigma_u (1 - \varepsilon_c) \quad (5)$$

The method based on the elastic theory and the Hook's law was used to determine the moduli of elasticity. The values of the moduli of elasticity were calculated as the slope of the linear part of the stress-strain curves on the basis of the regression method. The maximal values of the strain and the stress were determined from the maximum values of the loading curves.

The bulk modulus k (Pa) and the compressibility β (Pa⁻¹) of the material are defined as the dependence of the stress σ on the rate volume change ΔV relative to the original volume V :

$$\sigma = k \frac{\Delta V}{V} = \frac{1}{\beta} \frac{\Delta V}{V} \quad (6)$$

The values of the bulk moduli were calculated as the slope of the linear parts of the stress – $\Delta V/V$ curves on the basis of the regression method.

The apparent energy density W at failure was defined as the total work of deformation in the sample volume (Nedomová et al., 2017):

$$W = \int_0^{\varepsilon_c} \sigma_u d\varepsilon \quad (7)$$

RESULTS AND DISCUSSION

The geometrical parameters and bulk density of the spruce sawdust pellet samples are showed in Table 1. The following average values of the samples were calculated: the pellet mass $m = (0.456 \pm 0.015)$ g, the pellet length $l = (14.913 \pm 0.372)$ mm, the pellet diameter $d = (6.342 \pm 0.038)$ mm, the pellet volume $V = (470.9 \pm 1.258)$ mm³ and the pellet bulk density $\rho = (969.548 \pm 19.876)$ kg.m⁻³. The average value of the pellet heating capacity (Table 2), obtained using an IKA 5000 calorimeter, was $c = (18.842 \pm 0.026)$ MJ.kg⁻¹. The dependences of the stress on the strain obtained for the nine samples at a loading speed of 10 mm.min⁻¹ are shown in Fig. 2.

Table 1. Parameters of the BIOPEL A1 spruce sawdust cylindrical pellet samples (m – mass of the sample, l – length of the sample, d – diameter of the sample, V – volume of the sample, ρ – bulk density of the sample, SD – standard deviation, VC – coefficient of variation)

Biopel A1					
n	m (g)	l (mm)	d (mm)	V (m ³)	ρ (kg·m ⁻³)
1	0.424	13.32	6.17	3.981E-07	1065.18
2	0.450	15.58	6.44	5.072 E-07	887.16
3	0.396	13.17	6.40	4.235 E-07	935.15
4	0.514	15.60	6.42	5.047 E-07	1018.35
5	0.511	16.56	6.33	5.209 E-07	981.03
6	0.418	13.67	6.50	4.534 E-07	921.96
7	0.462	15.44	6.37	4.918 E-07	939.39
8	0.415	15.16	6.13	4.472 E-07	928.02
9	0.527	16.03	6.25	4.915 E-07	1072.13
10	0.446	14.60	6.41	4.709 E-07	947.10
Mean	0.456	14.913	6.342	4.709 E-07	969.548
SD	0.015	0.372	0.038	1.258 E-08	19.876
VC (%)	3.213	2.492	0.605	2.672	2.050

Table 2. Heating capacity of the spruce sawdust pellet cylindrical samples (m – mass of the sample, SD – standard deviation, VC – variation coefficient)

Biopel A1		
Sample	m (g)	Heating capacity (MJ·kg ⁻¹)
1	0.394	18.910
2	0.403	18.869
3	0.405	18.843
4	0.404	18.629
5	0.400	18.837
6	0.398	18.902
7	0.406	18.859
8	0.402	18.876
9	0.399	18.895
10	0.395	18.798
Mean	0.401	18.842
SD	0.001	0.026
VC (%)	0.356	0.138

The stress-strain curves were characterized by the peaks which represent the firmness limits of the cylindrical spruce sawdust pellet samples. The parameters of the samples such as the values of strain and stress, failure strength, failure strain, moduli of elasticity, bulk moduli and compressibility coefficients are displayed in Table 3.

Fig. 2. Compression diagrams of the nine spruce sawdust cylindrical pellets at a loading speed of 10 mm·min⁻¹ between two parallel plates

Table 3. Compressive parameters of the spruce sawdust pellet cylindrical samples. SD – standard deviation, VC – variation coefficient

n	Failure strength (MPa)	Failure Strain (-)	Modulus of elasticity (MPa)	Bulk Modulus (MPa)	Compressibility (MPa ⁻¹)
2	1.40	0.09	24.09	25.37	0.04
3	1.33	0.08	20.27	21.10	0.05
4	1.46	0.14	16.07	17.54	0.06
5	1.63	0.10	25.38	27.01	0.04
6	1.39	0.10	23.23	22.47	0.04
7	0.81	0.07	16.21	17.19	0.06
8	1.12	0.18	23.47	25.42	0.04
9	1.76	0.15	17.82	19.43	0.05
10	1.22	0.09	35.66	38.10	0.03
Mean	1.347	0.111	22.465	23.735	0.045
SD	0.093	0.012	2.018	2.143	0.003
VC (%)	6.915	11.068	8.985	9.030	7.682

The following average values were recorded:

the pellet strength $\sigma_p = (1.347 \pm 0.093)$ MPa, the pellet failure strain $\epsilon_p = (0.111 \pm 0.012)$, the pellet modulus of elasticity $E = (22.485 \pm 2.138)$ MPa, the pellet bulk modulus $k = (23.735 \pm 2.143)$ MPa and the pellet compressibility $\beta = (0.045 \pm 0.003)$ MPa⁻¹. The final compression diagram (Fig. 3) of the spruce sawdust cylindrical pellets at a loading speed of 10 mm·min⁻¹ between two parallel plates was also made. The stress and strain values were calculated as the mean value obtained from the values of the nine samples numbered 2, 3, 4, 5, 6, 7, 8, 10 and 12 in Fig. 2. The value of the sample failure strength was 1.088 MPa at a failure strain of 0.096 (Fig. 3). The value of the sample failure strength as the mean value obtained from the curve peaks (2, 3, 4, 5, 6, 7, 8, 10 and 12) was 1.347 MPa at a failure strain of 0.111 (Table 3). The values of the failure strength and failure strain determined using two methods differ by 19.2 % and 14.4 % respectively. The determination of the moduli of elasticity from the slopes of the linear parts of the compression diagrams on the basis of the Hook's law equation is shown in Fig. 4. The values are presented in Table 3.

Compression diagrams of stress on the strain - BIOPEL pure - mean value from nine samples

Fig. 3. Final compression diagram of the spruce sawdust cylindrical pellets at a loading speed of 10 mm·min⁻¹ between two parallel plates. The stress and strain were calculated as the mean value obtained from the values of the nine samples numbered 2, 3, 4, 5, 6, 7, 8, 10 and 12 in Fig 2.

Determination of bulk moduli from the slopes of the linear parts of the stress – $\Delta V/V$ curves on the base of Eq. 6 by the

regression method is shown in the Fig. 5. The values are also introduced in the Table 3.

Fig. 4. Compression diagrams – determination of the moduli of elasticity from the slopes of the linear parts of the stress – strain curves

The values of the moduli of elasticity and the bulk moduli of the pellet samples were practically consistent. The following equation expresses the relation between the modulus of elasticity E and the bulk modulus k for isotropic solids (Sokolnikoff, 1983):

$$k = \frac{E}{3(1-2\nu)}, \quad (8)$$

where ν is the Poisson's ratio of the material. We can calculate the value of the Poisson's ratio from Eq. 8, as well as the values of the modulus of elasticity E and bulk modulus k from Table 3.

Determination of the bulk modulus BIOPELpure

Fig. 5. Determination of the bulk moduli from the slopes of the linear parts of the stress – $\Delta V/V$ curves (at a loading speed of $10 \text{ mm} \cdot \text{min}^{-1}$)

The Poisson's ratio value of the sawdust pellet was $\nu = (0.493 \pm 0.028)$. The Poisson's ratio was further underpinned by the standard deviation SD_ν , which was calculated as follows:

$$SD_\nu = \left| -\frac{1}{6k} \right| SD_E + \left| \frac{E}{6k^2} \right| SD_k, \quad (9)$$

where SD_E is the standard deviation of the modulus of elasticity, SD_k is the standard deviation of the bulk modulus, E is the modulus of elasticity, and k is the bulk modulus.

The mean apparent energy density W at the failure of the pellet samples was determined by Eq. 7 based on the dependence of the true stress on the Hencky's strain in Fig. 3. The regression equation used for the integration is shown in Fig. 6. The value of the mean apparent energy density was $W = (55.400 \pm 0.005) \text{ MJ} \cdot \text{m}^{-3}$.

A correlation between the parameter values obtained was established using the Pearson correlation coefficient. The parameter values obtained are presented in Table 4.

A positive correlation was found between the following parameter values: length and mass of the samples, length and volume and mass and volume of the samples. Furthermore, a positive correlation was also found between the modulus of elasticity and the bulk modulus. However, a significantly negative correlation was found between the compressibility, the modulus of elasticity and modulus of bulk density.

Fig. 6. Final compression diagram – determination of the regression equation of the spruce sawdust cylindrical pellets at a loading speed of $10 \text{ mm} \cdot \text{min}^{-1}$ between two parallel plates. The stress and strain were calculated as the mean value obtained from the values of the nine samples numbered 2, 3, 4, 5, 6, 7, 8, 10 and 12 in Fig. 2.

Table 4. The correlation between the parameter values obtained (m – mass of the sample, l – length of the sample, d – diameter of the sample, V – volume of the sample, ρ – bulk density of the sample, σ_p – failure stress, ε_p – failure strain, E – modulus of elasticity, k – bulk modulus, β – compressibility)

	m	l	d	V	ρ	σ_p	ε_p	E	k	β
m	1.									
l	0.812	1.								
d	0.198	0.024	1.							
V	0.818	0.904	0.447	1.						
ρ	0.316	-0.132	-0.422	-0.284	1.					
σ_p	0.148	0.252	-0.613	-0.035	0.286	1.				
ε_p	-0.125	0.116	-0.347	-0.054	-0.148	0.294	1.			
E	0.427	0.235	0.046	0.240	0.330	-0.015	-0.182	1.		
k	0.350	0.166	0.043	0.177	0.302	-0.012	-0.126	0.991	1.	
β	-0.496	-0.303	0.059	-0.259	-0.422	-0.087	0.066	-0.967	-0.963	1.

CONCLUSION

The geometric parameters and the pellet heating capacity of the spruce sawdust pellet samples were measured and calculated.

A uniaxial compression of the sawdust pellet samples was performed, and the dependencies of the true stress on the Hencky's strain were calculated.

The following average pellet values were obtained: the failure strength $\sigma_p = (1.347 \pm 0.093)$ MPa, the pellet failure strain $\varepsilon_p = (0.11 \pm 0.012)$, the pellet modulus of elasticity $E = (22.485 \pm 2.138)$ MPa, the pellet bulk modulus $k = (23.73 \pm 2.143)$ MPa, and the pellet compressibility $\beta = (0.045 \pm 0.003)$ MPa⁻¹. The calculated value of the Poisson's ratio of the sawdust pellet was $\nu = (0.493 \pm 0.028)$. The mean apparent energy density at the failure of the pellet samples was $W = (55.400 \pm 0.005)$ MJ.m⁻³. The average value of the pellet heating capacity was $c = (18.842 \pm 0.026)$ MJ.kg⁻¹.

Similar findings on biomass pellets were reported in Kažimírová et al. (2017).

A positive correlation was found between the following parameter values: length and mass of the samples, length and volume and mass and volume of the samples. Moreover, a positive correlation was also found between the modulus of elasticity and the bulk modulus.

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