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Pellets and briquettes from fruit trees wood

ALEKSANDER LISOWSKI[1], MARCIN GRELA[1], MICHAŁ SYPUŁA[1], ADAM ŚWIĘTOCHOWSKI[1], MAGDALENA DĄBROWSKA-SALWIN[1], WOJCIECH STĘPIEŃ[2], RAFAŁ KORUPCZYŃSKI[3]
[1]Department of Agricultural and Forest Machinery
[2]Department of Soil Environment Sciences
[3]Department of Fundamental Engineering
Warsaw University of Life Sciences – SGGW

Abstract: *Pellets and briquettes from fruit trees wood*. The objective of the study was to determine the physical characteristics of biomass from apple tree branches of Idared, Gloster and Cortland varieties and pellets and briquettes made of it. Crushed biomass was used to prepare briquettes and pellets on a knife shredder with a sieve of mesh size of 25 × 8 or 23 × 4 mm. For biomass, the moisture content and particle size characteristics were determined; for pellets and briquettes, density and bulk density referring to dry mass and combustion heat, calorific value and technical durability, as well as strength parameters: modulus of elasticity, maximum stress, as well as shear, compression force and bending force measured by a two-point test of the agglomerate. Research was conducted in accordance with the appropriate standards. The results of assessment of physical characteristics of pellets were higher than those of the briquettes and lower than required by the standards under concern. The values of strength parameters were strictly connected with agglomerate durability.

Key words: wood, fruit trees, particle size, pellet, briquette, physical properties

INTRODUCTION

Durability and density of pellets or briquettes produced depends on many variables of the densification process, such as: densification pressure, pressure increase rate, lateral pressure, coefficient of friction of material against the die walls, quotient of product height to diameter, die and punch geometry, temperature of the process, use of binding agents, preliminary heating of biomass [Skonecki 2004, Kaliyan and Morey 2009, Tumuluru et al. 2010].

In general, it is assumed that the size of biomass particles is inversely proportional to pellet or briquette density. This is due to the fact that during densification, particles of smaller sizes have a greater contact surface and are easier to pack [Kaliyan et al. 2009, Taulbee et al. 2009, Tumuluru et al. 2010].

MacBain and Payne [Tumuluru et al. 2010] have found that small- and medium-sized particles are desirable in the granulation process as they have a greater surface area and are more susceptible to the impact of steam during the conditioning process, which results in better starch gelatinization. They also observed that smaller particles increased the efficiency of the process and reduction of granulation costs. They noted that very small particles could interfere with the granulation process due to clogging of granulator dies.

Mani et al. [2006] state also that dimensions of particles exert impact on mechanical properties of pellet made of wheat, barley and corn straw.

Densification of crushed materials of high bulk density increases performance and allows for achieving of higher density of the product. This is associated with lesser quantity of air forced out. High bulk density is associated with dimension and distribution of particles [Chlebowski 2012, Lisowski et al. 2012, Nowakowski and Ślesiński 2012]. On the other hand, agglomeration of particles takes place when lower pressure is exerted. Along with increase in bulk density of materials undergoing densification, demand for energy decreases [Obidziński 2005].

Our research, conducted so far [Świętochowski 2013], shows that pellet density, referred to dry substance mass, made of energy crops material (*Rosa multiflora*, *Sida hermaphrodita*, Jerusalem artichoke, *Miscant hus ×giganteus*, *Spartina pectinata*, *Fallopia sachalinensis*, basket willow) was greater by 45% than density of briquettes, amounting to 734 and 1,063 kg·m^{-3}, respectively, which indicates the potentially better packing of the smaller particles. The greater the pellet or briquette density, the higher mechanical durability and strength characteristics of energy crop products.

In the available literature, there are no results of research dedicated to wood biomass from wood of fruit trees with crowns, which are thinned out every year. Biomass of this type is treated as useful waste, which could be used for energy production purposes.

The objective of research was to develop physical characteristics of biomass from apple tree wood and pellets and briquettes made of it.

MATERIAL AND METHODS

Research was conducted using biomass from apple tree branches of Idared, Gloster and Cortland varieties, obtained during the annual thinning out of tree crowns. The branches of these trees of moisture content of 10.84 ±0.56% were crushed using a knife crusher, equipped with a sieve with mesh of dimensions of 25 × 8 mm. The mix of crushed chips in equal mass ratios were designated for production of briquettes using a hydraulic briquetting press made by Alchemik, model APT 40 with nominal diameter of 50 mm and maximum piston pressure of 90 MPa.

One half of the chips obtained were crushed again using the knife crusher equipped with a sieve of mesh dimensions of 23 × 4 mm. This part of the crushed material has been designated for production of pellets using pellet maker PD-1 made by Testmer, equipped with a ring die of nominal hole diameter of 6 mm.

In both cases, the biomass moisture content was 9.1 ±0.2% and it was designated for three samples using the dry oven test in accordance with standard S358.2 ASABE [ASABE Standards 2011c].

$$w = 100 \frac{m_w - m_s}{m_w} \quad (1)$$

where:
w – moisture content [%] (w.b.);
m_w – initial weight of sample [g];
m_s – dry matter content of sample [g].

Using a sieve separator (a sieve set from the bottom: dimensions of the bottom and sieve mesh in order: 1.65, 5.61, 8.98, 18 and 26.9 mm) with oscillating movement in the horizontal plane, crushed biomass was separated according to the standard ANSI/ASAE S424.1 [ASABE Standards 2011a]. Each type of material (from the first and the second crushing) was sieved five times. The volume of a single biomass sample subjected to separation in the separator was 10 dm^3. The sieving time was 120 s and it was controlled using a stopper. Individual particle fractions were weighed using electronic scales RADWAG WPS 600/C with the accuracy of 0.01 g. In the case when mass on the upper sieve of the separator exceeded 1% of the total sample mass, the length of particles on it was measured with a slide caliper with the accuracy of 0.1 mm.

In order to process the results of biomass particle dimension distribution, log-normal distribution was used, for which the average geometric length of particle was determined, as well as dimensionless standard deviation on the basis of the following correlations:

$$x_g = \log^{-1}\left[\frac{\sum (m_i \log x_{si})}{\sum m_i}\right] \quad (2)$$

$$s_g = \log^{-1}\sqrt{\frac{\sum \left(m_i \left(\log x_{si} - \log x_g\right)^2\right)}{\sum m_i}} \quad (3)$$

where:
x_g – geometric average of biomass particle dimensions [mm];
m_i – mass of material found on the *i*-th sieve [g];
x_{si} – average geometric particle length on the *i*-th sieve;
s_g – standard deviation [–].

Average geometric particle length on the *i*-sieve can be calculated using following equation:

$$x_{si} = \sqrt{x_i x_{i-1}} \quad (4)$$

where:
x_i – diagonal of mesh of the *i*-th sieve [mm];
x_{i-1} – diagonal of mesh of sieve located above the *i*-th sieve [mm].

The density of pellets and briquettes in relation to dry mass (ρ_{DM}) was calculated on the basis of direct measurements of 100 samples, their height and diameter in the middle of their length in two planes perpendicular to one another, using an electronic slide caliper with accuracy of 0.01 mm and weighing of each sample on the electronic scales RADWAG WPS 600/C with accuracy of 0.01 g. The outward facing surfaces of pellets and briquettes were polished using the tool, maintaining perpendicularity of surfaces to the shaft axis.

Bulk density of dry mass (ρ_{nDM}) of pellets and briquettes was established by weighing the sample on the electronic scales RADWAG WSP 600/C with the accuracy of 0.01 g with a tared container of capacity of 2 and 10 dm^3, respectively.

The combustion heat of material from pellets and briquettes was established on the basis of three trials using calorimeter KL-10 [Lisowski et al. 2010], and afterwards calorific value was calculated.

$$Q_o = Q_s \frac{100 - W}{100} - E_w (W + Hm_{H_2O}) \quad (5)$$

where:
Q_o – calorific value [kJ·kg^{-1}];
Q_s – heat of combustion of moist biomass [kJ·kg^{-1}];
W – biomass moisture content [%];
E_w – energy needed to evaporate the water from moist biomass [kJ·kg^{-1}];
H – hydrogen content in the sample examined [%] (H = 5.5%);
m_{H_2O} – the mass of water generated during the combustion process per unit of hydrogen (8.94 kg·kg^{-1} of hydrogen).

Testing of pellets durability was conducted in accordance with the standard PN-EN 15210-1:2010, while testing of briquette durability followed the standard ASABE S269.4 [ASABE Standards 2011b], performing five trials for each type of biofuel. The mechanical durability indicator was based on the equation presented below.

$$DU = 100 \frac{m_A}{m_E} \quad (6)$$

where:
DU – mechanical durability indicator [%];
m_A – sample mass after testing [g];
m_E – sample mass before testing [g].

The pellets and briquettes produced, of the length of 40 and 100 mm, respectively, were subjected to shear, compression and flexural strength tests using a TIRAtest machine at the head movement speed of 10 mm·min^{-1}. The deformation and displacement strength was measured with the accuracy of 1 N and 0.01 mm, respectively. For cutting of the samples, a flat knife of thickness of 5 mm and the blade angle of 30° was used, and the gap between the knife blade and the blunt edge amounted to 0.2 mm. For sample compression, a punch of the pressure surface of 25 × 50 mm was used. Two-point bending of pellets was conducted with the support span of 20 mm, and bending of briquettes – with the support span of 60 mm, which was consistent with the earlier experiment conditions [Lisowski et al. 2010]. For each type of biofuel and load 15 trials were conducted.

The force-displacement charts served as a basis for calculation of the modulus of elasticity, as the secant modulus, or as the quotient of stress to relative strain for the point, at which the first curve inflection took place. Thus, it was the point on the force-displacement diagram, at which the correlation ceased to be linear [Frączek et al. 2003]. Maximum stress values were defined for the maximum deformation strength and the area of the surface subject to stress. Unit energy was calculated as the quotient of total deformation energy (the value of the area integral under the deformation curve) and the area of inertia subject to stress (Table 1). Value of the inertia moment for pellets and briquettes was calculated for circular cross-section $I = d^4 / 64$, where d is the sample diameter.

RESULTS AND DISCUSSION

The complex test results have been presented in Table 2. The moisture content of biomass for production of pellets and briquettes was identical and amounted to 9.1 ±0.2%. The geometric average value of dimensions of biomass particles after the first crushing of the apple tree branches of Idared, Gloster and Cortland varieties in the knife crusher equipped with a sieve of mesh size of 25 × 8

TABLE 1. Correlations used to determine the strength parameters [Lisowski et al. 2010]

Parameter	Shear	Compression	Bending
Elasticity modulus	$E_t = \frac{F_{te} d}{S_t \Delta l_t}$	$E_c = \frac{F_{ce} d}{S_c \Delta l_c}$	$E_g = \frac{F_{ge} l_b^3}{48 I y}$
Maximum stress	$\tau_{t\max} = \frac{F_{t\max}}{S_t}$	$\sigma_{c\max} = \frac{F_{c\max}}{S_c}$	$\sigma_{g\max} = \frac{F_{g\max} l_b y}{4I}$
Unit energy	$E_{jt} = \frac{1}{S_t} \int F_t dx$	$E_{jc} = \frac{1}{S_c} \int F_c dx$	$E_{jg} = \frac{1}{S_g} \int F_g dx$

Legend:
E_t, E_c, E_g – elasticity modulus upon shear, compression, bending [MPa];
$\tau_{t\max}$, $\sigma_{c\max}$, $\sigma_{g\max}$ – maximum shear, compression, bending stresses [MPa];
F_t, F_c, F_g – shear, compression, bending force for a given displacement dx [N];
F_{te}, F_{ce}, F_{ge} – shear, compression, bending force (at the elasticity limit) [N];
$F_{t\max}$, $F_{c\max}$, $F_{g\max}$ – maximum shear, compression, bending force (sample deformation) [N];
E_{jt}, E_{jc}, E_{jg} – unit energy of shear, compression, bending [$J \cdot m^{-2}$];
Δl_t, Δl_c – perpendicular pellet or briquette displacement from the shear, compression force [m];
d – sample diameter prior to loading of the sample at the point of application of force [m];
I – polar moment of inertia of the sample cross-section [m^4];
S_t, S_g – cross-section of the sample in the place of cutting, bending [m^2];
S_c – area subject to load, as the product of length of the compressing punch (0.025 m) and diameter of a sample measured within the plane perpendicular to compressive strength [m^2];
l_b – distance of a sample support points (for pellet 0.020 m, for briquette 0.060 m) [m];
y – distance of external fibers from the neutral axis of a sample [mm];
x – displacement (knife travel, deformation of pellet or briquette, deflection) [m].

TABLE 2. A breakdown of average values and standard deviation values for physical characteristics of biomass, pellets and briquettes

Parameter	Product			
	pellets		briquettes	
	average value	standard deviation	average value	standard deviation
Material moisture content, *w* [%]	9.1	0.2	9.1	0.2
Dimensions of particles, x_g [mm]	5.11	0.31	11.31	0.42
Dimensionless standard deviation, s_g [–]	2.23	–	1.95	–
Product density, ρ_{DM} [$kg \cdot m^{-3}$]	937	36	737	29
Bulk density, ρ_{nDM} [$kg \cdot m^{-3}$]	620	12	437	15
Combustion heat, Q_s [$kJ \cdot kg^{-1}$]	16 183	529	16 023	487
Calorific value, Q_o [$kJ \cdot kg^{-1}$]	15 202	497	15 042	457
Mechanical durability, *DU* [%]	92.31	0.97	34.39	5.11
Shear				
Elasticity modulus, E_t [MPa]	15.31	8.76	2.46	1.43
Maximum stress, τ_{tmax} [MPa]	1.54	0.89	0.85	0.49
Unit energy, E_{jt} [$mJ \cdot mm^{-2}$]	3.69	2.29	3.16	2.41
Compression				
Elasticity modulus, E_c [MPa]	14.75	6.78	7.17	3.59
Maximum stress, σ_{cmax} [MPa]	8.64	1.54	7.46	1.37
Unit energy, E_{jc} [$mJ \cdot mm^{-2}$]	3.84	1.30	3.64	3.01
Bending				
Elasticity modulus, E_g [MPa]	8.47	6.49	5.62	2.17
Maximum stress σ_{gmax} [MPa]	1.47	0.73	1.19	0.62
Unit energy, E_{jg} [$mJ \cdot mm^{-2}$]	0.41	0.08	0.29	0.14

as 11.31 mm with dimensionless standard deviation of 1.95. Further crushing of the obtained chips with a sieve of dimensions of 23 × 4 mm allowed for reduction of particle size to 5.11 mm, with dimensionless standard deviation of 2.23. The dimensions of biomass particles for production of briquettes and pellets, were only slightly greater from those recommended in literature, amounting to 8–10 and 3–4 mm, respectively [Lisowski et al. 2010].

Pellet density, related to dry mass (ρ_{DM}) 937 $kg \cdot m^{-3}$ was 27% greater than briquette density (737 $kg \cdot m^{-3}$). These differences could be influenced by technical parameters of the pellet and briquette producing machines, as well as the biomass particle sizes. For smaller particle sizes, their packing in pellets and briquettes was better. Due to the different principles of operation of the two technical devices, in order to formulate clear conclusions, it would be necessary to conduct research for the same technical parameters of the machine – under laboratory conditions. These research results can thus be treated as inspiration for further experiments. Research conducted so far in this regard indicates that increase in crushing improves the susceptibility of biomass to pressure agglomeration [Tumuluru et al. 2010]; however, excessive quantity of the fine fraction is not a desired feature [Świętochowski 2013]. Wood pellet densities according to standards are greater: in Germany, according to DIN 51731 (greater than 1,000 kg·m^{-3}), in Austria – Ö-NORM M 7135 (greater than 1,200 kg·m^{-3}). The pellet and briquette density values obtained from research are greater than density of wood of typical deciduous trees (such as poplar, aspen, birch, oak, beech, robinia) or coniferous trees (spruce, fir, pine), which is within the range of 410–730 kg·m^{-3} [Dobrowolska et al. 2010]. Rynkiewicz [2013b] obtained pellets made of pine sawdust of density of 1,021–2,072 kg·m^{-3}, which increased along with increase in pellet curing in temperature of 20–70°C. However, the author did not specify, which tree parts were used to make sawdust.

Bulk density of pellets, referring to dry substance (ρ_{nDM}), amounted to 620 kg·m^{-3} and was greater by 42% than the bulk density of briquettes (437 kg·m^{-3}). This is associated not only with the diversified density of individual pellets and briquettes, but also with the possibility of spatial packing of these in the containers. Bulk transport of briquettes is probably less reasonable from the economic perspective in comparison with pellets. In retail trade of finished solid biomass products, briquettes are most often offered in cardboard boxes, while pellets are sold in bags. According to ISO 17225-1:2014, bulk density of pellets and briquettes should be greater than or equal to 650 kg·m^{-3}. The Swedish standard SS 18 71 20 requires that bulk density of pellets is greater than 500 kg·m^{-3}. Other standards fail to provide this value. Bulk density of pellets – as well as briquettes – is greater than bulk density of energy chips from coniferous and deciduous trees (149–295 kg·m^{-3}) [Dobrowolska et al. 2010], which means that for logistic purposes, pressure agglomeration of biomass is reasonable.

The combustion heat of material collected from pellets and briquettes produced was similar, amounting to 16,183 and 16,023 kJ·kg^{-1}, respectively. The calorific value of these biofuels amounted to 15202 kJ·kg^{-1} and 15042 kJ·kg^{-1}, respectively. Taking into account the fact that biomass came from branches containing a large quantity of bark, dominated by annual shoots, with high content of soft phloem, calorific value can be considered to be rather high, although it is lower than required value of greater than or equal to 18 MJ·kg^{-1} (for wood remains) by the standard ISO 17225-1 for pellets and briquettes. The quality requirements for pellets vary, e.g. according to the German standard DIN 51731, the calorific value should amount to 17.5––19.5 MJ·kg^{-1}, according to the Austrian standard Ö-NORM M 7135 greater than 18 MJ·kg^{-1} , while the Swedish standard SS 18 71 20 states it should be greater than 16.9 MJ·kg^{-1}. Bark and parenchyma is characterized by lower calorific value than actual wood, and thus the calorific values of pellets and briquettes are lesser in comparison with coniferous tree (19,045–19,998 kJ·kg^{-1}) and deciduous tree species (17,335–20,862 kJ·kg^{-1}) [Dobrowolska et al. 2010].

Mechanical durability of pellets of 92.31% is lower than that required for class TW3 (made of wood remains) by standard ISO 17225-1:2014 (greater than or equal to 95.0%), although it is proper for industrial purposes. In research conducted by Rynkiewicz [2013a], mechanical durability of pellets made of pine sawdust with the addition of oak and ash, walnut and sweet cherry sawdust was greater and it amounted to 98.34–98.87%.

The durability of briquettes of 34.39% was too low for such biofuel to be accepted on the retail market, as well as on the wholesale market – in the professional power industry, which requires mechanical durability of briquettes to reach at least the level of 80%. The ISO 17225-1:2014 standard does not specify mechanical durability of briquettes. For this durability, the value of standard deviation was also high (5.11%), which indicates a significant spread in durability of briquettes and non-repeatability of production. Low durability values, in association with density of a single briquette, may indicate weaker bonding of larger biomass particles and less effective packing of these particles. Probably, the insufficient moisture content in the biomass (9.1%) could be yet another factor that reduced susceptibility to bonding between particles, despite the fact that the agglomeration pressure was high and the head temperature reached about 90°C.

The agglomerate durability is associated strictly with the stress resistance parameters (Table 2). During shearing, compression and bending, higher values of the elasticity modulus, stress and unit energy were obtained for pellets in comparison with briquettes. The more durable pellets were characterized by higher elasticity, as the average elasticity value for pellets was 60% greater in comparison with briquettes. For the purpose of pellet deformation, maximum stress had to be 18% greater, and the amount of unit energy needed for such deformation was 11% higher in comparison with briquettes. The standard error for value of measures of physical characteristics of pellets was smaller in comparison with briquettes, which means that production of pellets is more stable. In this regard, further laboratory research is necessary to explain the reasons for diversified physical values of pellets and briquettes.

CONCLUSIONS

- The measures of assessment of physical features of pellets were greater in comparison with briquettes made of crushed, apple tree branches of Idared, Gloster and Cortland varieties which could be associated with smaller particle sizes of biomass, amounting to 5.11 and 11.31 mm, respectively, and the different rules of functioning of the pellet and briquette producing machines.

- The values of agglomerate density, dry mass, bulk density, calorific value and durability were lesser than required by the standards under concern, which was probably due to insufficient moisture content in biomass (9.1%) and large share of bark and parenchyma in the annual shoots.
- The values of stress parameters (module of elasticity, maximum stress, unit energy of deformation) were connected strictly with durability of agglomerates and they were greater for pellets in comparison with briquettes.
- It is recommended to conduct laboratory tests, using biomass of this type, in order to specify the optimum conditions of pressure agglomeration for production of pellets and briquettes.

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Streszczenie: *Pelety i brykiety z drewna drzew owocowych.* Celem badań było opracowanie charakterystyk fizycznych biomasy z gałęzi drzew jabłoni odmian Idared, Gloster i Cortland oraz wytworzonych z niej peletów i brykietów. Z rozdrobnionej biomasy na rozdrabniaczu nożowym z sitem o wymiarach 25 × 8 lub 23 × 4 mm wyprodukowano odpowiednio brykiety i pelety. Dla biomasy wyznaczono wilgotność, charakterystyki wymiarów cząstek, a dla peletów i brykietów oznaczono ich gęstość i gęstość nasypową odniesioną do suchej masy oraz ciepło spalania, wartość opałową i trwałość mechaniczną, a także parametry wytrzymałościowe: moduł sprężystości, naprężenia maksymalne i energię jednostkową podczas cięcia, ściskania i zginana dwupodporowego aglomeratów. Badania przeprowadzono zgodnie z wymaganiami norm. Miary ocen cech fizycznych peletów były większe niż brykietów i były mniejsze niż wymagane przez przedmiotowe normy. Wartości parametrów wytrzymałościowych były ściśle powiązane z trwałością aglomeratów.

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Authors' address:
Aleksander Lisowski, Marcin Grela, Michał Sypuła, Adam Świętochowski, Magdalena Dąbrowska-Salwin, Wojciech Stępień, Rafał Korupczyński
Wydział Inżynierii Produkcji SGGW
Katedra Maszyn Rolniczych i Leśnych
Wojciech Stępień
Wydział Rolnictwa i Biologii SGGW
Katedra Nauk o Środowisku Glebowym
Rafał Korupczyński
Wydział Inżynierii Produkcji SGGW
Katedra Podstaw Inżynierii
02-787 Warszawa, ul. Nowoursynowska 164
Poland
e-mail: aleksander_lisowski@sggw.pl