ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS

Volume LXI 153 Number 5, 2013

http://dx.doi.org/10.11118/actaun201361051377

INFLUENCE OF ANNEALING TEMPERATURE OF STRAW BRIQUETTES ON THEIR DENSITY AND HARDNESS

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Received: May 28, 2013

Abstract

RYNKIEWICZ MAREK, TRÁVNÍČEK PETR, KRČÁLOVÁ EVA, MAREČEK JAN: *Influence of annealing temperature of straw briquettes on their density and hardness.* Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 2013, LXI, No. 5, pp. 1377–1382

The study evaluated the effect of annealing temperature of non-wood, herbaceous ground briquettes on their density, hardness and fracture incidence. The study showed an average density of hay briquettes at 20 °C was 1 256.99 $kg \cdot m^{-3}$, whereas at 60 °C density increased to 1 369.44 $kg \cdot m^{-3}$. The analysis showed statistically significant differences in the average densities of briquettes, depending on their temperature. Temperature of briquettes also had a statistically significant effect on their hardness. In case the temperature increases from 20 to 60 °C both longitudinal and transverse cracks were observed for all samples.

biomass, briquette, energy crops

Currently biomass has become more and more appreciated renewable energy resource. Compared with fossil fuels, which are slowly running out of resources, biomass is the source of ecologically clean fuel and thus in the near future may be an important source of energy. The reason for which the European Union has decided to promote the use of renewable energy sources in Europe is primarily a continuous traditional source of uncertainty and the desire to reduce greenhouse gas emissions. The use of materials from the herbaceous mass as a source of renewable energy has many advantages, such as: acquiring continuous and reliable supply of raw materials from domestic producers, the additional income received by farmers, the ability to obtain subsidies from the European Union to reduce CO_2 emissions (Grzybek 2004; Grzybek *et al.*, 2002).

The large volume of unprocessed biomass requires the agglomeration for energy purposes. The finished product must meet certain requirements. Therefore, after the process of biomass agglomeration, quality of briquettes is evaluated. For qualitative parameters determining the quality of briquettes include density, hardness, mechanical strength and the presence of cracks (EN 14961-3:2011; Hejft, 2002; Hejft *et al.*, 2006). However, the prevailing variable temperature conditions of storage and transportation of finished materials in the agglomerated form may affect the change of its physical parameters. Therefore, there is a need for research in this area. The aim of the study was to determine the effect of annealing temperature of briquettes made of hay and straw on their density, hardness and fracture incidence.

MATERIALS AND METHODS

The study was conducted for the briquettes produced from biomass derived from herbaceous plants, which have the timber stem and which die at the end of the vegetation. In this case it was: hay, wheat, rye and rapeseed straw. Materials used for the production of briquettes were agglomerated within 6 months of obtaining them from the field.

Groups of tested briquettes were divided according to their composition in the following way:
A – 100% hay
B – 50% of wheat straw and 50% of hay
C – 100% rapeseed straw
D – 50% of rapeseed straw and 50% of wheat straw
E – 100% rye straw.

Various raw materials used in the production of briquettes made it possible to obtain 5 different groups of research material. Each group of test material divided into three groups.

Tests were performed for each subgroup after heating the samples at 20 °C, 40 °C and 60 °C. The process of heating briquettes for each sample was carried out for 210 min (after stabilization of the temperature in the oven). After annealing the samples their density and hardness were measured, also the fracture type was determined.

Humidity of samples was performed according to standard EN 14774–3:2009 and was calculated using the following formula:

$$M_{ad} = \frac{(m_2 - m_3)}{(m_2 - m_1)} \times 100, \tag{1}$$

M_{ad} ... relative humidity [%],
m_1 .... mass of the empty dish plus lid [kg],
m_2 .... mass of the dish plus lid with sample before drying [kg],
m_3 .... mass of the dish plus lid with sample after drying [kg].

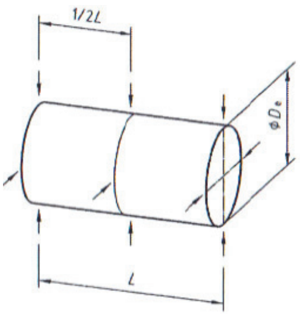
Briquette density determined according to standard EN 15150:2011. For this purpose measurement of the length, diameter and weight for 3 samples briquettes was made. Diameter measurement was performed 6 times, in accordance with Figure 1. Density was determined using the following formula:

$$\rho = \frac{m}{V_p}, \tag{2}$$

where:
ρ .... briquettes density [kg·m⁻³],
m ...... mass of the sample [g],
V_p ..... volume of the briquette [m³], where:

$$V_P = \frac{D_{em}^{\ 2} \times \pi \times L}{4}, \tag{3}$$

where:
L .... length [cm],
D_{em} ... average value for 6 measurements of the diameter [cm].



1: *Briquette diameter measurement points [EN 15150:2011]*

ZGW–1 unit of DHN was used to measure the hardness. Examination consisted of exerting the force with head of hardness tester on a given briquettes sample. In the research was used mandrel with a rectangular base of 18 mm × 6 mm. The load, at which the briquette was disintegrating, was a measure of its hardness in kg. The measurement was performed in triplicate for each batch of tested briquettes.

Type of cracks was determined by appearance. Cracks parallel to the axis of briquettes were determined as longitudinal cracks, and perpendicular to the axis was defined as transverse.

Briquette production line from which research material was obtained consisted of the following components: chipper, mill, tank dispenser and briquetting mixer of eccentrically-piston. Humidity of agglomerated materials ranged from 12 to 20 %. Mill sieve mesh was 8 mm. However, the briquetting press output diameter was 60 mm.

Statistical calculations

Statistical analysis was performed using Statistica and Excel. For tested parameters their compatibility with normal distribution was verified. Degradation studies were carried out using the Shapiro–Wilk test. The critical level for significance was $p = 0.05$. To check the homogeneity of variance Levene's test was used.

The significance of differences in average values of more than two populations with normal distributions and homogeneous variances verified using ANOVA test. To verify the differences between the average values Tukey's test was used. Spearman correlation coefficient was calculated for the parameters when at least one of them had different from the normal distribution (Stanisz, 1998).

RESULTS AND DISCUSSION

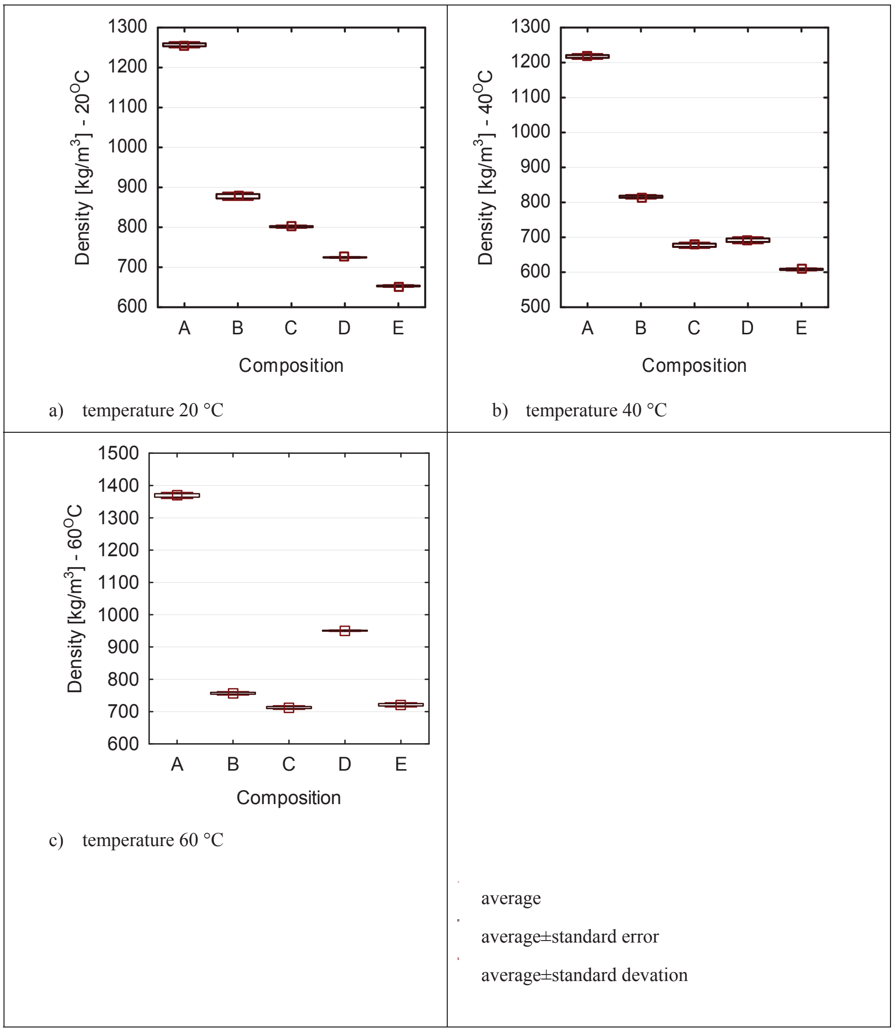
Moisture of analyzed samples of briquettes ranged from 5 to 6 %. Tab. I shows the characteristic parameters of the tested briquettes density obtained during the study.

From Tab. I it can be concluded that for each batch of briquettes with changes of their annealing temperature occurs changes in their density. For briquettes from straw (A), rapeseed and wheat straw (D) and rye straw (E) with the change of temperature from 20 °C to 60 °C increased density of briquettes, while in the case of briquettes from wheat straw and hay (B) and rapeseed straw (C) decrease in density was observed. The highest values of density was observed for briquettes of hay (369.44 kg·m⁻³) at 60 °C, and the lowest for rye straw briquettes (608.22 kg·m⁻³) at 40 °C.

The statistical analysis of variance ANOVA revealed statistically significant differences in the average density of briquettes in group A, B, C, D and E depending on the temperature at $p<0.05$. However, Tukey's test confirmed statistically

I: *Characteristic parameters of the tested briquettes density depending on the annealing temperature*

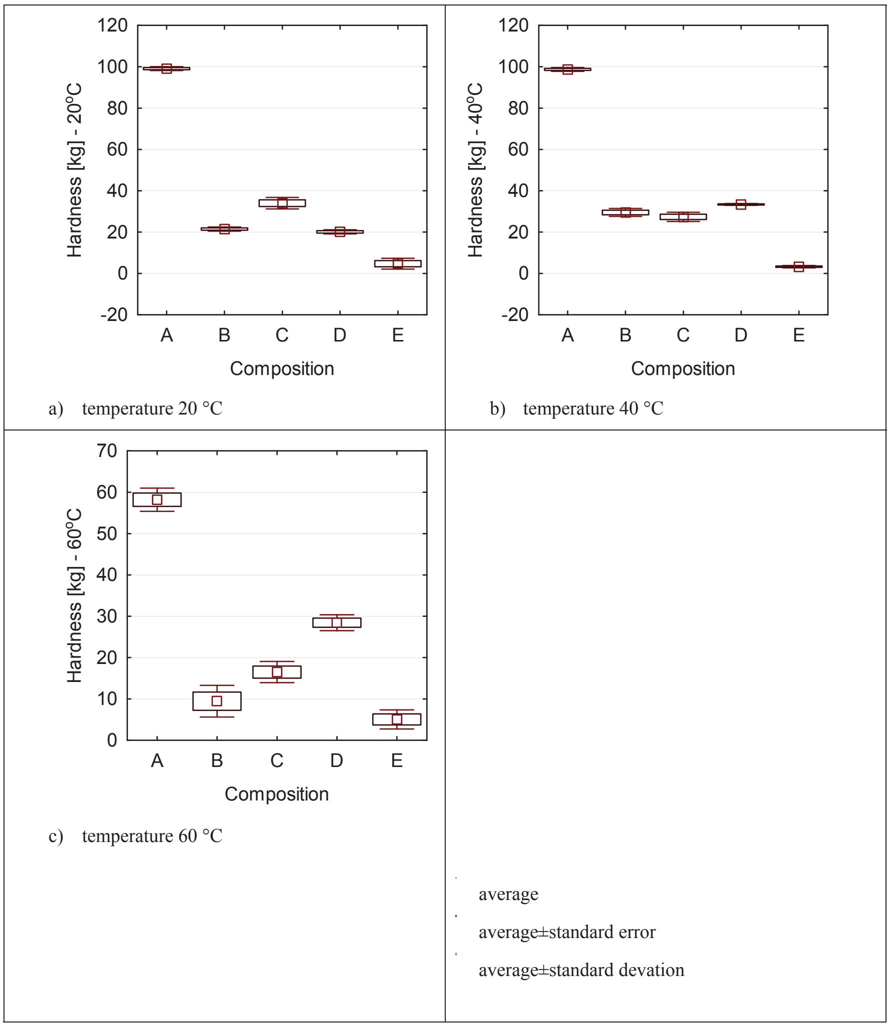
No.	Mark () and the composition of examined briquettes	Temperature [°C]	Parameters of briquettes density [kg·m^{-3}]			
			Average	Minimum	Maximum	Standard deviation
1	(A) 100% hay	20	1 256.99	1 251.76	1 264.38	6.58
2		40	1 217.55	1 212.94	1 225.51	6.92
3		60	1 369.44	1 359.43	1 377.61	9.23
4	(B) 50% of wheat straw and 50% of hay	20	877.81	869.19	887.72	9.33
5		40	816.07	812.21	821.72	5.00
6		60	756.77	750.73	759.91	5.23
7	(C) 100% rapeseed straw	20	801.70	799.10	804.76	2.86
8		40	677.22	669.26	684.67	7.72
9		60	712.59	707.16	718.17	5.51
10	(D) 50% rapeseed straw and 50% of wheat straw	20	724.67	723.54	725.85	1.16
11		40	691.67	682.29	699.46	8.69
12		60	950.45	948.62	952.87	2.18
13	(E) 100% rye straw	20	653.16	650.87	654.46	1.99
14		40	608.22	605.08	611.10	3.02
15		60	721.11	716.73	728.52	6.45



2: *Briquette density depending on the composition (A, B, C, D and E) for the annealing temperature at 20, 40 and 60 °C*

II: *Characteristic parameters of tested briquettes hardness depending on the annealing temperature*

No.	Mark () and the composition of examined briquettes	Temperature [°C]	Parameters of briquettes hardness [kg]			
			average	minimum	maximum	standard deviation
1	(A) 100% hay	20	99.09	98.11	99.98	0.94
2		40	98.70	97.68	99.42	0.91
3		60	58.20	55.43	61.04	2.81
4	(B) 50% of wheat straw and 50% of hay	20	21.48	20.60	22.56	0.99
5		40	29.53	27.37	31.09	1.93
6		60	9.46	5.95	13.53	3.82
7	(C) 100% rapeseed straw	20	34.00	31.22	36.79	2.79
8		40	27.39	25.22	29.69	2.24
9		60	16.50	14.10	19.18	2.55
10	(D) 50% rapeseed straw and 50% of wheat straw	20	20.11	19.15	21.14	1.00
11		40	33.40	33.09	33.89	0.43
12		60	28.45	26.75	30.54	1.92
13	(E) 100% rye straw	20	4.75	2.80	7.75	2.63
14		40	3.29	2.76	3.89	0.57
15		60	5.05	2.39	6.57	2.31



3: *Briquette hardness depending on the composition (A, B, C, D and E) for the annealing temperature at 20, 40 and 60 °C* significant differences for each examined subgroup of briquettes.

Based on Fig. 2 it can be concluded that a straw briquettes had the highest average density at 20 °C (1 256.99 kg·m^{-3}) and rye straw briquette obtained the lowest density at this temperature (653.16 kg·m^{-3}), i.e. a reduction of 48.0 %. A similar relationship was observed for the temperature of 40 °C. In the case of temperature 60 °C, the briquett of hay received the highest density result (1 369.44 kg·m^{-3}), while the lowest density results obtained from rapeseed straw briquettes (712.59 kg·m^{-3}).

The statistical analysis of variance ANOVA revealed statistically significant differences in average values for each group of density of tested briquettes at $p < 0.05$. Therefore was performed a detailed examination of the differences between the averages of each subgroup with post-hoc test (Tukey test). After the Tukey test, there was no statistically significant difference between the density in a subgroup of rapeseed straw briquettes (C) and briquettes from rapeseed straw with wheat straw (D) at a temperature between 40 °C and between a subset of rapeseed straw briquettes (C) and rye straw (E) at 60 °C.

Based on Tab. II, it can be concluded that the increase in temperature of hay briquettes from 20 to 60 °C caused a decrease in hardness from 99.09 kg to 58.20 kg. A similar phenomenon occurred in the case of briquettes from wheat straw supplemented with hay and briquette from rape.

The statistical analysis of variance ANOVA found statistically significant differences in average values for the group of briquettes A, B, C and D, but there was no statistically significant difference for the briquettes from rye straw. Detailed studies of the differences between the average of the subgroups A, B, C and D made with post-hoc test (Tukey test) did not confirm statistically significant differences only for hay briquettes at 20 °C and 40 °C.

Based on Fig. 3 can be concluded that at 20 °C the highest hardness (99.09 kg) had a briquette of hay, and the lowest (4.75 kg) – rye straw briquettes. A similar relationship was observed for these briquettes for temperatures 40 and 60 °C.

Statistical analysis of variance ANOVA confirmed statistically significant differences in average values of tested briquettes at temperatures of 20, 40 and 60 °C. Detailed post-hoc analysis not confirmed statistically significant differences in the temperature 20 °C between wheat straw briquettes with hay (B) and briquettes from rapeseed straw and wheat (D), for a temperature of 40 °C between the briquettes from wheat straw and hay (B) and rapeseed straw briquette. At a temperature of 60 °C, there was no statistically significant difference between the briquettes from wheat straw and hay (B) and rapeseed straw briquette (C) and wheat straw briquettes and hay (B) and rye straw briquette (E).

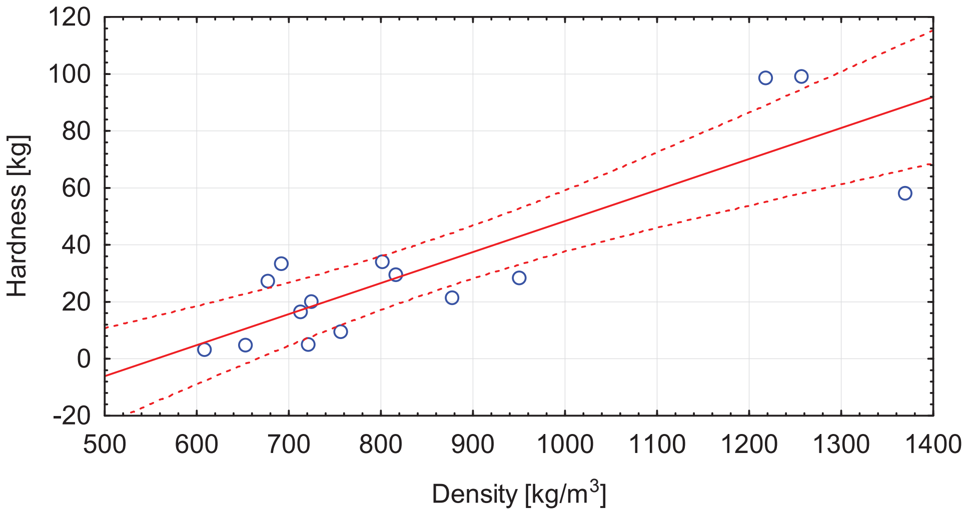
Functional dependence of the density and hardness is given by equation:

$$y = 0.1090x - 60.6207.$$

It is linear function with coefficient of determination $r^2 = 0.7292$

To examined value coefficient of correlation according to Spearman obtained a value of r = 0.75 with a significance level of $p < 0.05$ indicating a very high correlation, while a positive value of the slope of the regression line (0.109) indicates a positive linear correlation (Fig. 4).

Tab. III shows the types of cracks observed in the examined briquettes depending on the temperature of annealing. Transverse cracks occurred in all the temperature range except straw briquettes at 20 and 40 °C. At 60 °C was observed in both the transverse and longitudinal cracks for all tested briquettes, and at 20 °C this type of fracture did not occur.



4: *Linear regressions function of hardness depending on the density of the tested briquettes*

III: *Types of cracks observed in the studied briquettes in different temperature ranges*

Type of fracture	Temperature					
	20 °C		40 °C		60 °C	
	Transverse	Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal
(A) 100% hay	–	–	–	–	+	+
(B) 50% of wheat straw and 50% of hay	+	–	+	+	+	+
(C) 100% rapeseed straw	+	–	+	+	+	+
(D) 50% rapeseed straw and 50% of wheat straw	+	–	+	–	+	+
(E) 100% rye straw	+	–	+	–	+	+

SUMMARY

1. Compositions of examined briquettes have an impact on its density. The highest density had hay briquettes, for which the density results were > 1 200 kg·m^{-3}. The higher the density the greater the amount of energy able to be stored per unit volume.
2. The lowest density results were observed for the rye straw briquettes where density was about 50% lower compared to the briquettes from hay. For this reason, to use of raw materials from which the briquettes have a lower density, the hay should be added to the briquetted materials which can increase their density.
3. Rise of temperature from 20 °C to 60 °C caused an increase in the density compared to the briquette of rape, for which the density is decreased from 801.70 to 712.59 kg·m^{-3}.
4. Annealing temperature increase of briquettes had an impact on obtained results hardness. In most cases, followed its fall. The lower hardness means the greater tendency to develop cracks. The pressure moved from the upper to the lower parts of transported or stored briquettes can cause them cracking. For this reason, it is recommended to transport at temperatures below 40 °C.
5. There is a very high correlation between the density and hardness of tested briquettes.

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