RESEARCH OF THE INFLUENCE OF ADDING ROTTEN WOOD ON THE MECHANICAL QUALITY OF PELLETS

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ABSTRACT

This paper analyzes the effect of adding wood attacked by brown rot fungi to basic wood raw material with the aim of increasing the mechanical strength of wood pellets. Wood attacked by brown rot fungi has an increased share of lignin which is natural glue and can contribute to better mechanical properties of wood pellets. Wood pellets were produced on a single pellet press and pressed with adjusted production parameters at two different temperatures. Produced pellets were tested on some mechanical and physical properties. The analysis of experimental results has shown the statistical significant improvement of the mechanical properties of pellets by adding brown rot fungi wood.

Key words: wood pellets, brown rot fungi wood, single pellet press, mechanical properties.

INTRODUCTION

In the long period of human history, energy of wood biomass was the only source of energy. Later, other sources of energy such as coal, oil and natural gas took over. In time, wood biomass was of less importance, so by the end of the 20th century the share of biomass energy in developed European countries fell to level below 3% (Eurostat, 2017). In the last two decades, the situation has changed in a positive direction, but much effort and knowledge has to be invested to utilize biomass potential efficiently. Biomass compared to other sources of energy does not increase greenhouse gas emissions, and CO_2 released during its combustion is recycled as part of the carbon cycle (Gil, 2010). In order to use biomass in automated systems of heat and electric energy production, it must be chipped to obtain a homogeneous mixture suitable for automated feeding systems (Šafran, 2018). The bulk density of wood chips ranges between 150 and 200 kg/m^3 and is regularly about three times lower than the density of solid wood from which it was produced (Robbins, 1982). Distances between the place of biomass collection and the location where it is processed or used in energy production are often long, leading to expensive transportation (Stelte, 2011).

The effort to make better use of biomass has been present for a long time but one of the best ways is to produce and burn pellets (Šafran, 2015). Wood grinding and pressing to pellets creates the fuel that reached the level of automated use as well as fossil liquid and gaseous fuels (Risović, 2008). According to previous text, pellets are technologically the most advanced solid biofuel that provides the possibility of automated use in heating systems. The technological process of pellet production is complex and energy-intensive, so it is necessary to monitor and control it with the aim of achieving the highest quality of the end product. One of the important characteristics of the pellet, apart from the water content and the ash content, is certainly mechanical resistance. It is the ability of the pellets to remain intact when handling (Briggs et al., 1999; Amerah et al., 2007). Resistance is expressed by the proportion of fine particles with size less than 3.15 mm which are separated by sieving the pellet after they were subjected to mechanical or pneumatic treatment (Lehtikangas, 2001, Thomas and van der Poe, 1996). Mechanical properties play an important role in use because insufficient pellet quality can cause blockage of the feeding system and large amount of dust indicates an increased risk of fire and explosion.

The raw material in pellet production is obtained from various sources. Fuel properties and pellet compactness are directly related to the selection of raw materials for production. When selecting raw materials, it is important to take into account the properties and raw material availability (Arranz, 2011). Also it is very important to take in consideration the possibility of exploiting available raw materials in other branches such as paper and pulp production and the production of wood plates. The main goal of such approach is ecological and long-term sustainable production. In addition to healthy growing trees, great potential for biomass production lies in naturally degraded trees that have no commercial value. Whether it is trees attacked by fungi or insects, or if they are dead trees damaged by bad weather, they could be a valuable raw material for energy production.

EXPERIMENTAL METHODS

The species used in this study were fir (*Abies alba* Mill.), beech (*Fagus sylvatica* L.) and white pine (*Pinus sylvestris* L.). Basic properties of fir, beech and pine wood are shown in table 1. Healthy samples of fir and beech are made from fresh fallen healthy trees and artificially dried to 10% water content. The third sample was a degraded beech wood (Beech-rotten), taken from nature, which was primarily attacked by brown rot fungi, but was also degraded by other fungi, mildew and atmosphere (Figure 1.a). The fourth sample was a white pine wood that was laboratory inoculated with the aggressive brown rot fungi *Poria placenta* (Pine-PP) which destroyed wood structure in 90 days (Figure 1.b). Wood samples were grinded using a mill with spiral blade and 4 mm square opening. Grinded samples were conditioned for 30 days in a closed vessel using a saturated water solution of NaCl to achieve the uniform water content of 12% in all samples (atmosphere of 20 ºC temperature and 65% relative humidity gives 12% equilibrium moisture content).

Table 1: Main properties of wood species used in this paper (The Wood Database, www.wood-database.com)

Properties of wood species	fir (*Abies alba* Mill.)	beech (*Fagus sylvatica* L.)	white pine (*Pinus sylvestris* L.).
Average dried density, ρ_0 (kg/m^3)	415	710	550
Higher calorific value, H_0 (MJ/kg)	19,5	18,8	21,2
Elastic modulus (MPa)	8,28	14,31	10,08
Crushing strength (MPa)	41,0	57,0	41,5

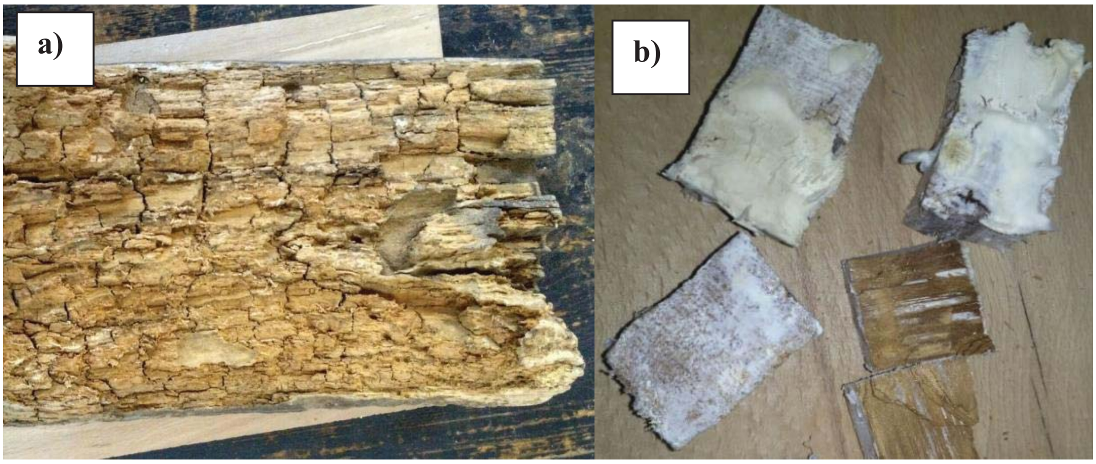

Figure 1: a) – Beech wood sample degraded with brown root fungi taken from nature
b) **White pine sample laboratory inoculated with *Poria placenta* fungi treated for 90 days**

After conditioning it was formed mixtures of samples Pine-PP and Beech-rotten in ratio 50:50% (PP-rotten), fir and beech in ratio 50:50%, fir + beech + PP-rotten in ratio 45:45:10%, fir + beech + PP-rotten in 40_40:20%. After mixing of all samples and mixtures, moisture content according to HRN EN ISO 18134-2: 2015 standard, ash content according to HRN EN ISO 18122: 2015 and fuel value at IKA C200 according to HRN EN ISO 18125: 2017 were determined.

After the main properties of the raw material were determined, pellets were pressed using a hydraulic single pellet press (SPP). For pellet production next mixtures were used: fir + beech (F + B) in the ratio of 50:50%, fir + beech + PP-rotten wood (F + B + 10%) in the ratio of 45:45:10% and fir + beech + PP-rotten wood (F + B + 20%) in the ratio 40:40:20%. SPP has the ability to control the force and piston speed (Figure 2). The press is equipped with an 300 W electric heater with die temperature regulation and HBM C9C / 20 kN force gauging equipment which collects data with HBM Spyder 8 amplifier and Catman 4.0 software. The press parameters can be divided into fixed and variable: the fixed parameters are pressing time (20 s), sample mass (0.25 g) pressing force (7 kN) and particle size (4 mm), while the variable are composition of the raw material (F + B, F + B + 10%, F + B + 20%) and pressing temperature (120 °C and 200 °C).

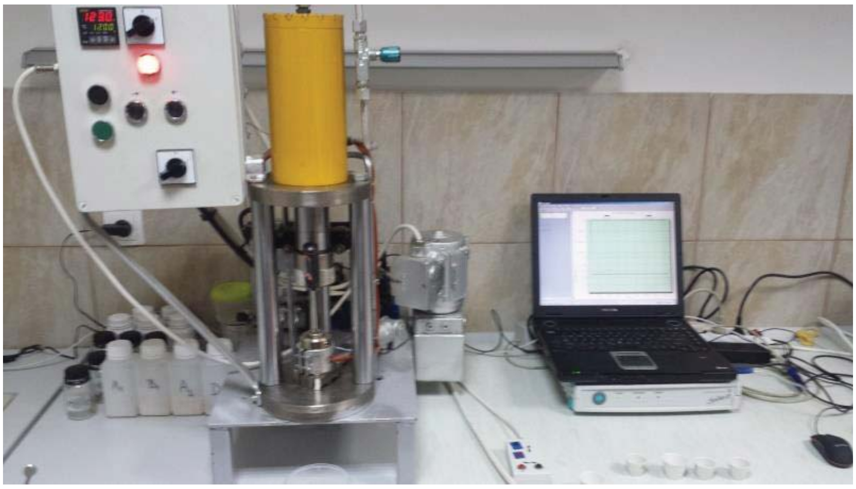

Figure: Measuring equipment for pellet pressing (Single pellet press – SPP)

Total amount of 90 pellet samples was pressed, 15 pellets for every group and temperature. After pressing the pellets, dimensions and mass were determined by micrometer (Mitutoyo, 500-CD-15PMX) and analytical scale with accuracy of 0.1 mg (Sartorius Talent TE214S-OCE). Pressed and measured pellets were deposited in plastic tubes. Pellet density was calculated and then the mechanical properties were measured by testing the compressive strength in the radial direction. The compressive strength analysis was carried out using a Shimadzu Autograph AG-X plus equipped with a 1000 N load cell. Trapezium X software has carried out measuring process, while pellet testing speed was 1.5 mm / min (Figure 3).

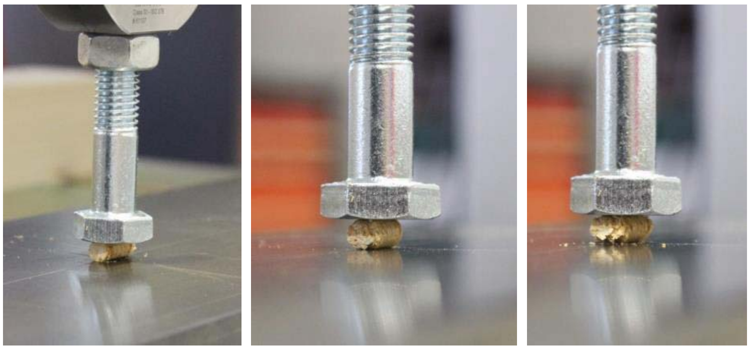

Figure 3: Examining course of pellet pressure strength measurement in a radial direction

Result of the compressive strength test is the force/displacement diagram and maximum force value at which the pellet brakes. The stress at maximum force to projected surface gives the pellet compressive strength in the radial direction. The projected pellet surface was defined by graphic analysis of the diagrams constructed during the test. The pressing depth of the pressure element at the maximum force ranged from 0.25 to 0.35 mm, so the average depth of 0.3 mm was taken into account, which defines the pressure surface as a mathematical product of the pressing width of 2.62 mm and the measured pellet length. The obtained test results were statistically processed and analyzed.

RESULTS AND DISCUSSION

Figure 4 shows the moisture content in the raw wood samples used in this paper after conditioning. Desired moisture content by conditioning was 12%. Healthy samples of fir and beech wood had the values of moisture content close to desired, while the rotten beech and pine samples had slightly lower moisture content of around 10.9%. The reason for this can be found in the fact that grinded samples of fir and beech wood had particles at around 4 mm and relatively high porosity between the wood particles. Occasional mixing of grinded samples, allowed a quicker equalization of the moisture content of samples with the moisture balance inside the conditioning vessel. Due to the highly degraded structure samples of rotten pine and beech wood during grinding turned into powder, creating a dense layer of material on the surface of the container that did not allow the entire sample to be conditioned, regardless of occasional mixing for 30 days.

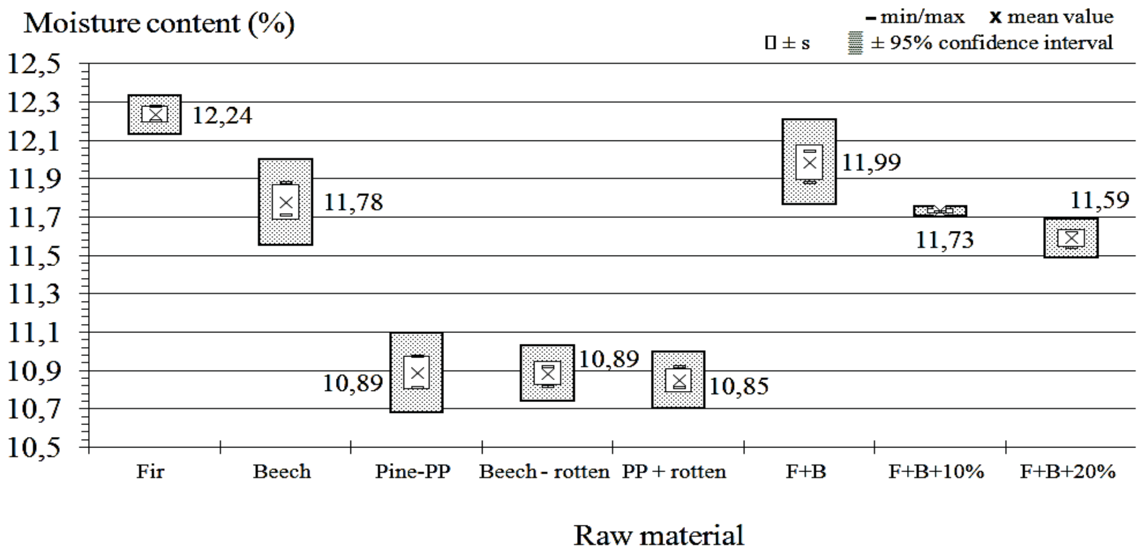

Figure 4: Moisture content of conditioned wood samples and mixes

Figure 5 shows the ash content of raw wood samples used in this paper. The ash content of healthy samples of fir (0.26%) and beech (0.57%) corresponds to the values of previous studies where ash content ranged from 0.3-0.4% and beech 0.5-0.6%. A sample of rotten pine wood degraded by *Poria placenta* had an ash content of 0.77%. The increased proportion of ash in the pine sample is also logical because in the sample that was laboratory inoculated by the *Poria placenta* fungi, the wood mass was reduced by the degradation of cellulose and hemicellulose, while the mass of the mineral residue remained the same so the mass share of ash in the sample increased. The degraded beech wood taken from nature has a high ash content of around 2.1% due to soil and sand entering the cracks and pore during wood exposure to external influences and its degradation. Ash content of a mixture of healthy and rotten wood formed in this study is logical consequence of mixing different proportions of individual raw materials with minor deviations.

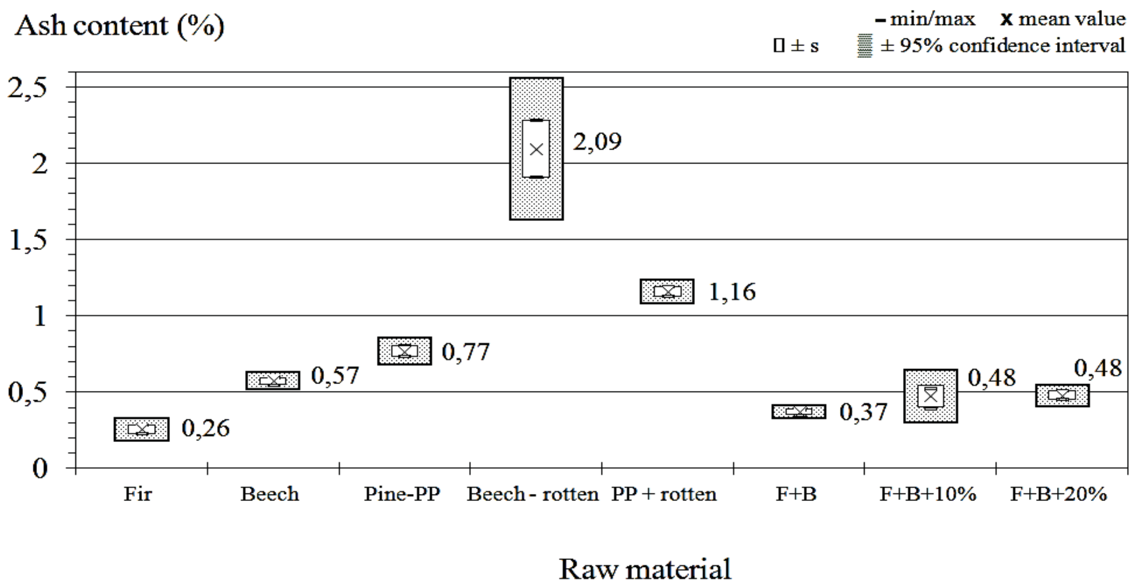

Figure 5: Ash content of raw wood samples and mixes used in experiment

In the further part of the research, the analysis of the calorific value of the samples was carried out. Since the same moisture content in the samples was not achieved by conditioning, the results of the heating value were expressed at 0% water content (Figure 6). In this way, it is possible to compare and evaluate the heating value of all raw materials and mixtures. The heating value of the fir wood was 20 kJ/g while the result for beech wood was 19.5 kJ/g. The degraded pine sample has a very high calorific value which is around the value of 23.5 kJ/g. That is a result of the mass decrease of cellulose and hemicellulose in the sample and the increase of the mass share of lignin (25–26 kJ/g) and extractives (33–38 kJ/g). Rotten beech wood collected in the nature has a higher calorific value compared to healthy beech wood, also for the same reasons as in the case of pine wood. Table 2 (Lehtikangas, 1999) shows the calorific values of individual wood components. The shown data confirm the increase in the calorific value of the potential raw material in pellet production by adding rotten wood attacked by brown rot fungi.

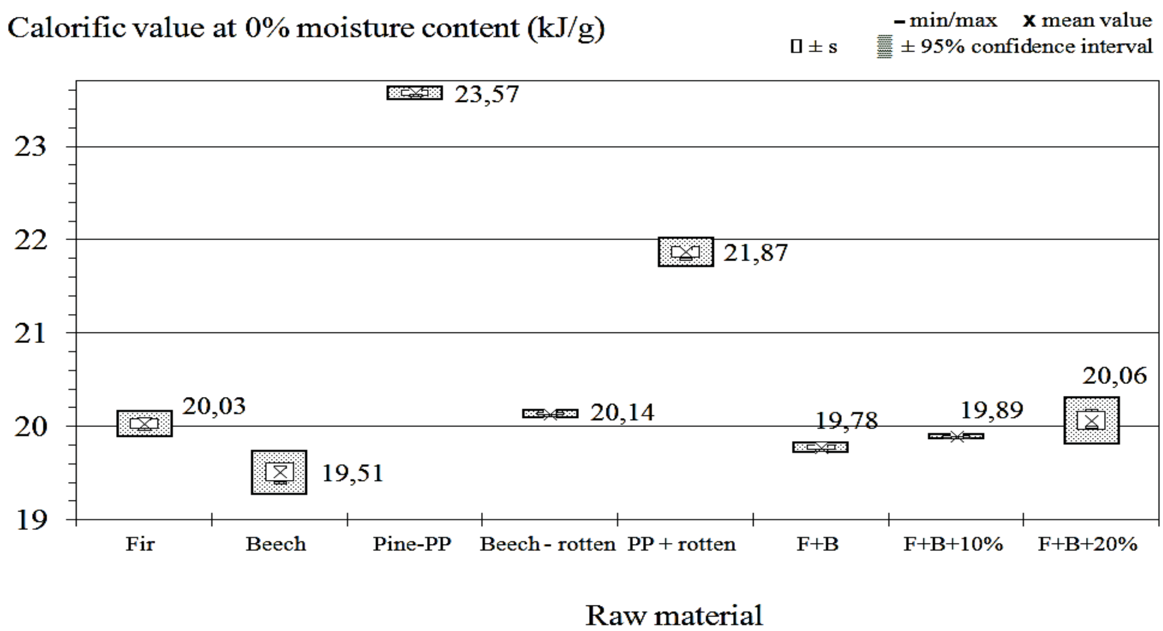

Figure 6: Calorific value at 0% moisture content of raw wood samples and mixes used in experiment

Table 2: Calorific value of softwood and hardwood components (Lehtikangas, 1999)

Wood component	Calorific value [kJ/g]
Celulose	17 – 18
Hemicelulose	16 – 17
Lignin	25 – 26
Extractives	33 – 38

After analyzing the raw material, pellets were made from selected mixtures of fir and beech with the addition of a mixture of rotten wood of pine and beech. Fir and beech (F + B), fir, beech and 10% addition of mixture of rotten wood (F + B + 10%) and fir, beech and 20% of mixture of rotten wood (F + B + 20%) were pressed into pellets at temperatures 120 and 200 °C. After pressing 15 pellets of each raw material and temperature, dimensions of all pellets were measured and mass and density were determined. The results of the density measurements (Figure 7) show the increase of the pellet density with the addition of 10% rotten wood at both temperatures, while the pellet density at the addition of 20% rotten wood is slightly smaller than the 10%

addition of rotten wood. The pellet density of all mixtures at 200 °C differed in a very small range and the mean value of difference was within 3 kg/m^3. It is also apparent that pellets made from a mixture of fir and beech, without the addition of rotten wood at temperature of 200 °C, have almost the same density as those with an addition of 20% rotten wood. From the Figure 7 it is obvious that at the pressing temperature of 120 °C the raw material with the increased lignin content is better and the pellets have a higher density compared to the pellets pressed from the raw material without the increased lignin content. At the temperature of 200 °C all wood components, including cellulose, change the aggregate state and the process of degradation of the wood material begins, so all the mixtures give approximately the same density of pellets. The above claims can be substantiated by the illustration in Figure 8 showing the temperature at which changes in the structure of the wood components (Koukios, 1994) occur, where at 200 °C all the wood material components have been modified.

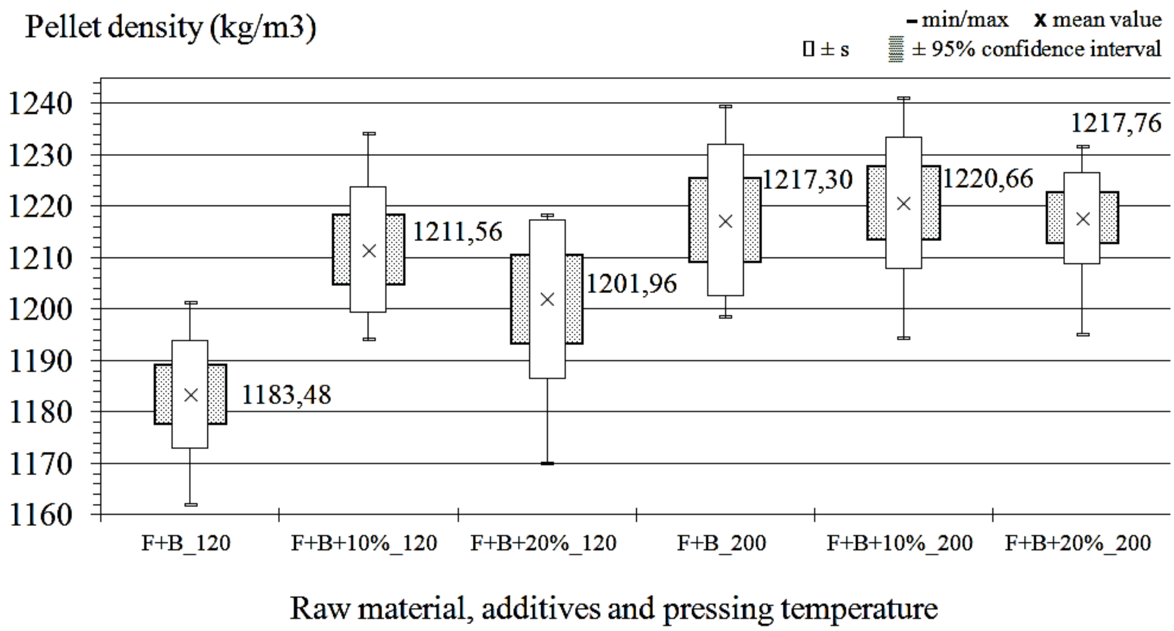

Figure 7: Pellet density of pellets pressed at 120 °C and 200 °C

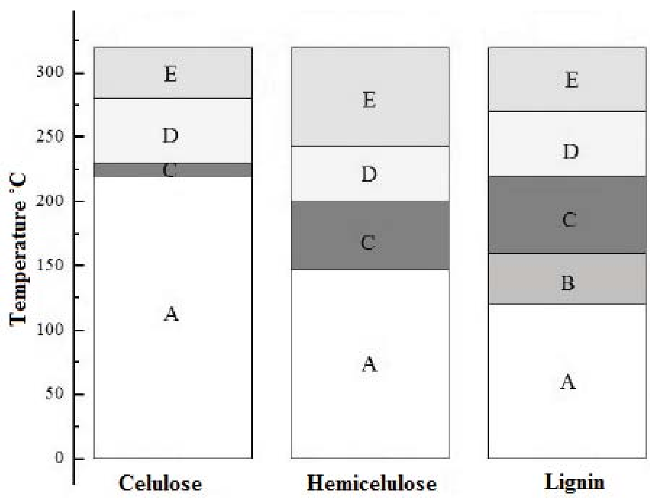

Figure 8 : Temperature range of physical-chemical changes of main wood components – (A – drying; B – glass transition of lignin; C – depolymerisation, D – vaporization and carbonization of polymers)

Table 3 shows the influence of raw material on pellet density. The table shows a statistically significant increase of pellet density by adding 10 and 20% of the rotten wood to the raw material at pressing temperature of 120 °C. The difference between adding 10 and 20% of rotten wood to raw material is not significant. The difference in density of all groups of pellets pressed at 200 °C is not significant due to the very high pressing temperature at which the physico-chemical changes in the structure of the wood occur, forming bonds between the particles that prevent the pellet expansion.

Table 3: Influence of raw material on pellet density

Influence of raw material on pellet density			
Comparison	**F+B – F+B+10%_120**	**F+B – F+B+20%_120**	**F+B+10% – F+B+20%_120**
t-value	6,765	3,840	1,883
p-value	0,00	0,18	8,07
Comparison	**F+B – F+B+10%_200**	**F+B – F+B+20%_200**	**F+B+10% – F+B+20%_200**
t-value	0,665	0,103	0,720
p-value	51,70	91,91	48,33

Table 4 shows the influence of pressing temperature on the density of the pellets. The table shows a significant difference in the density of pellets pressed from the raw material at temperatures of 120 and 200 °C. This is due to the increase in the pressing temperature and the dissolution of the wood components at 200 °C. The difference in the density of pellets with the addition of 10% rotten wood between temperatures of 120 and 200 °C is not significant, but it is very close to the significance limit. By addition of 20% of rotten wood in the raw material, the increase in the density of pellets pressed at 200 °C is significant in comparison to the temperature of 120 °C.

Table 4: Influence of pressing temperature on pellet density

Influence of pressing temperature on pellet density			
Comparison	**F+B_120 – F+B_200**	**F+B+10%_120 – F+B+10%_200**	**F+B+20%_120 – F+B+20%_200**
t-value	7,247	1,987	3,432
p-value	0,00	6,69	0,40

Figure 9 shows the compressive strength of the pellets in the radial direction. Significant increase of the compressive strength (31.5%) was seen from the figure at the temperature of 120 °C for the pellet with 10% of rotten wood compared to pellets pressed from pure raw material of fir and beech. Further increase of the compressive strength is also evident for pellets with 20% of rotten wood compared to fir and beech pellets (38.8%), but it is not significant compared to pellets with 10% of rotten wood addition. The strength of pellets from pure raw material of fir and beech pressed at 200 °C is equal to the strength of fir and beech pellets with a 20% addition of rotten wood pressed at 120 °C. By adding 10% of rotten wood and pressing at 200 °C the pellet strength increased by 27%, and by adding 20% of the rotten wood the increase of strength compared to the strength of pellets from pure fir and beech raw material was 40.8%.

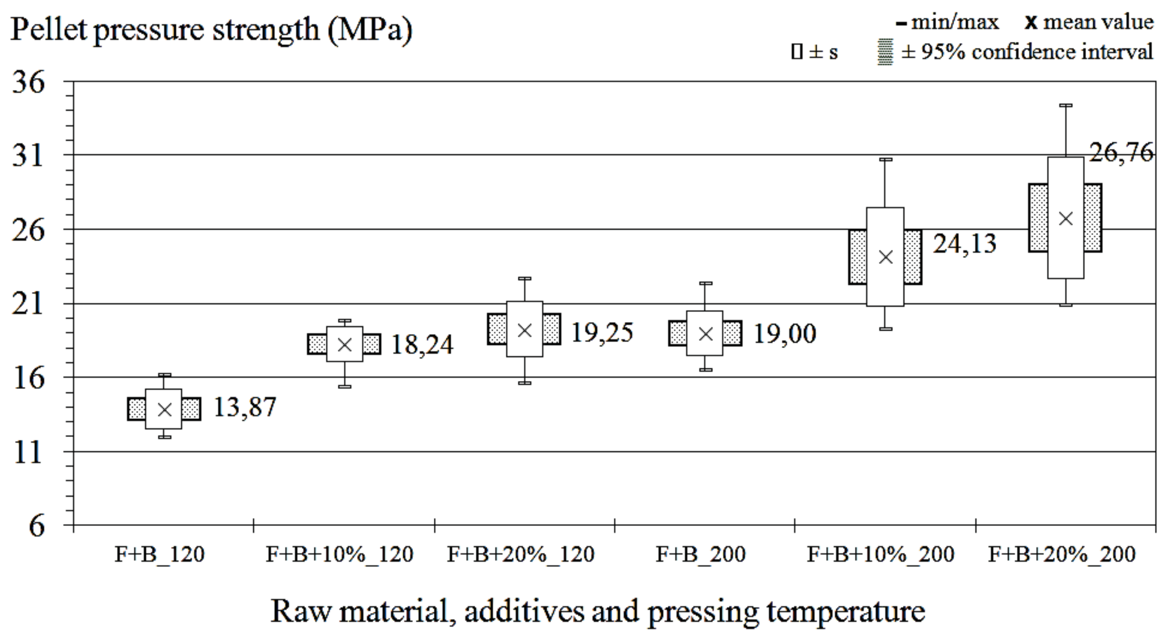

Figure 9: Compressive strength of pellets pressed at 120 °C and 200 °C

Table 5 shows the influence of the raw material on the compressive strength of the pellets in the radial direction. The table shows statistically significant increase in compressive strength of pellets by adding 10 and 20% of rotten wood to the raw material, while the difference between adding 10 and 20% of rotten wood is not significant at both pressing temperatures.

Table 5: Influence of raw material on compressive strength

Influence of raw material on compressive strength			
Comparison	**F+B – F+B+10%_120**	**F+B – F+B+20%_120**	**F+B+10% – F+B+20%_120**
t-value	9,541	9,140	1,768
p-value	0,00	0,00	9,88
Comparison	**F+B – F+B+10%_200**	**F+B – F+B+20%_200**	**F+B+10% – F+B+20%_200**
t-value	5,506	6,885	1,936
p-value	0,01	0,00	7,33

Table 6 shows the influence of the pressing temperature on the compressive strength of the pellets in the radial direction, where statistically significant difference is seen for all three mixtures by increasing the pressing temperature from 120 to 200 ° C.

Table 6: Influence of pressing temperature on compressive strength

Influence of pressing temperature on compressive strength			
Comparison	**F+B_120 – F+B_200**	**F+B+10%_120 – F+B+10%_200**	**F+B+20%_120 – F+B+20%_200**
t-value	9,980	6,516	6,453
p-value	0,00	0,00	0,00

CONCLUSIONS

- After conditioning of raw wood samples degraded with brown rot fungi the moisture content was 1% less than by healthy wood samples. Possible reason for this was the dusty granulation and the formation of a layer of material on surface which did not allow the penetration of moisture to the lower layer in the conditioning vessel.
- The ash content of the degraded beech wood sample found in the nature was very high and was 2.09%, while the ash content of the pine wood attacked by the *Poria placenta* fungi was 0.77%. Mixing of these two samples resulted in a mixture of raw material with 1.16% of ash content. Addition of this mixture to fir and beech wood raw material did not increase the total ash content. The ash content was within 0.5%, which was satisfactory for commercial wood pellet production.
- Calorific value of the pine wood degraded with *Poria placenta* fungi was very high and amounted 23.57 kJ/g as a result of degradation of cellulose and hemicellulose and high mass share of lignin. There is also a noticeable increase in the calorific value of beech wood degraded by brown rot fungi which was taken from nature (20.14 kJ/g) in comparison to the calorific value of healthy beech wood (19.51 kJ/g). Some part of the pine and beech wood material in the process of the degradation disappeared and thus the total amount of energy contained in the wood of pine and beech decreased.
- Pellet density produced from mixture with 10% of rotten wood, pressed at 120 °C increased by 2.4%. By adding 20% of rotten wood to mixture, density increased by 1.01%. Pellet density pressed at 200 °C by adding 10 and 20% of rotten wood remained at almost the same level. The results can be explained by the fact that at 200 °C wood material components change the aggregate state and begin to degrade so the ability to compress all mixtures is equal.
- With the addition of 10% rotten wood to mixture of fir and beech the compressive strength of pellets pressed at 120 °C increased by 31.5% in relation to the basic raw material. With the addition of 20% of rotten wood the compressive strength of pellets increased by 38.8%. The compressive strength of fir and beech pellets with 20% of rotten wood pressed at 120 °C is equivalent to the strength of pellets without the addition of rotten wood pressed at 200 °C. With the addition of 10% of rotten wood, the strength of pellets pressed at 200 °C increased by 27%. With the addition of 20% of rotten wood to the basic material the increase of strength was almost 41%.

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