SYLWAN 168 (5): 328-340, May 2024
https://doi.org/10.26202/sylwan.2023105
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

Assessment of selected physical, mechanical and calorific properties of post-consumer spruce *Picea abies* (L.) H. Karst wood – a case study

Monika B. Gach[(1)]✉, Arkadiusz Gendek[(2)], Monika Aniszewska[(2)], Barbora Tamelová[(3)], Jan Malaťák[(3)], Krzysztof Michalec[(1)], Bartłomiej Bednarz[(4)], Radosław Wąsik[(1)], Łukasz Mateusiak[(1)]

[(1)] Department of Forest Utilization and Forestry Technology, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland

[(2)] Department of Biosystems Engineering, Institute of Mechanical Engineering, Warsaw University of Life Sciences, Nowoursynowska 164, 02-787 Warsaw, Poland

[(3)] Department of Technological Equipments of Buildings, Faculty of Engineering, Czech University of Life Sciences Prague, Kamycka 129, 165 21 Prague 6, Czech Republic

[(4)] Department of Forest Ecosystems Protection, University of Agriculture in Krakow, Al. 29 Listopada 46, 31-425 Kraków, Poland

ABSTRACT

The article presents the characteristics of the physical, mechanical, and calorific properties as well as the elemental composition of post-consumer wood. The study was applied to approximately 100-year-old spruce *Picea abies* waste from the conservation of the roof truss at the Parish Church in Gilowice and building structures from the Open-Air Museum in Ślemień. Studies were carried out to determine the possibility of safely use of the discussed post-consumer timber waste. Based on applicable standards, wood density, compressive and static bending strength of wood, elemental composition and calorific properties were determined. The tested wood presented a density approximately 7% lower compared to fresh wood, and it exhibited lower resistance to bending and compressive stress, whereas its lignin (xylogen) content tested over 30% higher. The calorific value was on average 18.79 MJ·kg^{-1}, and the ash content did not exceed 1%. The tested wood samples meet the standards of construction wood ISO PN-EN 338:2016-06 class C40.

KEY WORDS

calorific value, chemical composition of wood, compressive and bending stress, timber waste, wooden beams

Introduction

Wood is considered a 'perfect' material from a functional, aesthetic, and environmental point of view. For this reason, the demand for wood raw materials is constantly growing. Currently, there is a significant trend – especially prominent in the furniture industry on the European market – to obtain raw materials for the production from recycling (Danecki, 2007; Kunikowski *et al*., 2008; Strykowski, 2012). Post-consumer wood is a valuable raw material that is available in large

✉e-mail: monika.gach@urk.edu.pl

Received: 28 November 2023; Revised: 9 May 2024; Accepted: 23 May 2024; Available online: 5 July 2024

quantities and, depending on its quality, it is either suitable for reuse or otherwise it can be expended as fuel (Kürsten and Militz, 2004; Szostak *et al*., 2004; Hirashima *et al*., 2005; Mahút *et al*., 2007). In Europe, approximately 70 million Mg of post-consumer wood waste is generated annually, and according to Eurostat, in 2014 EU countries alone produced 50 million Mg (Mahút *et al*., 2007; Castillo *et al*., 2011; Ratajczak, 2013; Pietras, 2017). Post-consumer wood waste constitutes the most diverse group of wood intended for reuse. Wood that has not been contaminated with various types of protective agents, *i.e.* pieced wood in the form of boards or rafters, chips, shavings and sawdust, can be reused for the production of wood-based boards, wood composites as well as fuel in the form of pellets or fuel briquettes. The amount of wood waste generated in individual European countries is not precisely known (Braniewski, 1993; Baldwin, 1995; Szubel and Dernbecher, 2017). There is also a lack of detailed data on the sources of this kind of waste (Oniśko *et al*., 1998; Igliński *et al*., 2009; Nadziakiewicz *et al*., 2012). Difficulties in accurately estimating the amount of wood waste in Europe springs from the deficiency of rational legal solutions and from the lack of a uniform system for classifying wood waste. In the case of Poland, a significant problem in determining the amount of waste stems from the fact that companies generating up to 10 Mg of waste from wood, shavings, sawdust, bark, veneer waste or chipboard waste per annum are exempt from the requirement to keep records of such waste (Danecki and Paluchiewicz, 2009; Castillo *et al*., 2011; Poletto *et al*., 2012; Sonderegger *et al*., 2015). A frequently analysed issue in the context of wood waste is the type, chemical composition and degree of contamination depending on the place of its origin (Szostak and Ratajczak, 2003; Merl *et al*., 2007; Cichy, 2010; Piątkowski, 2010) and on the technological parameters of the production process. Waste generated in specific production sectors is usually characterized by similar forms and chemical and mechanical properties (Dobrowolska and Matejak, 1999; Petersen and Solberg, 2003; Brzęcki *et al*., 2018). Estimation of the potential database of existing wood waste, including post-consumer wood, taking into account its form and place of concentration, would be justified from the point of view of waste management, and would be vital in terms of logistics and economics of this activity (Danecki and Jakiełek, 2003; Cichy and Prądzyński, 2007; Okstad, 2007; Poletto *et al*., 2012). When we analyse the wood market, we observe that the largest amounts of waste contaminated with adhesives, and/or with strengthening and impregnating preparations, are generated by the furniture industry, as well as chipboard and fibreboard (MDF, LDF, HDF) industries (Dewitz *et al*., 2007; Oleniacz *et al*., 2014; Kajda-Szcześniak, 2015; Krukowska, 2015). Spruce *Picea abies* (L.) H. Karst. wood, second only to pine *Pinus sylvestris* L. wood, is the main material used in construction in Europe. Many wooden buildings from past eras were protected with simple products based on wood tar, vegetable oils and lime (Deppe and Ernst, 1996; Irle, 2010). A significant part of the old wood, largely coming from buildings, was protected with simple means, mainly using lime and burnt oil. In the Beskid Mountains (in southern Poland), vegetable oil predominated in safeguarding wooden objects, later followed by spent engine oil. Due to the fact that engine oil contains carcinogenic compounds, wood obtained during renovation works or demolition of buildings where that agent was used is designated for disposal (Mathot, 1994; Asikainem *et al*., 2002; Onusseit, 2006). The amount of impregnated post-consumer wood in Poland adds up to approximately 3.1 million Mg per annum, half of which comes from construction (Galewski and Korzeniowski, 1958; Surmiński, 2000; Al-Salem *et al*., 2009). According to the German classification, wood impregnated with burnt oil belongs to class A IV wood waste, and special boilers with a power of 1 to 50 MW should be used for its combustion (Ratajczak *et al*., 2003; Onusseit, 2006; Pudełko, 2013; Yapici *et al*., 2015). In recent years, in Europe, there has been a clear trend of moving and reconstructing old or historic wood-

en objects, especially those made of logs. During the reconstruction work, it is important to properly assess the technical condition of the building, including the possibility of reassembling the structure, or reusing the wood from which it is made. If there are any doubts regarding the condition of the raw material, the latter is subjected to assessment, and technical tests are carried out to check the compliance of its mechanical properties with the standards for construction wood. Defective wood is disposed of. In order to rationally use post-consumer wood, it is necessary to carry out a number of analyses confirming the changes that have occurred within it over time, and determining the possibility of reusing the obtained raw material (Krzysik, 1974; Kunikowski *et al*., 2008). During the use and also during the storage of wood, a number of changes occur over time, caused by natural factors and resulting from the previous use of that wood as a material. The most important factors causing the depreciation of the raw material include: biological factors, including the infestation with insect and fungal pests; physical factors, including swelling and shrinkage of wood; the effects of ultraviolet radiation; and the impact of chemical factors. Wood durability is the material's resistance to destructive factors. The durability of wood may vary significantly depending on the species, the form of wood, and the part of the tree from which the material was obtained (sapwood, heartwood, top, butt). Age also affects the natural durability of wood. The highest durability is found in heartwood harvested at the age of physical maturity of the tree, *i.e.* at 100-140 years (Jambeck *et al*., 2007; Asikainen *et al*., 2008; Krajewski and Witomski, 2016). Currently, the wood production cycle is significantly shortened, which affects the quality of the raw material. In this study, the aim was to assess the potential reuse of salvaged timber from old timber buildings, taking into account their positive impact on the environment and the possibilities for further economically viable processing in various industries. The publication presents research undertaken with the aim to determine the physical and mechanical properties of spruce *P. abies* wood from wooden buildings subjected to conservation treatments. The purpose of this study was to examine the properties of spruce wood harvested from old buildings and compare it with fresh spruce wood to illustrate the changes that occur in wood, when it is exposed to varying conditions over time. Additionally, an attempt was made to indicate whether the wood could be used for further construction works after approximately 100 years. The elemental composition and calorific value of such wood were also determined – in cases where it was ascertained that such wood needed to be disposed of by burning.

Research methodology

Origin and designation of research material. In our research we have used approximately 100-year-old spruce *P. abies* wood obtained during the conservation works of the church in Gilowice (GPS: 49°42'46.3"N, 19°18'25.2"E), and from the buildings of the open-air museum Etnopark Ziemia Żywiec (GPS: 49°72'31.7"N, 19°38'11.2"E). During the use of the two aforementioned buildings, the wood was protected with burnt oil – against changing climatic conditions and wood-decomposing fungi, including mould. The oil was applied using the brush lubrication method, which involves spreading the impregnation on the surface of the object one wishes to protect. In accordance with the PN EN-335:2013 standard regarding the permissible method of impregnation, the wood is categorized as class II – as timber used under a roof, exposed to moisture. For the obtained research material (Fig. 1), based on available historical documents, the approximate year of wood harvesting and its impregnation was determined. Wood collected for testing from the church and the open-air museum was divided into four groups according to its respective origins, and the groups were given code names: 01-K – wood from the church, year of origin approx. 1933; 02-K – wood from the church, year of origin

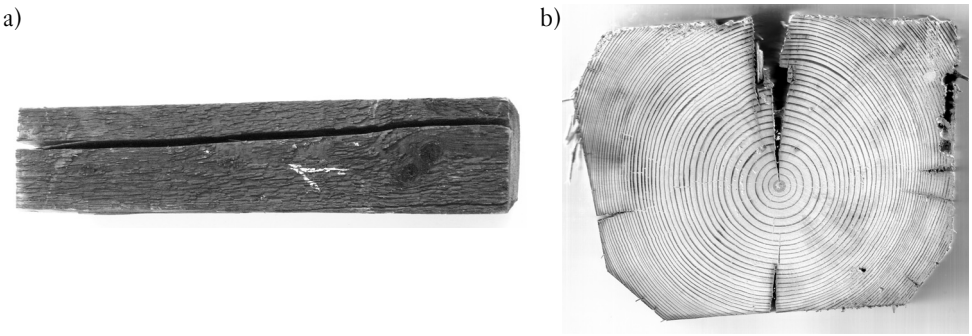

Fig. 1.
Sample view of a single wooden beam obtained for testing
a – general view, b – cross-section

approx. 1895; 03-SK – wood from the open-air museum, year of origin approx. 1920; and 04-SK – wood from the open-air museum, year of origin approx. 1910.

From each location, 10 spruce beams with dimensions of 0.3×0.3×1.0 m were taken for testing from different parts of the building, and test samples were made from these fragments.

Determination of moisture, density and shrinkage of wood. For all groups, 40 cuboid samples with cross-sectional dimensions of 20×20 mm and length along the fibres of 25 mm were made from each wooden beam. Before placing the samples in the dryer, the external dimensions (length, width, height) were measured with an AOS ABSOLUTE Digimatic Standard 150 mm electronic calliper (MITUTOYO Corp., Kawasaki, Japan) with accuracy down to ±0.1 mm. Weight was determined using a Mettler Toledo Excellence analytical balance (Mettler Toledo, Columbus, Ohio, USA) with accuracy down to ±0.01 g. Re-measurement of the external dimensions and weight of the samples, needed to determine moisture content, dry density and wood shrinkage, was performed after the drying process. The moisture content (MC) of wood samples was determined by the gravimetric (drying and weighing) method in accordance with the ISO 18134-3:2015 standard. The test involved drying wood samples at a temperature of 103 ±2°C for a minimum of 24 hours to obtain constant weight. A Heraus UT 6120 laboratory dryer (Kendro Laboratory Products GmbH, Hanau, Germany) was used. The dry density of wood (ń_dry) was calculated according to the PN-EN 384:2010 standard based on the weight and external dimensions after drying. Wood shrinkage as a change in linear dimensions in the radial (Kr), longitudinal (Kl) and tangential (Kt) directions was determined according to the PN-EN 408:2010 standard based on the external dimensions of the samples before and after drying.

TGA analysis, elemental composition, heat of combustion and calorific value. TGA analysis (thermogravimetric analysis) was performed on the TGA/DSC3 device (Mettler Toledo, Columbus, Ohio, USA city) at the Central Mining Institute (GIG) in Katowice, Poland. The pertinent measurement procedure was described, among others, by Zawadzki (2013), Tyutkowa *et al.* (2017), and Işleyen and Kesik *et al.* (2021). The temperature inside the device was raised during 1 hour, every 1°C, from room temperature of approx. 22°C up to 600 ±1°C. Based on the data obtained, the combustion values of hemicellulose, cellulose and lignin were determined and recorded, after which the percentages of these compounds were calculated. For all samples, proximate and elemental compositions were determined, and so were respective calorific values. Moisture and ash contents were determined in LECO TGA701 thermogravimetric analyser

(LECO Corporation, USA) at 105°C and 550°C respectively (Piętka *et al*., 2019; Tamelová *et al*., 2022; Gendek *et al*., 2023; Malaťák *et al*., 2023). Carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) contents were measured using a LECO CHN628 + S analyser (LECO Corporation, USA) by combustion analysis. LECO flour standards were used for calibration of the instrument. Oxygen (O) content was calculated as a difference. Results of the analysis were converted to dry state data according to ISO 16993:2015. LECO AC600 bomb calorimeter (LECO Corporation, USA) was used for the determination of higher heating value (HHV). The lower heating value (LHV) was obtained by conversion according to ISO 1928: 2009. A detailed measurement procedure has been described in the publication by Piętka *et al*. (2019) and Tamelová *et al*. (2022).

Determination of the strength of wood against static bending and compression. Wood samples were prepared in accordance with the ISO 3129: 2019 standard. From the collected test material, 40 samples were prepared for each group with a cross-section of 20×20×300 mm, to determine the static bending strength of wood (flexural strength), and samples with the dimensions of 20×20×30 mm, to determine the strength of wood against compression (compressive strength). The external dimensions were measured using an Aos Absolute Digimatic Standard electronic calliper with an accuracy down to ±0.1 mm. The static bending strength (flexural strength) was determined in accordance with ISO 13061-3: 2014 standard, and the compressive strength, in accordance with ISO 13061-17:2017 standard. The research procedures and mathematical formulas have been described, among others, by Fataraitë-Urbonienë *et al*. (2019), Ozkan, Hirashima *et al*. (2021) and Işleyen and Kesik (2021). A Shimadzu testing machine model AG-XV (Shimadzu, Tokyo, Japan) was used for the tests. During the measurements, the control software recorded the force during the bending (Fg) and compression (Fc) of the sample with accuracy down to ±0.1N, and the displacement with accuracy down to ±0.01 mm. The test speed was set so that the failure of the sample in static bending and compression occurred within 90 ±30 seconds from the start of the load. Based on the recorded data, the software determined the maximum bending stresses (?g), the maximum compressive stresses (?c), and the modulus of elasticity in bending (?g) and compression (?c). Mechanical analysis of wood was performed on samples with analytical humidity (approx. 5%), and then, in accordance with the PN EN ISO 04227:1977 standard, the results were converted to 12% humidity.

Statistical analyses. Statistical processing of the results was performed using Statistica 13.3 software (TIBCO, 2017). In order to determine differences between mean values, and to detect homogeneous subsets, analysis of variance (ANOVA) tests and *post-hoc* tests for multiple comparisons were performed at the confidence level of α=0.05.

Results

Humidity, density and shrinkage of wood. The results for humidity, dry density of the material, and wood shrinkage in three directions are summarized in Table 1. The initial humidity of the samples used for testing ranged from 4.9 to 5.3%. The dry density of the tested wood ranged from 372.1 to 421.6 kg·m^{-3}, while the shrinkage, depending on the direction, ranged from 3.30 to 11.42%. The analysed wood waste is characterized by much higher longitudinal shrinkage compared to fresh wood – see the results presented in Table 1.

The obtained results of the TGA analysis are presented in Table 2. The hemicellulose content in the tested samples ranged from 5.2% for the 02-K group, to 11% for the 03-SK group. The percentage share of cellulose ranged from 48.6% for 03-SK, to 57.2% for 04-SK. The lignin

content ranged from 31.52% for 01-K, to 33.75% for 03-SK. A higher amount of other ingredients was also noticed, from 4.6% for 04-SK, to 7.04% for 02-K, while for spruce wood, according to the data published in subject literature, this value is estimated at 4%.

The results of the elemental composition, ash content, heat of combustion, and calorific value of wood are presented in Table 3. The ash content for the tested samples ranged from 0.42 to 1.01%; it was the lowest in the sample of 03-SK, and the highest in the sample of 04-SK. The carbon content ranged from 50.63% for 02-K, to 51.22% for 04-SK. Hydrogen occurred in amounts ranging from 5.95% for 02-K, to 6.02% for 01-K. The nitrogen content in the samples was much higher than in spruce wood from the literature data and amounted to an average of 0.21%, whereas sulphur content was less than 0.02% in all samples (the sulphur content for all

Table 1.

Test results or sample moisture, dry wood density, and material shrinkage in the tangential, radial and longitudinal direction

Material	MC [%]	ρ_{dry} [kg·m^{-3}]	K_t [%]	K_r [%]	K_l [%]
Spruce timber (Galewski and Korzeniowski, 1958)	–	300-640	7.70-7.90	3.50-3.70	0.20-0.40
01-K	5.31 (±0.03)	398.7 (±0.02)	9.45 (±0.02)	7.20 (±0.03)	3.30 (±0.05)
02-K	5.12 (±0.02)	403.9 (±0.04)	11.42 (±0.03)	7.15 (±0.04)	4.60 (±0.04)
03-SK	4.97 (±0.03)	421.6 (±0.02)	10.30 (±0.02)	7.49 (±0.04)	5.11 (±0.02)
04-SK	5.30 (±0.03)	372.1 (±0.02)	10.12 (±0.01)	8.28 (±0.01)	5.78 (±0.01)

Table 2.

TGA analysis of wood waste in %

Material	Hemicellulose	Cellulose	Lignin	Other
Spruce timber – published data	11.00-11.7	53.1-57.00	25.2-28.00	4.00-7.7
01-K	8.37	53.75	31.52	6.36
02-K	5.20	54.31	33.45	7.04
03-SK	11.00	48.60	33.75	6.65
04-SK	5.75	57.20	32.45	4.60

Table 3.

Results of elemental analysis of a series of dry post-consumer wood samples

Material	Ash_{dry} [%]	C_{dry} [%]	H_{dry} [%]	N_{dry} [%]	S_{dry}* [%]	O_{dry}** [%]	$Q_{vad\ dry}$ MJ·kg^{-1}	$Q_{net\ dry}$** MJ·kg^{-1}
Spruce timber – published data	0.71--0.77	49.81--50.81	6.0--6.4	0,04 (±0.16)	<0.02	42.3--43.0	20.50	18.31--19.20
01-K	0.75a (±0.05)	50.73a,b (±0.17)	6.02a (±0.03)	0.20a (±0.03)	<0.02	42.30	20.13a (±0.08)	18.82
02-K	0.88b,c (±0.13)	50.63a,b (±0.44)	5.95b (±0.06)	0.22a (±0.03)	<0.02	42.32	20.10a (±0.08)	18.81
03-SK	0.42d (±0.04)	50.96a,c (±0.12)	5.99a,b (±0.02)	0.19a (±0.04)	<0.02	42.44	20.06a (±0.09)	18.75
04-SK	1.01c (±0.07)	51.22c (±0.16)	5.98a,b (±0.01)	0.21a (±0.03)	<0.02	41.57	20.08a (±0.03)	18.78

Note: *Values below measurement error, omitted from calculations; **Values calculated; a,b,c,d - identical letters next to the values indicate homogeneous subsets of mean values, with the differences significant for $p \leq 0.05$

samples was below the calibration range, *i.e.* 0.02% wt) , and oxygen content was estimated at an average of 42.3%; it was the lowest for the 04-SK sample – 41.57%, and the highest for the 03-SK sample – 42.44%.

The value of the heat of combustion in all tested groups was above 20 $MJ \cdot kg^{-1}$, and the calculated calorific value was on average 18.79 $MJ \cdot kg^{-1}$. According to the literature, spruce wood has a slightly lower calorific value (Iglinski *et al*., 2009). Even though the ANOVA analysis indicated statistically significant differences between the average content of specific elements (carbon and hydrogen) as well as ash content, the measured values of the heat of combustion did not differ statistically significantly between the materials of different origin, and were classified into one homogeneous subset.

The results of the maximum stresses in static bending and compression of wood and the elastic moduli are given in Table 4. The calculated óg mean values range from 42.01 MPa to 65.50 MPa, and the óc mean values range from 35.47 MPa to 41.99 MPa. Based on the ANOVA analysis, it can be concluded that the 04-SK material showed the highest resistance to bending, and that it differed significantly from the other three materials that form one homogeneous subset. In the case of óc, wood marked 01-K and 02-K showed similar resistance to compression, and after the ANOVA analysis it was classified into one homogeneous subset (p>0.05). In turn, the material from the 03-SK and 04-SK groups was characterized by slightly greater compressive resistance; therefore, together with the 02-K wood, it belonged to the second homogeneous subset (p>0.05). The flexural modulus (Íg) ranged from 4.94 GPa for 01-K, to 7.89 GPa for 04-SK, with variations of 0.35 and 0.16, respectively. The ANOVA analysis demonstrated the existence of two homogeneous subsets, the first being wood from the church elements, and the second coming from the open-air museum. Wood from groups 01-K and 02-K has lower elasticity than wood from groups 03-SK and 04-SK. The compressive elastic modulus (Íc) ranged from 1.02 GPa to 1.30 GPa. The coefficient of variation for this parameter ranged from 0.26 to 0.46. ANOVA analysis demonstrated that the mean values do not differ significantly, and that they belong to one homogeneous subset (p>0.05).

Discussion

Timber elements, when exposed to weather conditions, and moisture in particular, tend to depreciate (biodegrade). This phenomenon is common in temperate climate zones. In Poland, the most common factors of wood degradation include fungal pathogens, insect infestation, and fire. Properly protected wood, not exposed to weather conditions, remains durable, and can last for hundreds or even thousands of years (Galewski and Korzeniowski, 1958). Fungi produce cellulolytic enzymes, which decompose light cellulose and hemicellulose. Dark (brown) lignin remains in the wood; in the final phase of brown decomposition, timber loses its mechanical properties, cracks into prismatic cubes, and falls apart. Wood with signs of depreciation due to partial or complete destruction of hemicellulose, cellulose and lignin may have significantly lower calorific value than healthy

Table 4.

Stress results as well as flexural and compressive elastic modulus of post-consumer spruce wood

Material	$\int_g$ [MPa]	$\sum_g$ [GPa]	$\int_c$ [MPa]	$\sum_c$ [GPa]
01-K	42.01a (±14.64)	4.94a (±1.72)	35.47a (±3.55)	1.02a (±0.35)
02-K	47.45a (±11.22)	5.47a (±1.17)	39.10a, b (±3.54)	1.21a (±0.31)
03-SK	50.66a (±23.03)	7.11b (±1.63)	41.57b (±8.59)	1.30a (±0.41)
04-SK	65.50b (±11.17)	7.89b (±1.30)	41.99b (±6.17)	1.07a (±0.49)

Note: a, b – homogenous subsets for $p \leq 0.05$

wood (Czarnowska and Stasiak, 1984; Krukowska, 2016; Işleyen and Kesik, 2021). The elemental composition is the basic characteristic of fuel suitability of the tested materials. Based on elementary tests, it is possible to calculate the approximate calorific value and the amount of waste after combustion, including ash and volatile ingredients (Liu *et al*., 2005; Hillring *et al*., 2007; Jambeck *et al*., 2007; Tyutkova *et al*., 2017). Considerable variation in physical and mechanical properties within species, which may be further compounded by some possible aging effects, is an important obstacle to determining the weight of particular changes in wood depreciation. Uncontrolled decomposition of used wood contributes to carbon dioxide and methane emissions (Poletto *et al*., 2012; Yapici *et al*., 2015; Krukowska, 2016). And yet, post-consumer wood waste from old buildings can be an important resource for use in the production of bioenergy or biofuels. In order to better understand the processes of reducing the utility value of post-consumer wood and its reuse, more research is necessary (Galewski and Korzeniowski, 1958; Irle, 2010). The calculated dry density of the tested groups of spruce wood after approximately 100 years of use fell within the range of 372-421 kg·m^{-3}. These values were 2-14% lower than the density reported in the subject literature (approx. 430 kg·m^{-3}) (Greszta and Panek, 1989; Liu *et al*., 2005; Jambeck *et al*., 2007; Cavalli *et al*., 2016) for wood that had not yet been used. The calorific value of cellulose is on average from 17.3 to 18.2 MJ·kg^{-1}, while the calorific value of lignin is approximately 25.5 MJ·kg^{-1}. The resin has a calorific value ranging from 35.5 to 38.1 MJ·kg^{-1}, which means that the presence of resin significantly increases the calorific value of wood (Greszta and Panek, 1989; Jambeck *et al*., 2007; Cavalli *et al*., 2016). Comparing the results obtained from the analysis of spruce waste from the church and from the open-air museum, it can be concluded that the analysed waste was characterised by a decrease in the percentage share of hemicellulose and cellulose, and an increase in the share of lignin and other components, which include, among others, ash, resins and impurities nevertheless, the initial (past) properties of the studied material are unknown, so it is difficult to compare them with the actual (present) properties (Czarnowska and Stasiak, 1984; Greszta and Panek, 1989; Cavalli *et al*., 2016). The observed phenomenon most probably results, to a large extent, from the progressive decomposition of wood in the tested samples by fungi and the introduction of pollutants, for instance, by the wind. Analysis of the content of individual chemical compounds showed relatively minor differences in the tested samples. In terms of calorific considerations, a relatively high share of carbon over 50%, is beneficial. Another advantageous phenomenon is the low ash content in the tested wood. Literature data (Greszta and Panek, 1989; Taylor *et al*., 2009; Tum *et al*., 2011; Krukowska, 2016) confirm that the waste has a calorific value similar to that of pure spruce wood, amounting to 18.8 MJ·kg^{-1} dry weight of waste. Taking into account only the tested technical parameters, we can conclude that the tested waste is suitable for use in thermal processes. However, because the wood had been protected with burnt oil, its combustion may result in increased emissions of toxic substances (combustion gases). Due to the above, this kind of waste should be burned in facilities adapted for this purpose, equipped with combustion gas treatment installations, so that the process does not pose a threat to the environment (Dobrowolska and Matejak, 1999; Kürsten and Militz, 2004; Nadziakiewicz *et al*., 2012). Healthy spruce wood has an average longitudinal compressive strength of approximately 54.4 MPa (Greszta and Panek, 1989; Liu *et al*., 2005; Jambeck *et al*., 2007) and static bending strength of 67.7 MPa (Greszta and Panek, 1989; Liu *et al*., 2005; Jambeck *et al*., 2007; Krukowska, 2016; Wasilewski and Stelmach, 2014; Cavalli *et al*., 2016). All the samples we analysed show both parameters below the values specified in the ISO PN-EN 338:2016-06 standard. The obtained results indicate a reduction in the construction usefulness of the tested raw material, and at the same time, better properties and better suitability for grinding for the production of energy components. Taking into account the tested

mechanical properties and the relatively low moisture as well as the increased lignin content compared to freshly harvested spruce wood, it can be concluded that the tested wood waste is suitable for energy use and can be deployed as fuel, either in unprocessed form, or after processing into chips, briquettes, or pellets (Patersen and Solberg, 2003; Hirashima *et al*., 2005; Wasilewski and Stelmach, 2014; Krukowska, 2015).

Conclusions

Our analysis showed that, the strength parameters of the timber meet the standards for structural timber described in ISO EN 338:2016-06 for bending, depending on the sample, for grade C40 and above, and meet the standards for compression for all grades. In summary, such timber can be successfully reused for construction purposes. Despite the passage of time, the dry density of the tested material remained between 372 and 421 $kg \cdot m^{-3}$, which corresponds to the characteristic density of coniferous structural timber in strength classes C14-C40. The spruce wood waste tested also has, good fuel properties, similar to those of woody biomass, and that it is suitable for use as fuel in thermal processes. The waste is characterised by low ash content, increased carbon content and a good calorific value of 18.8 $MJ \cdot kg^{-1}$.

Authors' contributions

M.B.G. – conceptualization, methodology, formal analysis, material collection, statistical analyses, investigation, preparation of material for analysis, writing – original draft preparation; A.G. – statistical analyses, formal analysis, conceptualization, methodology, writing-original draft preparation; M.A. – statistical analyses, formal analysis, conceptualization, methodology, writing-original draft preparation; B.T. – elemental analyses, conceptualization, methodology, manuscript review and editing; J.M. – elemental analyses, conceptualization, methodology, manuscript review and editing; K.M. – conceptualization, methodology, material collection, manuscript review and editing; B.B. – conceptualization, methodology, material collection, manuscript review and editing; R.W. – conceptualization, methodology, manuscript review and editing; Ł.M. – preparation of material for analysis, strength analyses of wood.

Conflict of interest

The authors declare no conflict of interest.

Funding source

This Research was financed by the Ministry of Science and Higher Education of the Republic of Poland.

References

Al-Salem, S.M., Lettieri, P., Baeyens, J., 2009. Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Management*, 29 (10): 2625-2643. DOI: https://doi.org/10.1016/j.wasman.2009.06.004.

Asikainen, A., Liiri, H., Peltola, S., Karajalainen, T., Laitila, J., 2008. Forest Energy Potential in Europe (EU-27). Available from: http://www.metla.fi/julkaisut/workingpapers/2008/mwp069.htm [accessed: 07.07.2023].

Baldwin, R.F., 1995. Plywood and veneer-based products: manufacturing practices. San Francisco: Miller Freeman Books, 388 pp.

Braniewski, S., 1993. Zawartość metali ciężkich w drewnie sosny (*Pinus sylvestris* L.) i buka (*Fagus sylvatica* L.) w Ojcowskim Parku Narodowym. [Content of heavy metals in wood of pine (*Pinus sylvestris* L.) and beech (*Fagus sylvatica* L.) in the Ojcow National Park]. *Prądnik. Prace i Materiały Muzeum im. prof. W. Szafera*, 7-8: 161-193.

Castillo, A., Panoutsou, C., Bauen, A., 2011. Report on biomass market segments within the transport, heat and electricity – CHP sectors for EU-27 and Member States. Available from: www.biomassfutures.eu/work_packages/WP2 Demand [accessed: 07.07.2023].

Cavalli, A., Cibecchini, D., Togni, M., Sousa, S.H., 2016. A review on the mechanical properties of aged wood and salvaged timber. *Construction and Building Materials*, 114: 681-687. DOI: https://doi.org//10.1016/j.conbuildmat.2016.04.001.

Cichy, W., 2010. Odpady drzewne – problem z klasyfikacją. Seminarium naukowe „Ochrona środowiska – nowoczesne technologie w drzewnictwie". Poznań.

Cichy, W., Prądzyński, W., 2007. The influence of the degree of contamination of wood waste with urea-formaldehyde resins on the emission of gaseous combustion products during burning in low-power boiler. In: Proceedings of the 3rd European COST E31 Conference – Management of Recovered Wood, 2-4 May 2007. Klagenfurt, Austria, pp. 173-184.

Czarnowska, K., Stasiak, J., 1984. Zawartość składników mineralnych w igłach, drewnie i korze sosny zwyczajnej (*Pinus sylvestris* L.) w zależności od wieku drzew. Reakcje biologiczne drzew na zanieczyszczenia przemysłowe. II Krajowe Sympozjum, 16-19 maja 1984, Kórnik. Poznań: Wydawnictwo Naukowe Uniwersytetu im. A. Mickiewicza w Poznaniu, pp. 183-188.

Danecki, L., Jekiełek, M., 2003. Ocena przydatności drewna poużytkowego do wtórnego przerobu w porównaniu ze stanem i osiągnięciami zagranicznymi. Opracowanie Ośrodka Badawczo-Rozwojowego Przemysłu Płyt Drewnopochodnych w Czarnej Wodzie, nr 420.1532.1.03.

Danecki, L., 2007. Potencjał recyklingowy zużytych mebli. *Recykling*, 81 (9): 26-27.

Danecki, L., Paluchiewicz, Z., 2009. Opracowanie danych dotyczących ilości drewna poużytkowego z opakowań, palet i płyt o budowie włóknistej. Ośrodek Badawczo-Rozwojowy Przemysłu Płyt Drewnopochodnych w Czarnej Wodzie.

Deppe, H.J., Ernst, K., 1996. MDF – Mitteldichte Faserplatten. Leinfelden-Echterdingen: DRW – Verlag Weinbrenner GmbH & Co., 200 pp.

Dewitz, K.D., Kielczewski, R., Wegner, R., Friedle, A., 2007. Ocena emisji z materiałów budowlanych, przeprowadzone badania i wyniki badań dla tworzyw drzewnych. Szkolenie „Drewno a materiały drewnopochodne", 25-26 października 2007. Tleń, pp. 1-11.

Dobrowolska, E., Matejak, M., 1999. Propozycja kwalifikacji drewna poużytkowego w Polsce. *Przemysł Drzewny*, 1: 14-20.

Galewski, W., Korzeniowski, A., 1958. Atlas najważniejszych gatunków drewna. Warszawa: Państwowe Wydawnictwo Rolnicze i Leśne, 255 pp.

Gendek, A., Piętka, J., Aniszewska, M., Malaták, J., Velebil, J., Tamelová, B., Krilek, J., Moskalik, T., 2023. Energy value of silver fir (*Abies alba*) and Norway spruce (*Picea abies*) wood depending on the degree of its decomposition by selected fungal species. *Renewable Energy*, 215: 118948. DOI: https://doi.org/10.1016/j.renene.2023.118948.

Greszta, J., Panek, E., 1989. Wpływ metali ciężkich na drzewa. In: S. Białobok, ed. *Życie drzew w skażonym środowisku*. Warszawa-Poznań: Dom Wydawniczy PWN, pp. 195-222.

Hillring, B., Canals, G., Olsson, O., 2007. Market for recovered wood in Europe – an overview. Proceedings of the 3rd European COST E31 Conference – Management of Recovered Wood, 2-4 May 2007. Klagenfurt, Austria, pp. 201-213. DOI: https://doi.org/10.1108/17506221211216553.

Hirashima, Y., Sugihara, M., Sasaki, Y., Kosei, A., Yamasaki, M., 2005. Strength properties of aged wood III: Static and impact bending strength properties of aged keyaki and akamatsu woods. *Mokuzai Gakkaishi*, 51: 146-152. DOI: https://doi.org/10.2488/jwrs.51.146.

Igliński, B., Buczkowski, R., Cichosz, M., 2009. Technologie bioenergetyczne. Toruń: Wydawnictwo Naukowe Uniwersytetu Mikołaja Kopernika, 316 pp.

Irle, M.A., 2010. The cleanliness of recovered wood. W: R.M. Rowell, F. Caldeira, J.K. Rowell, ed. *Sustainable development in the forest products industry*. Porto: Universidade Fernando Pessoa, pp. 85-97.

Işleyen, Ü.K., Kesik, H.Ý, 2021. Experimental and numerical analysis of compression and bending strength of old wood reinforced with CFRP strips. *Structures*, 33: 259-271. DOI: https://doi.org/10.1016/j.istruc.2021.04.070.

Jambeck, J., Weitz, K., Solo-Gabriele, H., Townsend, T., Thorneloe, S., 2007. CCA – Treated wood disposed in land-fills and life-cycle trade-offs with waste-to-energy and MSW landfill disposal. *Waste Management*, 27 (8): 21-28. DOI: https://doi.org/10.1016/j.wasman.2007.02.011.

Kajda-Szcześniak, M., 2015. Bezpieczne zagospodarowanie odpadów więźby dachowej. (Safe management of wastes from the timber roof truss). *Archiwum Gospodarki Odpadami i Ochrony Środowiska*, 17 (4): 21-28.

Krajewski, A., Witomski, P., 2016. Ochrona drewna: surowca i materiału. Warszawa: Wydawnictwo SGGW, 332 pp.

Krukowska, A., 2015. Odpady drzewne w świetle polskich i unijnych przepisów prawnych. (Wood waste in the light of Polish and EU legal regulations). *Sylwan*, 159 (5): 355-360. DOI: https://doi.org/10.26202/sylwan.2014090.

Krukowska, A., 2016. Struktura podaży odpadów drewnianych w Polsce. (Waste wood supply structure in Poland). *Sylwan*, 160 (3):187-196. DOI: https://doi.org/10.26202/sylwan.2015089.

Krzysik, F., 1974. Nauka o drewnie. Warszawa: Państwowe Wydawnictwo Naukowe, 653 pp.

Kunikowski, G., Rutkowska-Filipczak, M., Wróbel, A., Gańko, E., 2008. Deliverable Residue biomass potential inventory results. *Fuel*, D5.01.03. Available from: http://www.renew-fuel.com. [accessed: 07.07.2023].

Kürsten, E., Militz, H., 2004. Possibilities for the use of the different types of wood residues as raw material. In: Proceedings of the European COST E31 Conference – Management of Recovered Wood. 22-24 April 2004. Thessaloniki, Greece, pp 190-203. Available from: http:\\www.wood.uni-goettingen.de [accessed: 07.07.2023].

Liu, Q., Lv, Ch., Yang, Y., He, F., Ling, L., 2005. Study on the pyrolysis of wood-derived rayon fiber by thermogravimetry – mass spectrometry. *Journal of Molecular Structure*, 733: 193-202. DOI: https://doi.org/10.1016/S1473-3099(15)00424-7.

Mahút, J., Réh, R., Výglaský, J., 2007. Plywood and decorative veneers. Zvolen: Technical University in Zvolen, 238 pp.

Malaťák, J., Jankovský, M., Malaťáková, J., Velebil, J., Gendek, A., Aniszewska, M., 2023. Substituting solid fossil fuels with torrefied timber products. *Materials*, 16 (24): 7569. DOI: https://doi.org/10.3390/ma16247569.

Mathot, V.B.F., ed. 1994. Calorimetry and thermal analysis of polymers. Munich-Vienna-New York: Hanser Publisher, 369 pp. DOI: https://doi.org/10.1007/BF02548788.

Merl, A.D., Humar, M., Okstad, T., Picardo, V., Ribeiro, A., Steierer, F., 2007. Amounts of recovered wood in COST E31 countries and Europe. In: Proceedings of the 3rd European COST E31 Conference – Management of Recovered Wood, 2-4 May 2007. Klagenfurt, Austria, pp. 79-116.

Nadziakiewicz, J., Wacławiak, K., Stelmach, S., 2012. Procesy termiczne utylizacji odpadów. Gliwice: Wydawnictwo Politechniki Śląskiej, 272 pp.

Okstad, T., 2007. Terminology for recovered wood in the forest product chain – a scientific perspective. In: Proceedings of the 3rd European COST E31 Conference – Management of Recovered Wood, 2-4 May 2007. Klagenfurt, Austria, pp. 35-47.

Oleniacz, R., Bacik, B., Spiszak, M., 2014. Niekontrolowane spalanie odpadów i pozostałości roślinnych na terenach wiejskich – przykład inwentaryzacji źródeł emisji i oceny wpływu na jakość powietrza. In: J. Kuropka, A. Musialik-Piotrowska, ed. *Inżynieria i ochrona powietrza*. Wrocław: Oficyna Wydawnicza PWR, pp. 314-323.

Oniśko, W., Dobrowolska, E., Matejak, M., Danecki, L., 1998. Opracowanie założeń i zasad kwalifikacji drewna poużytkowego według kierunków jego zużycia (energetyczne, technologiczne itp.). Opracowanie Ośrodka Badawczo-Rozwojowego Przemysłu Płyt Drewnopochodnych w Czarnej Wodzie, nr 74.1379.3.98.

Onusseit, H., 2006. The influence of adhesives on recycling. *Resources, Conservation and Recycling*, 46: 168-181. DOI: https://doi.org/10.1016/j.resconrec.2005.05.009.

Poletto, M., Dettenborn, J., Pistor, V., Zeni, M., Zattera, A.J., 2010. Materials produced from plant biomass: Part I: Evaluation of thermal stability and pyrolysis of wood. *Materials Research*, 13: 375-379. DOI: https://doi.org/10.1590/S1516-14392010000300016.

Poletto, M., Zattera, A.J., Forte, M.M.C., Santana, R.M.C., 2012. Thermal decomposition of wood: Influence of wood components and cellulose crystallite size. *Bioresource Technology*, 109: 148-153. DOI: https://doi.org/10.1016/j.biortech.2011.11.122.

Petersen, A.K., Solberg, B., 2003. Environmental and economic impacts of substitution between wood products and alternative materials: A review of micro-level analyses from Norway and Sweden. *Forest Policy and Economics*, 7 (3): 249-259. DOI: https://doi.org/10.1016/S1389-9341(03)00063-7.

Piątkowski, J., 2010. Problemy z klasyfikacją odpadów. *Gazeta Przemysłu Drzewnego*, 11: 20.

Pietras, E., 2017. Analiza możliwości wykorzystania wybranych składników biomasy w kontekście ich własności energetycznych. (Analysis of the possibility of using chosen elements of biomass in the context of their energy properties). *Inżynieria i Ochrona Środowiska*, 20 (1): 59-70. DOI: https://doi.org/10.17512/ios.2017.1.5.

Piętka, J., Gendek, A., Malaťák, J., Velebil, J., Moskalik, T., 2019. Effects of selected white-rot fungi on the calorific value of beech wood (*Fagus sylvatica* L.). *Biomass and Bioenergy*, 127: 105290. DOI: https://doi.org/10.1016/j.biombioe.2019.105290.

Pudełko, R., 2013. Ocena potencjałów biomasy ubocznej i odpadowej w UE-27 i Szwajcarii oraz ich regionalizacja. Monografie i Rozprawy Naukowe, 39. Puławy: Instytut Nawożenia i Gleboznawstwa Państwowy Instytut Badawczy, 80 pp.

Ratajczak, E., 2013. Sektor leśno-drzewny w zielonej gospodarce. Poznań: Instytut Technologii Drewna, 207 pp.

Ratajczak, E., Szostak, A., Bidzińska, G., 2003. Drewno poużytkowe w Polsce. Poznań: Instytut Technologii Drewna, 166 pp.

Sonderegger, W., Kránitz, K., Bues, C.T., Niemz, P., 2015. Aging effects on physical and mechanical properties of spruce, fir and oak wood. *Journal of Cultural Heritage*, 16 (6): 883-889. DOI: https://doi.org/10.1016/j.culher.2015.02.002.

Strykowski, W., 2012. Czy drewno jest surowcem strategicznym? In: W. Strykowski, A. Gałecka, J. Pawłowska, eds. *Drewno – surowiec strategiczny?* Warszawa: Instytut Technologii Drewna, Centrum Informacyjne Lasów Państwowych, pp. 11-25.

Surmiński, J., 2000. Zarys chemii drewna. Poznań: Wydawnictwo Akademii Rolniczej w Poznaniu, 109 pp.

Szostak, A., Ratajczak, E., 2003. Zasoby odpadów drzewnych w Polsce. *Czysta Energia*, 6: 21-23.

Szostak, A., Ratajczak, E., Bidzińska, G., Gałecka, A., 2004. Rynek przemysłowych odpadów drzewnych w Polsce. (The industrial wood waste market in Poland). *Drewno*: *Prace Naukowe*, *Doniesienia*, *Komunikaty*, 47 (172): 69-90.

Szubel, M., Dernbecher, A., 2017. Wybrane aspekty kinetyki spalania paliw biomasowych. In: M. Szubel, W. Goryl, eds. *Drewno w Energetyce*. Poznań: Fundacja na rzecz Czystej Energii, pp. 73-86.

Tamelová, B., Malaták, J., Velebil, J., Gendek, A., Aniszewska, M., 2022. Impact of torrefaction on fuel properties of aspiration cleaning residues. *Materials*, 15 (19): 6949. DOI: https://doi.org/10.3390/ma15196949.

Taylor, J.A., Herr, A., Siggins, A.W., 2009. The influence of distance from landfill and population density on degree of wood residue recycling in Australia. *Biomass and Bioenergy*, 33 (10): 1474-1480. DOI: https://doi.org/10.1016/j.biombioe.2009.07.003.

Tum, M., Buchhorn, M., Günther, K.P., Haller, B.C., 2011. Validation of modelled forest biomass in Germany using BETHY/DLR. *Geoscientific Model Development*, 4: 1019-1034. DOI: https://doi.org/10.5194/gmd-4-1019-2011.

Tyutkova, E.A., Loskutov, S.R., Shashkin, A.V., Benkova, V.E., 2017. Thermal analysis of earlywood and latewood of larch (*Larix gmelinii* (Rupr.) Rupr.) found along the Polar tree line: Correlation of wood destruction values with climatic factors. *Journal of Thermal Analysis and Calorimetry*, 130 (3): 1391-1397. DOI: https://doi.org/10.1007/s10973-017-6550-7.

Wasilewski, R., Stelmach, S., 2014. Problem zagospodarowania zużytych drewnianych podkładów kolejowych. (The problem of waste management of wooden railway sleepers). *Archiwum Gospodarki Odpadami i Ochrony Środowiska*, 16 (3): 7-16.

Yapici, F., Esen, R, Erkaymaz, O., Baş, H., 2015. Modeling of compressive strength parallel to grain of heat treated Scotch pine (*Pinus sylvestris* L.) wood by using artificial neural network. *Drvna Industrija*, 66 (4): 347-352. DOI: https://doi.org/10.5552/drind.2015.1434.

Zawadzki, J., Radomski, A., Gawron, J., 2013. The effect of thermal modification on selected physical properties of wood of Scots pine (*Pinus sylvestris* L.). *Wood Research*, 58 (2): 243-250.

STRESZCZENIE

Ocena wybranych właściwości fizycznych, mechanicznych i energetycznych świerkowego drewna poużytkowego – studium przypadku

W artykule przedstawiono charakterystykę właściwości fizycznych, mechanicznych i energetycznych oraz składu elementarnego drewna poużytkowego. Do badań wykorzystano ok. 100-letnie drewno świerkowe pozyskane w trakcie prac konserwatorskich kościoła w Gilowicach (GPS: 49°42'46,3"N 19°18'25,2"E) oraz pochodzące z obiektów budowlanych skansenu Etnopark Ziemi Żywieckiej (GPS: 49°72'31,7"N 19°38'11,2"E). W czasie użytkowania wskazanych obiektów budowlanych drewno było zabezpieczone przepalonym olejem przed zmiennymi warunkami klimatycznymi i grzybami rozkładającymi drewno, w tym przed pleśnią. Olej był aplikowany metodą smarowania za pomocą pędzla, polegającą na rozprowadzeniu impregnatu na powierzchni zabezpieczanego obiektu. Zgodnie z normą PN EN-335:2013 dotyczącą dopuszczalnego sposobu impregnacji drewno zakwalifikowano do II klasy – jako drewno użytkowane pod dachem, narażone na zawilgocenie. Drewno pobrane do badań z kościoła i skansenu podzielono zgodnie z jego pochodzeniem na 4 grupy, którym nadano nazwy kodowe: 01-K – drewno z kościoła, rok pochodzenia ok. 1933, 02-K – drewno z kościoła, rok pochodzenia ok. 1895, 03-SK – drewno ze skansenu, rok pochodzenia ok. 1920 i 04-SK – drewno ze skansenu, rok pochodzenia ok. 1910. Przykładowe próbki drewna pokazano na rycinie 1.

Badania przeprowadzono w celu określenia możliwości bezpiecznego użytkowania omawianych odpadów poużytkowych drewna. Na podstawie obowiązujących norm określono gęstość drewna, jego wytrzymałość na ściskanie i zginanie statyczne, a także skład elementarny i właściwości energetyczne. Badane drewno cechuje niższa o ok. 7% gęstość w porównaniu do drewna świeżego (dane dotyczące wilgotności początkowej drewna, gęstość oraz skurcze przedstawiono w tabeli 1), niższa odporność na naprężenia zginające i ściskające oraz wyższa o ponad 30% zawartość ligniny (wyniki analizy TGA przedstawiono w tabeli 2). Analiza zawartości poszczególnych

związków chemicznych wykazała stosunkowo niewielkie różnice w badanych próbkach. Z energetycznego punktu widzenia korzystny jest stosunkowo wysoki udział węgla (ponad 50%), odpady cechuje również niska zawartość popiołu (poniżej 1%) oraz dobra kaloryczność – na poziomie 18,8 $MJ \cdot kg^{-1}$ (szczegółowe wyniki analizy elementarnej przedstawiono w tabeli 3). Mimo upływu lat gęstość badanego surowca w stanie suchym wynosiła od 372 do 421 $kg \cdot m^{-3}$, co odpowiada charakterystycznej gęstości konstrukcyjnego drewna iglastego w klasach wytrzymałości C14-C40. Parametry wytrzymałościowe drewna spełniają normy drewna konstrukcyjnego opisane w normie ISO PN-EN 338:2016-06: na zginanie w zależności od próbki dla klasy C40 i wyższej, a na ściskanie dla wszystkich klas. W związku z tym takie drewno może być ponownie wykorzystane w celach konstrukcyjnych. Przeprowadzona analiza wykazała, że badane odpady drewna świerkowego cechują się dobrymi właściwościami energetycznymi, zbliżonymi do biomasy drzewnej, i nadają się do wykorzystania jako paliwo w procesach termicznych.

Uwzględniając zbadane właściwości mechaniczne (tab. 4) oraz stosunkowo niską wilgotność, można stwierdzić, że badane odpady drzewne nadają się do stworzenia zrębki, brykietu oraz peletu. Z powodu pierwotnego zabezpieczenia drewna przepalonym olejem może w trakcie spalania dochodzić do zwiększonej emisji toksycznych substancji (spalin), dlatego odpady te powinny być spalane w przystosowanych do tego celu obiektach wyposażonych w instalację oczyszczania spalin, tak by nie zagrażały środowisku.