MECHANICAL PROPERTIES OF BIOMASS PELLETS

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Abstract

The paper dealt with the determination of mechanical properties of the cylinder pellet samples. Wheat straw, rapeseed straw and 50/50% mixed wheat and rapeseed straw were used for study of compress loading. The pellets were made by the granulating machine MGL 200 (Kovonovak). The compressive loading curves of dependencies of stress on strain were realised by the equipment Andilog Stentor 1000 (Andilog Technologies, Vitrolles, France). Initial force, initial stress, strain in maximum of loading curve, stress in maximum of loading curve and modulus of elasticity were determined. Significant correlations of the mechanical parameters pellet samples were observed among initial force and initial stress and modulus of elasticity. Significant correlations of force in maximum with stress and strain in the maximum were observed.

Key words: biomass pellets, compression, mechanical parameters.

INTRODUCTION

Straw has a different chemical composition depending on the species of plant, location and growing technology, so straw should be properly processed in order to improve its energy efficiency. Hence, efforts are being made to compact these plant resources by briquetting or pelleting, which leads to a higher concentration of mass and energy per unit of volume and the distribution and utilization of this type of biofuel is significantly facilitated (NIEDZIOŁKA ET AL., 2015). Mechanical properties of wheat straw, barley straw, corn stover and switchgrass at different compressive forces, particle sizes, and moisture contents are very interesting to determination of mechanical quality of pellets. Barley straw had the highest asymptotic modulus among all biomasses (SUDHAGARET ET AL., 2006). BOŽIKOVÁ ET AL. (2015) studied physical parameters as density, heat of combustion, calorific value and basic thermophysical parameters (thermal conductivity, thermal diffusivity and volume specific heat) of rape straw pellets, straw pellets, softwood pellets and hardwood pellets. The highest volume specific heat 0.6562×107 J.m^{-3}.K^{-1} had straw pellets and then rape straw pellets 0.5122×107 J.m^{-3}.K^{-1}. The second series of measurement was focused on combustion heat and calorific value determination. Obtained values of combustion heat were from range 14.3 – 20.2 MJ.kg^{-1} and calorific values were from range 12.2 – 19.0 MJ.kg^{-1}. MIŠLJENOVIĆ ET AL. (2016) interested in the determination of the strength of pellets through a three-point bending test. The three-point bending test was selected in lieu of the typically used diametric compression test because of the inability to precisely determine the length of pellets. The three-point bending test was used to asses pellet strength. A pellet was placed on a specially designed holder attached to the Lloyd LR 5K texture analyzer. The pellet was loaded at a speed of 1 mm.min^{-1} until breakage, and the force was recorded. SHAW ET AL. (2009) reported higher mechanical resistance when using smaller particle sizes to produce wheat straw and poplar wood pellets. By contrast, SERRANO ET AL. (2011) found no significant differences in the mechanical durability of barley straw pellets when milling the raw materials at 4 and 7 mm. BERTHET ET AL. (2015) evaluated nominal stress at break, nominal strain at break and Young's modulus from stress strain curves of the wheat straw fibres. The energy for the rupture was calculated from the total area under the curve of the force as a function of the elongation. Initial grip distance and cross-head speed were 45 mm and 10 mm.min^{-1}. MANI ET AL. (2006) studied mechanical properties of wheat straw, barley straw, corn stover and switchgrass at different compressive forces, particle sizes and moisture contents. Ground biomass samples were compressed with five levels of compressive forces (1000, 2000, 3000, 4000 and 4400 N) and three levels of particle sizes (3.2, 1.6 and 0.8 mm) at two levels of moisture contents (12% and 15% (wet basis)) to establish compression and relaxation data. Compressive force, particle size and moisture content significantly affected the pellet density of barley straw, corn stover and switchgrass. However, different particle sizes of wheat straw did not produce any significant difference on pellet density. NEDOMOVÁ ET AL. (2013) investigated the effect of the compression orientation on the mechanical properties of Ostrich eggs. The mechanical properties examined were rupture force, specific deformation, rupture energy and firmness. STRNKOVÁ ET AL. (2016) have been studied the mechanical behaviour of eggshell membranes under tensile loading. Samples were cut out of the membrane in latitudinal direction. TIRA test 27025 tensile testing machine equipped with a 200 N load-cell was used. Tensile deformation exhibits both non-linear as well as linear region. The experiments were performed at five loading velocities 1, 10, 100, 400 and 800 mm.min^{-1}. The main parameters describing the eggshell strength increase with the loading rate. VALACH ET AL. (2015) interested in the pressure and measurements of the biomass. The viscosity of the material increases at the pressure 7 MPa by 20 – 25% and at pressure 40 MPa increases by 120 – 160%. In gears and bearing with high pressures, it is necessary to consider the increase of viscosity. HLAVÁČOVÁ (2005) studied electrical properties of the granular materials. She found out that the conductivity increases and the resistivity decreases with temperature exponentially for all samples at all moisture contents. The permittivity of all samples increases with temperature linearly in frequency range from 2 to 50 MHz. The electrical properties dependence on temperature of treated material is necessary in the case of its thermal treatment.

The objective of this study was the investigation of the effects of the compression load on the pellets and determination of the mechanical parameters at the loading.

MATERIALS AND METHODS

The pellets were made from wheat straw (*Triticumaestivum*), rapeseed straw (*Brassicanapus*) and mixed straw, 50% wheat straw and 50% rapeseed straw, by the granulating machine MGL 200 (Kovonovak). Granulator is equipment in which the transformation of the crushed biomass on the pellets is realized. Basic components of the granulator are scrolls (driving drums) extruding biomass trough matrix and the matrix (metal plate with the holes of the specific size the biomass is extruded through. In the production of the wheat, rapeseed straw and 50/50% mixed straw pellets no binding agent was used except for water. The moisture of the wheat pellets was 13.6%, the moisture of the rapeseed straw pellets was 16% and the moisture of 50/50% mixed straw pellets was 13.5%. The bulk density of the wheat pellets was 335.880 kg.m^{-3}, the bulk density of rapeseed pellets was 531.556 kg.m^{-3} and 50/50% mixed straw was 431.990 kg.m^{-3}. Heat of combustion value of the wheat straw pellets was 17.013 MJ.kg^{-1}, heat of combustion of the rapeseed straw pellets was 16.241 MJ.kg^{-1} and heat of combustion of the 50/50% mixed straw pellets was 16.511 MJ.kg^{-1} (ADAMOVSKÝ AND OPÁTH, 2013).

The pellets were submitted to the compressive loading. The strength of the pellets was evaluated via the quasi static compression test, which was used to study the compaction behavior of tomatoes by BLAHOVEC ET AL. (1988). The result of the single test were the loading curves, which represent dependence between compressive stressesσ(MPa) and compressive strains ε (mm.mm^{-1}) of the pellets. The initial firmness of the pellets was determined as the initial force F_{10} (N) at the 10 % of the compressive strain on the loading curve and as the initial stress σ_{10} (MPa) at the 10% of the compressive strain. The next parameters of the firmness were force F_p (N), the stress σ_p (MPa) and compressive strain ε_p (mm.mm^{-1}) in the maximum of the loading curve. The last important parameter was Young's modulus of elasticity E (MPa). Young's modulus of elasticity E (MPa) was evaluated as the slope of the linear part of dependences of stress σ (MPa) on the strain ε (mm.mm^{-1}). The regression equations were determined as:

$$\sigma = E\,\varepsilon + b \tag{1}$$

where:

σ – compressive stress (MPa)

ε – compressive strain (mm.mm^{-1})

E – regression coefficient –Young's modulus of elasticity (MPa)

b – regression coefficient (MPa)

The cylindrical pellets were compressed between a lower steel plate and an upper steel circular plate in the longitudinal direction. The upper plate, attached to the Andilog Stentor 1000 test stand (Andilog Technologies, Vitrolles, France), compressed the cylinder of sample at a speed of 10 mm.min^{-1} until failure was observed.

RESULTS AND DISCUSSION

Eight regular samples were selected for wheat straw pellets, nine regular samples for rapeseed pellets and eight samples for mixed straw pellets. The loading curves were created in the software Microsoft Excel 2010. Results of mechanical parameters are presented in the Tab. 1, 2, and 3. Selected compression curves of the cylinder pellet samples (sample WS4, RS1, and WS50RS50_10 according to Tab. 1, 2, and 3) as dependence of stress σ (MPa) on strain ε ($mm.mm^{-1}$) are presented in Fig. 1. Loading curves showed similar shape with the characteristic maximum.The loading curves of different pellets had similar development and the line shapes. Determination of the Young's modulus of elasticity is presented in the Fig. 2 for the selected materials. Dependencies were fitted by the linear regression equations (1). The slopes of the equations represent the moduli of elasticity. Mean value of the initial force (force at 10% of compress strain) was maximal for mixed straw pellet samples (52.49 N, according to Tab. 3). Mean values of the initial force of the wheat straw samples and the rapeseed straw samples were smaller and almost identical (43.58 N and 43.12 N, according to Tab. 1 and 2). The variation of the mean value of the initial force was from 12 to 16 %.

Fig. 1. – Compression curves of the selected cylinder pellet samples as a dependence of stress (MPa) on strain ($mm.mm^{-1}$). 50% WS and 50% RS means 50% wheat straw and 50% rapeseed straw, 100% WS means 100% wheat straw and 100% RS means 100% rapeseed straw, (sample WS4, RS1, and WS50RS50_10 according to Tab. 1, 2, and 3).

Mean values of the initial stress of loading curve, of the wheat straw samples reached 1.46 MPa, according to Tab. 1, the rapeseed straw samples reached value 1.40 MPa, according to Tab. 2 and the mixed straw samples reached value 1.63 MPa according to Tab. 3. The variation of the mean value of the force in maximum of loading curve was from 13 to 17 %.

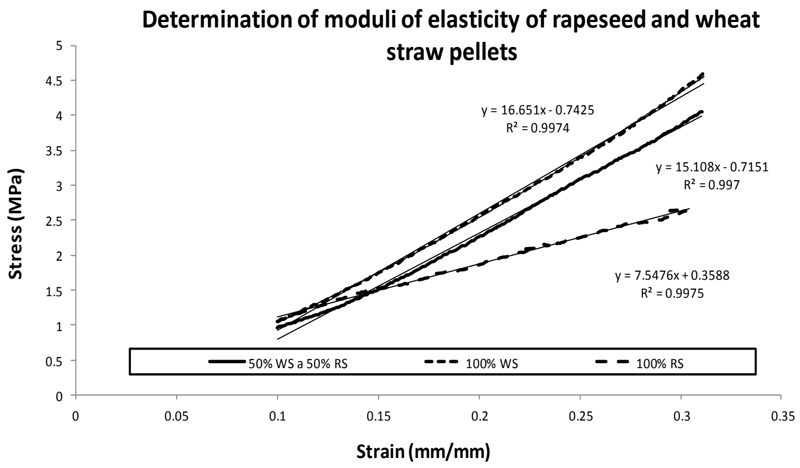

Fig. 2. – Determination of moduli of elasticity of wheat, rapeseed and mixed straw pellets. 50% WS and 50% RS means 50% wheat straw and 50% rapeseed straw, 100% WS means 100% wheat straw and 100% RS means 100% rapeseed straw, (sample WS9, RS7, and WS50RS50_10 according to Tab. 1, 2, and 3). The slopes of equation represent the moduli of elasticity.

Tab. 1. – Tab. of wheat straw pellet samples initial length (l), diameter of sample (d), initial force (F_{10}), force in maximum (F_m), strain in maximum (ε_m), initial stress (σ_{10}), stress in maximum (σ_m) and modulus of elasticity (E)

Wheatstraw 100 %				Moisture	13.6%			
				Compression	August,11th 2011			
				Measurement	March,16th 2015			
Sample	**l (mm)**	**d (mm)**	**F_{10} (N)**	**F_m(N)**	**ε_m (%)**	**σ_{10} (MPa)**	**σ_m (MPa)**	**E (MPa)**
WS3	12.20	6.10	49.74	110.14	32.62	1.70	3.77	18.70
WS4	12.35	6.10	30.61	238.77	45.58	1.05	8.17	20.57
WS5	11.80	6.10	82.49	186.29	24.48	2.82	6.38	24.97
WS7	10.80	6.30	18.36	167.44	53.51	0.59	5.35	12.64
WS8	12.05	6.20	32.70	231.21	55.26	1.08	7.66	14.62
WS9	12.05	6.20	28.88	186.20	34.18	0.96	6.17	16.65
WS10	11.95	6.20	62.27	156.92	25.85	2.06	5.20	20.09
WS13	10.20	6.30	43.64	147.90	30.97	1.40	4.75	17.13
Mean	11.68	6.19	43.58	178.11	37.81	1.46	5.93	18.27
Standard deviation	0.27	0.03	7.37	15.08	4.27	0.25	0.52	1.34
Coefficientofvariation	2.30	0.48	16.90	8.46	11.28	17.41	8.79	7.34

Mean value of the force in maximum of loading curve was also maximal for mixed straw pellet samples (213.26 N, according to Tab. 3). Mean values of the force in maximum of loading curve of the wheat straw samples reached 178.11 N, according to Tab. 1. The rapeseed straw samples reached value 95.95 N according to Tab. 2 and the mixed straw samples reached value 213.26 N according to Tab. 3. The variation of the mean value of the force in maximum of loading curve was from 8 to 19 %. Mean values of the strain in maximum of loading curve, of the wheat straw samples reached 37.81 %, according to Tab. 1, the rapeseed straw samples reached value 26.81%, according to Tab. 2 and the mixed straw samples reached value 47.01% according to Tab. 3. The variation of the mean value of the force in maximum of loading curve was from 4 to 11%.

Tab. 2. – Tab. of rapeseed straw pellet samples initial length (l), diameter of sample (d), initial force (F_{10}), force in maximum (F_m), strain in maximum (ε_m), initial stress (σ_{10}), stress in maximum (σ_m) and modulus of elasticity (E)

Rapeseedstraw 100 %			Moisture	16%				
			Compression	August,11th 2011				
			Measurement	March,16th 2015				
Sample	**l (mm)**	**d (mm)**	**F_{10} (N)**	**F_m(N)**	**ε_m (%)**	**σ_{10} (MPa)**	**σ_m (MPa)**	**E (MPa)**
RS1	11.20	6.30	32.70	180.10	58.12	1.05	5.78	8.51
RS2	13.70	6.10	57.12	108.36	13.80	1.96	3.71	19.98
RS4	12.40	6.60	48.56	91.28	20.08	1.42	2.67	13.40
RS5	13.60	6.50	36.85	60.72	20.58	1.11	1.83	8.82
RS7	11.50	6.45	22.82	54.07	24.60	0.70	1.66	7.54
RS10	13.95	6.10	16.99	49.10	21.29	0.58	1.70	10.32
RS11	10.40	6.10	58.76	90.69	22.68	2.01	3.10	15.42
RS12	12.60	6.20	57.07	115.28	32.84	1.89	3.82	14.47
RS13	14.30	6.20	57.21	113.97	27.26	1.90	3.75	19.59
Mean	12.63	6.28	43.12	95.95	26.81	1.40	3.11	13.08
Standard deviation	0.46	0.06	5.41	13.53	4.29	0.19	0.45	1.58
Coefficientofvariation	3.61	1.01	12.54	14.10	15.99	13.39	14.33	12.05

Mean values of the stress in maximum of loading curve, of the wheat straw samples reached 5.93 MPa according to Tab. 1, the rapeseed straw samples reached value 3.11 MPa according to Tab. 2 and the mixed straw samples reached value 7.10 MPa according to Tab. 3. The variation of the mean value of the force in maximum of loading curve was from 9 to 16%.

Mean values of the modulus of elasticity, of the wheat straw samples reached 18.27 MPa according to Tab. 1, the rapeseed straw samples reached value 13.08 MPa according to Tab. 2 and the mixed straw samples reached value 14.97 MPa according to Tab. 3. The variation of the mean value of the force in maximum of loading curve was from 7 to 9%.The maximal firmness at compression in the initial state and in the maximal compress loading showed the mixed straw pellet samples. The quantities determined in the compression test of the pellets were correlated. These are confirmed mathematically by the matrix of the correlation coefficients in Tab. 4. The initial force of the wheat straw pellet samples significantly influenced on the initial stress and modulus of elasticity of the wheat straw pellet samples and significantly negative proportionally influenced on the strain in maximum.

Tab. 3. – Tab. of mixed straw pellet samples initial length (l), diameter of sample (d), initial force (F_{10}), force in maximum (F_m), strain in maximum (ε_m), initial stress (σ_{10}), stress in maximum (σ_m) and modulus of elasticity (E)

Wheatstraw 50 %			Moisture	13.5%				
Rapeseedstraw 50 %			Compression	August,11th 2011				
			Measurement	March,16th 2015				
Sample	**l (mm)**	**d (mm)**	**F_{10} (N)**	**F_m(N)**	**ε_m (%)**	**σ_{10} (MPa)**	**σ_m (MPa)**	**E (MPa)**
WS50RS50_01	11.20	6.30	29.88	283.18	59.28	0.96	8.79	17.88
WS50RS50_02	13.70	6.10	49.97	117.52	49.70	1.71	8.15	12.06
WS50RS50_04	12.40	6.60	80.03	179.00	37.00	2.34	5.12	11.85
WS50RS50_05	13.60	6.50	58.03	238.04	52.49	1.75	7.21	19.81
WS50RS50_07	11.50	6.45	56.66	98.02	24.95	1.74	3.00	12.43
WS50RS50_09	11.50	6.45	91.37	421.33	46.43	2.80	12.90	19.93
WS50RS50_10	11.50	6.45	26.69	246.01	56.43	0.82	7.53	15.10
WS50RS50_11	10.40	6.20	27.28	123.03	49.80	0.90	4.08	10.85
Mean	11.98	6.38	52.49	213.26	47.01	1.63	7.10	14.97
Standard deviation	0.41	0.06	8.59	38.18	3.94	0.25	1.10	1.32
Coefficientofvariation	3.45	0.92	16.37	17.90	8.39	15.45	15.49	8.84

Force in maximum of the wheat straw pellet samples significantly influenced on the strain in maximum and stress in maximum of wheat straw samples and correlates proportionally with the initial stress of mixed straw samples and non-proportionally with strain in maximum, force in maximum and stress in maximum of rapeseed straw samples and strain in maximum of mixed straw pellets. Strain in maximum of wheat straw pellet samples correlated non-proportionally with initial stress and modulus of elasticity of wheat straw pellet samples. Initial stress of wheat straw pellets samples correlated with modulus of elasticity of wheat straw pellet samples. Stress in maximum of wheat pellet samples correlated proportionally with initial stress of mixes straw samples and correlated non-proportionally with force in maximum, strain in maximum and stress in maximum of rapeseed straw pellet samples and with the strain in maximum of mixed straw pellet samples. Modulus of elasticity of wheat pellet samples correlated proportionally with the modulus of elasticity of the rapeseed pellet samples. Initial force of rapeseed pellet samples correlated significantly proportionally with the initial stress and modulus elasticity of the rapeseed samples and correlated non-proportionally with the initial force, force in maximum, initial stress and modulus of elasticity of mixed pellet samples. Force in maximum of rapeseed pellet samples correlated proportionally significantly with strain in maximum and stress in maximum of rapeseed samples and correlated with strain in maximum of mixed straw samples. Force in maximum of rapeseed pellet samples correlates non-proportionally with initial force and initial stress of the mixed straw samples. Strain in maximum of rapeseed pellet samples correlated proportionally with stress in maximum of the rapeseed pellet samples and correlated non-proportionally with the initial force and initial stress of mixed straw pellet samples. Initial stress of rapeseed pellet samples correlated with the modulus of elasticity of the rapeseed pellet samples and correlated non-proportionally with initial force, initial stress and modulus of elasticity of mixed straw pellet samples.

Tab. 4. – Tab. of correlation coefficients of initial force (F_{10}), force in maximum (F_m), strain in maximum (ε_m), initial stress (σ_{10}), stress in maximum (σ_m) and modulus of elasticity (E)for wheat, rapeseed and mixed pellets samples

	Wheatstraw						**Rapeseedstraw**						**Mixedstraw**					
	F_{10}	F_m	ε_m	σ_{10}	σ_m	E	F_{10}	F_m	ε_m	σ_{10}	σ_m	E	F_{10}	F_m	ε_m	σ_{10}	σ_m	E
Wheatstraw																		
F_{10}	1																	
F_m		1																
ε_m	-0.80	0.53	1															
σ_{10}	1.00		-0.79	1														
σ_m		0.99			1													
E	0.83		-0.74	0.85		1												
Rapeseed-straw																		
F_{10}							1											
F_m		-0.60			-0.54			1										
ε_m		-0.77			-0.74			0.77	1									
σ_{10}							0.99			1								
σ_m		-0.58			-0.52			0.99	0.74		1							
E						0.58	0.83			0.86		1						
Mixedstraw																		
F_{10}							-0.55	-0.63	-0.50	-0.59			1					
F_m							-0.50							1				
ε_m		-0.68			-0.67			0.56			0.61		-0.50		1			
σ_{10}		0.51			0.52		-0.54	-0.62	-0.52	-0.57	-0.65		0.99			1		
σ_m														0.87	0.52		1	
E							-0.59			-0.57		-0.53		0.85			0.74	1

Stress in maximum of rapeseed pellet samples correlated proportionally with the strain in maximum of the mixed pellet samples and correlated non-proportionally with the initial stress of the mixed straw pellet samples. Modulus of elasticity of rapeseed pellet samples correlated non-proportionally with modulus of elasticity of the mixed straw pellet samples. Initial force of the mixed straw pellet samples correlated proportionally significantly with the initial stress of the mixed straw pellet samples and correlated non-proportionally with strain in maximum of the mixed straw pellet samples. Force in maximum of the mixed straw pellet samples correlated proportionally significantly with the stress in maximum and modulus of elasticity of the mixed straw pellet samples. Strain in maximum of the mixed straw pellet samples correlated proportionally with stress in maximum of the mixed straw pellet samples. Stress in maximum correlated proportionally with modulus of elasticity of the mixed straw pellet samples. According to Tab. 4, the initial firmnessof the wheat straw pellets samples depends mainly on the coordinates: strain in maximum, initial stress and modulus of elasticity. The maximal firmness of the wheat straw pellets samples depends mainly on the stress in maximum and strain in maximum. The initial firmness of the rapeseed straw samples depends mainly on the initial stress and modulus of elasticity. The maximal firmness of the rapeseed straw samples depends mainly on the force in maximum, strain in maximum and stress in maximum. The initial firmness of the mixed straw samples depends mainly on the initial stress. The maximal firmness of the mixed straw samples depends mainly on the stress in maximum and modulus of elasticity.

LIU ET AL. (2014) present the values of the tensile strength of the pellets in the range from 1.51 MPa to 7.10 MPa. MANI ET AL. (2006) present the values of modulus of elasticity of the pellets in the range from

0.92 MPa to 1.33 MPa. KALIYAN AND MOREY (2009) introduce the minimum pellet hardness for 6.0 – 8.0 mm diameter pellets of 63.7 N and for 4.0 – 5.0 mm diameter pellets of 39.2 N. CARONE ET AL, (2011) present the dependence of compression strength of the biomass pellets on the density of pellets, when the diameter of pellets ranged between 6.03 and 6.31 mm, from 2 MPa to 16 MPa. Dependence of the modulus elasticity of the biomass pellets on the density ranged from 0.1 GPa to 6 GPa. Strong correlation between density and modulus of elasticity and between compression strength and modulus of elasticity was found. STELTE ET AL. (2011) studied straw pellets 16 mm in length and between 7.9 and 8.2 mm in diameter which were manufactured in a single pellet press. The average calculated force at break of straw pellets was 240 ± 60 N.

CONCLUSIONS

The initial firmness of the wheat straw pellets samples depends mainly on the coordinates: strain in maximum, initial stress and modulus of elasticity. The maximal firmness of the wheat straw pellets samples depends mainly on the stress in maximum and strain in maximum. The initial firmness of the rapeseed straw samples depends mainly on the initial stress and modulus of elasticity. The maximal firmness of the rapeseed straw samples depends mainly on the force in maximum, strain in maximum and stress in maximum. The initial firmness of the mixed straw samples depends mainly on the initial stress. The maximal firmness of the mixed straw samples depends mainly on the stress in maximum and modulus of elasticity. Significant correlations of the mechanical parameters pellet samples were observed among initial force and initial stress and modulus of elasticity. Significant correlations of force in maximum with stress and strain in the maximum were observed. The maximal firmness at compression in the initial state and in the maximal compress loading showed the mixed straw pellet samples.

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