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The radial variation of the selected physical and mechanical properties of Norway spruce (*Picea abies* (L.) H. Karst) wood from the provenance area in Głuchów

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Abstract: *The radial variation of the selected physical and mechanical properties of Norway spruce (Picea abies (L.) H. Karst) wood from the provenance area in Głuchów.* Spruce wood (*Picea abies* (L.) H. Karst) is one of the main species used in building constructions. Due to the wide occurrence, it is important to test various origins and in this way select those with the best material properties. Wood was obtained from one habitat from a provenance experimental area in Głuchów from 40-year-old trees. For the study, trees from three different origins were selected: Nowe Ramuki, Bliżyn and Rycerka Praszywka II (origin from respectively northern, central and southern Poland - seedlings came from these places). Spruce wood from Bliżyn, which is the closest to the proven research area in Głuchów, reached the highest average values in all studied traits (density, ultrasonic wave velocity, dynamic and static modulus of elasticity and static bending strength) and was characterized by the highest variability of these features. Regardless of the origin, the above-mentioned features of the wood showed a clear upward trend going from the pith to the to the side of the trunk.

Keywords: Norway spruce, wood density, wood properties, mechanical and physical parameters

INTRODUCTION

Norway spruce (*Picea abies* (L.) H. Karst), right after Scots pine (*Pinus sylvestris* L.), is the most common coniferous tree in Poland and constitutes 6% of the forest area (Forests in Poland, 2018). Spruce wood (PCAB code according to EN13556:2003) with many applications is important in the wood industry of Poland and Europe (Kozakiewicz and Zatoń 2018).

In the Central European lowlands, this species found its way through migration from two refugia, formed during the last glaciation, in the Carpathian and North East (Russian refuges) (Jaworski, 2011). Currently spruce occurs in Poland in two geographical ranges: north-eastern (Nordic-Baltic range) and southern (Hercen-Sudecko-Carpathian range) separated by a spruce free belt with a width of 50-100 km called the Central-Polish disjunction - Fig.1 (Jaworski, 2011). These ranges include five natural-forest regions: Mazury-Podlasie II, part I of the Baltic Sea, VIII Karpathian, VII Sudecka, V Silesian and 12 motherland regions (Puchniarski, 2008).

For many years, studies have been carried out on the impact of the habitat on dendrometric features and the properties of the formed spruce wood. Barzdajn (2003) analyzed the taxation features and the standing volume of different provenance trees. The diameter breast hight increment of the stands of the Western Beskidy Mountains was described by Grabczyński (1998). Annual rings increments, share of late wood and density have already been studied by, among others, Bieniasz et al. (2017), Zawadzka and Kozakiewicz (2018). Barszcz and Michalec (2007), Szaban and others (2011) and Michalec

(2011) also analysed the quality of spruce wood. According to Borkowski and others (2015), one of the highest spruces grows in the Bialowieża Forest, even up to 52 m high.

For the sake of morphological and phenotypic differences within the species, it is also necessary to study spruce to identify the origins of the best adaptive properties and ones producing the highest quality raw material, for which main determinant is density. These studies are all the more important as spruce wood is one of the main species used for load-bearing elements in construction. Such wood must meet strict strength requirements, guaranteeing construction safety (Borysiuk et al. 2019).

In general, in coniferous wood, the density increases radially from the pith to the side of the trunk. Galewski and Korzeniowski (1958), Krzysik (1978) and Wagenführ (2007) agree on the range of density variation of spruce wood in air-dry state from 330 kg/m^3 to 680 kg/m^3 and an average density of 470 kg/m^3. Genetic origin also influences these values. In a study conducted on 35 years old material from LZD Rogów by Bieniasz and others (2017), the samples of the Nowe Ramuki provenance were characterized by the highest density and compressive strength along the fibers of the studied origins, the values were respectively: 452 kg/m^3 and 61.9 MPa.

This origin was also characterized by high static bending strength - 91.9 MPa - and a high elastic modulus for static bending. In the Matras (2001) study carried out on wood from the experimental plot in Knyszyn, the Nowe Ramuki also had a relatively high density (445 kg/m^3), taking the 4th position out of the 18 researched origins. In the same study, the density of the origin of Rycerka Praszywka II, which reached 394 kg/m^3, was analyzed. In his research on spruce growth, Chmura et al. (2018) lists the origin of the Bliżyn as having high adaptability.

As part of this work, three different spruce origins were compared. Radial variation in density, dynamic and static modulus of elasticity and bending strength were investigated. As part of the research hypothesis, it was assumed that genetic origin can affect the above-mentioned features of wood.

MATERIAL AND METHODS

The research material was obtained in 2017 from the provenance of the Forest Experimental Plant Rogów in the Forestry Głuchów (branch 231d, formerly - 179c, placed at 146 m a.s.l). The experimental plot was a forty-year-old spruce stand created using three-year-old seedlings of 19 different spruce origins (17 domestic and 2 from Germany), which were planted in a 1.5x1.5 m truss on an area of 3 ha. From among 19 sources, 3 were selected for research: one from the northern, central and southern parts of Poland.

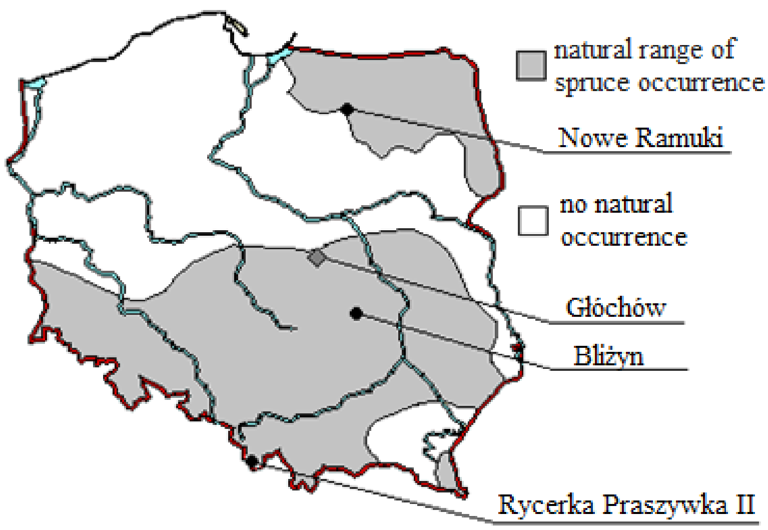

Figure 1. Natural occurrence of Norway spruce in Poland with specified provenances of studied origins from experimental surface in Głuchów.

A total of 38 trees were subjected to research: 13 - from the origin of Nowe Ramuki (160 m a.s.l and 230 km in a straight line from Głuchów), 13 - Rycerka Praszywka II (950 m a.a.s.l, and 300 km in a straight line from Głuchów) and 12 - Bliżyn (310 m a.s.l, and 100 km in a straight line from Głuchów) - Fig.1.

From the butt end parts of trunks (down from breast height), rollers with a length of approx. 0.6 m were obtained from which beams on the north-south axis were cut. After the natural drying of the beams to air-dry conditions, samples (bars) were cut out in accordance with the main anatomical directions with the cross-sectional dimensions 20x20 and length 350 mm.

The density test was carried out using the stereometric method, according to the recommendations of ISO 13061-2: 2014 and moisture content of wood according to the ISO 13061-1:2014,

The dynamic modulus of elasticity was determined using the transition method using ultrasonic waves. The UMT-1 materials tester equipped with two cylindrical heads (transmitter and receiver) with a diameter of 40 mm and a frequency of 100 kHz and UMT-LINK specialized software for visualization of measurements were used for the tests. The tests were carried out with the following tester settings: transmission power 40 dB, amplification at 60V, temperature 20°C, delay time = 8.88 μs. Heads were put, with slight pressure, on the forehead of samples coated with a coupling substance which was an ultrasound gel (polyacrylic acid sodium salt) and ultrasonic impulses were passed along the fibers every 12 hertz.

On the basis of the measurement of the passage time of the longitudinal ultrasonic waves, along the wood fibers, the velocity of the ultrasound transition and the dynamic elastic modulus from the following relationships were calculated:

- speed of longitudinal waves:

$$c_{||} = \frac{L}{t}$$

where: $c_{||}$ - velocity of longitudinal waves along fibers [m/s]

L - sample length [m] (L>>λ- wave lenght)

$t = t_1 - t_0$ – real time of longitudinal wave transition [s]

t_1 - wave transition time read from computer monitor [s]

t_0 - delay time [s]

- dynamic modulus of elasticity:

$$E = c_{||}^2 \cdot g$$

where: E – modulus of elasticity [GPa]

$c_{||}$ - velocity of longitudinal waves along fibers [m/s]

g – density [kg/m^3]

The bending strength (MOR) is determined according to ISO 13061-3: 2014 and the static elastic modulus (MOE) according to ISO 13061-4: 2014. The analysis of the failures of samples after bending test was carried out on the basis of ASTM D 143 - 84: 2000.

Obtained results of the study were subjected to statistical analysis. The significance of differences between the mean values of the tested features was checked with the Student's t-test at the 0.05 confidence level. When determining correlation relationships between selected properties, their significance was confirmed on the basis of the Pearson correlation coefficient distribution table.

RESULTS AND DISCUSSION

The highest average density of wood and at the same time the biggest difference (8%) was characterized by spruce wood of Bliżyn origin and reached to 429 kg/m^3. The average density of the origin of Nowe Ramuki was a little lower - 427 kg/m^3, 5% variation - so the origin was worse than in the Bieniasz study (2017) carried out on 35 years of material from the same research plant where the average density reached 452 kg/m^3. Wood from the origin Rycerka Praszywka II reached the lowest values, the average density was only 412 kg/m^3 (variation of 3%). All these values are below the value given by literature for the spruce wood, 470 kg/m^3 (Warywoda 1957, Galewski and Korzeniowski 1958, Krzysik 1978 and Wagenführ 2007). Of the studied origins, Nowe Ramuki and Bliżyn do not differ significantly in terms of density.

On the north-south axis there were no significant differences in density distribution between individual origins, however, in all of them the increase in density from the pith to the to the side of the trunk is clearly visible (Fig. 2). This is most likely the result of a significant proportion of juvenile wood in the examined 40-year-old spruce trunks. Juvenile wood is characterized among others by a lower density compared to mature wood (Fabisiak 2005). In addition, the origin of Bliżyn was characterized by higher values of standard deviation, especially in the periphery zone.

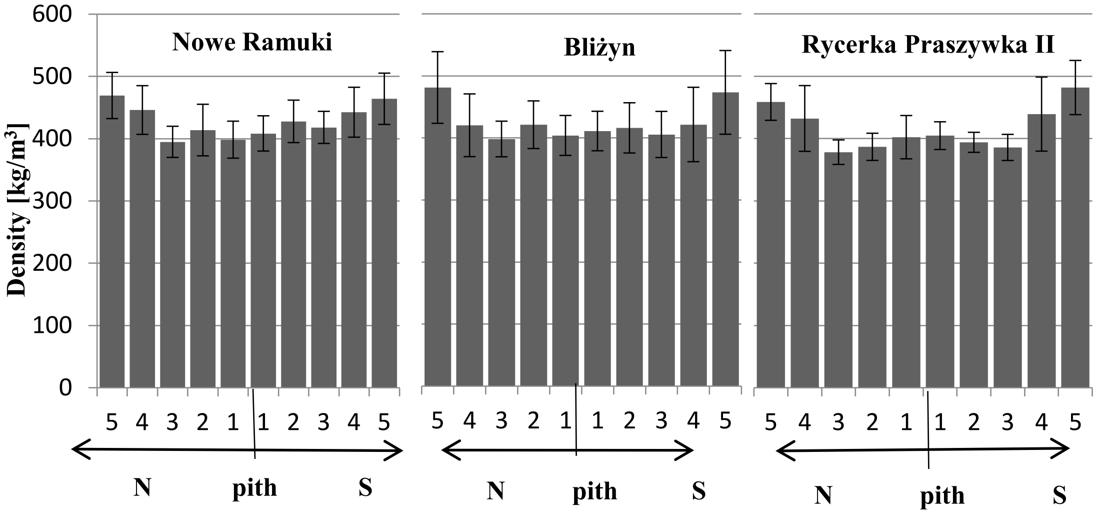

Figure 2. The average density variation on the cross-section of the trunk (Norway spruce wood) on the N-S axis.

The highest average velocity of sound propagation, analogous to density, was characterized by samples of Bliżyn origin (6214 m/s, coefficient of variation 4%), followed by Nowe Ramuki (6208 m/s, coefficient of variation 4%) and Rycerka Praszywka II (6089 m/s, coefficient of variation 5%). As in the case of density, also in terms of velocity of ultrasound passage through wood of origin, Nowe Ramuki and Bliżyn do not show significant statistical differences.

Depending on the source, different sound propagation speeds along fibers in the spruce wood are given: from 4790 m/s (Krzysik, 1978), through 5353 m/s (Stanciu, 2007) to 6000 m/s (Kozakiewicz, 2012). Results tests are consistent with the data provided by Kozakiewicz (2012), obtained using the same research equipment and methodology.

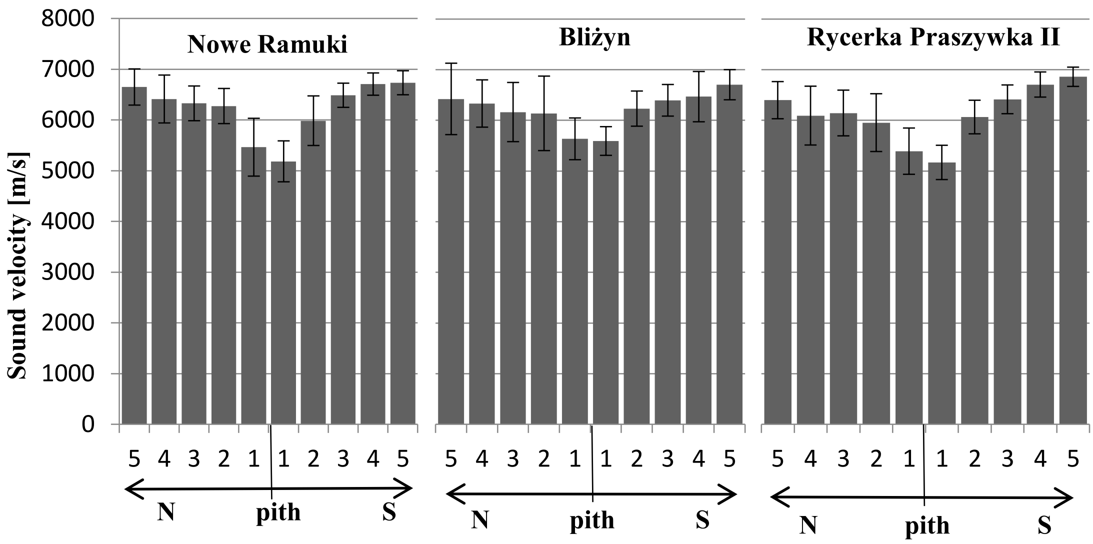

Figure 3. The average variation of the speed of sound transmission at the cross-section of the trunk (Norway spruce wood) on the N-S axis.

On the north-south axis in each origin a clear decrease in velocity was observed in the samples located near the pith (Fig.3). The velocity of ultrasonic waves in wood is largely dependent on the length of structural elements. The pith is made of short parenchymal cells and surrounded by juvenile wood containing shorter tracheids with a higher angle of fibrillation (Roszyk et al. 2010). These layers are a hindrance to the transmission of ultrasonic waves.

It was also noticed that on average (regardless of origin) wood on the south side of the trunks was characterized by slightly higher wave transitions compared to wood on the northern side.

The average value of the modulus of elasticity (MOE) of spruce wood is 11.00 GPa (Kozakiewicz, 2005). For the dynamic elastic modulus, the results reached 12.52 GPa at a variability of 15% (origin of Bliżyn), 12.44 GPa at a variation of 8% (Origin of Nowe Ramuki) and 11.51 GPa at variation of 11% (origin of Rycerka II). In all the analyzed provenances, the static modulus of elasticity was lower and, in the same order as above, reached values: 8.77 GPa at 14% variability, 8.56 GPa variability 9% and 7.81 GPa at 9% variabilty. The greater value of the dynamic modulus of elasticity in comparison to the static modulus of elasticity determined with static bending is a natural relation resulting from methodical simplifications. All average of particular origins show significant statistical differences.

In the case of elastic modulus, their increase is clearly visible going from the pith to the side of the trunk (Fig. 4 and 5). The modulus of elasticity depends on the length of structural elements and the density of wood, and these two features show a favorable change (increase) along with increasing distance from the pith (Fabisiak 2005, Roszyk et al. 2010).

All origin, except the origin of Nowe Ramuki - where the difference between the N and S sides was minimal, were characterized by a higher modulus of elasticity on the southern side. The greatest differences between the north and south perimeter zone occurred in the origin of Rycerka Praszywka II.

The origin of Bilżyn was characterized by very high variability, especially in the zone near the side surface of the trunk, where the coefficient of variation oscillated to 28%.

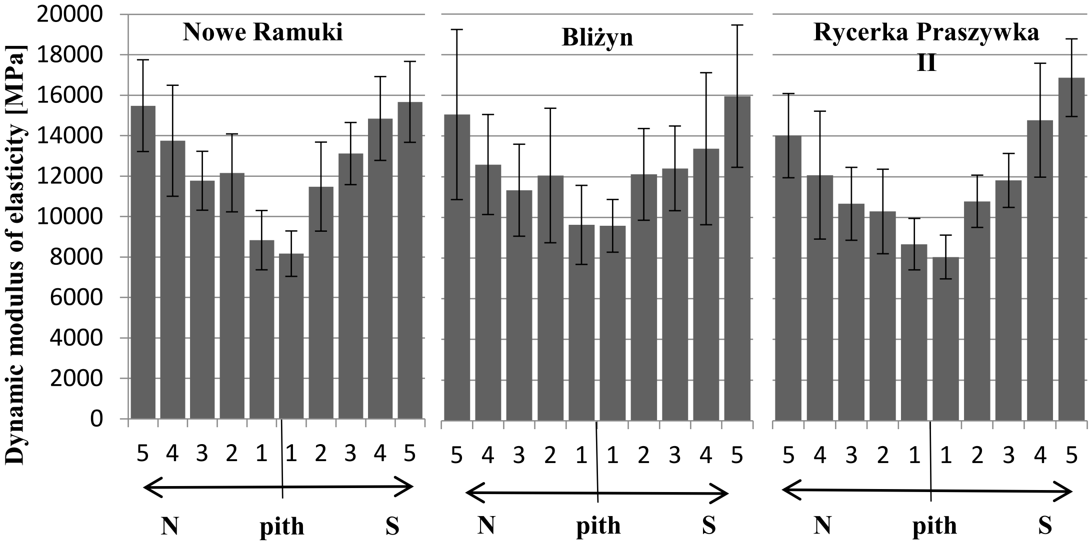

Figure 4. The average variation of the dynamic elastic modulus at the cross-section of the trunk (Norway spruce wood) on the N-S axis.

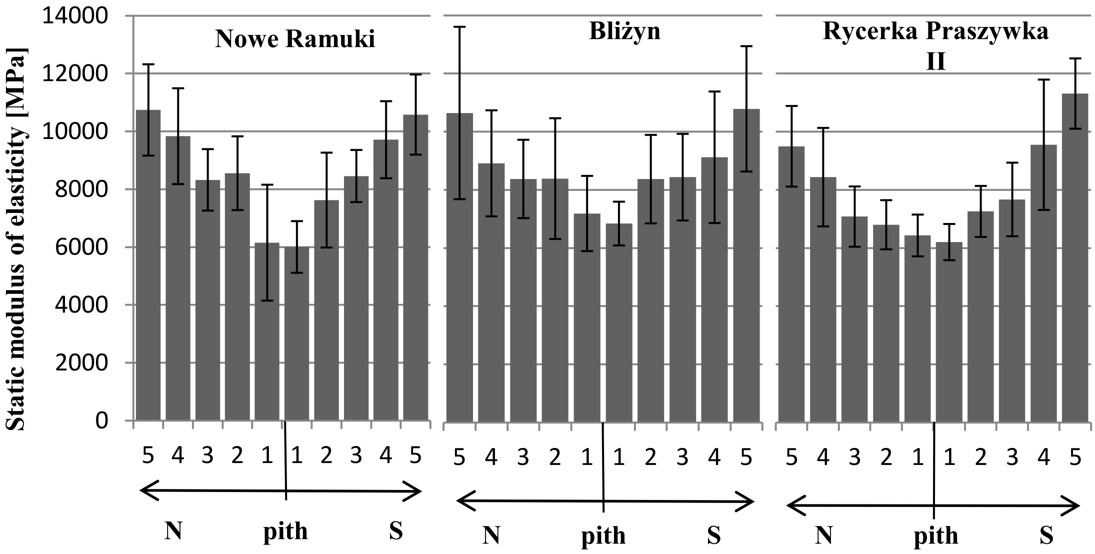

Figure 5. The average variation of the static modulus of elasticity at the cross-section of the trunk (Norway spruce wood) on the N-S axis.

The average static strength of the tested samples in each origin was higher than the literature mentioning 66 MPa (Kozakiewicz, 2005), for the origin of Bliżyn and Nowe Ramuki 81 MPa (variation respectively 15 and 11%) and 77 MPa for the provenance of Parszywka II with a coefficient of variability 10%. The average of the last two mentioned origins does not show significant statistical differences. Wood from the origin of Nowe Ramuki, was characterized by lower strength than in the Bieniasz study (2017) (average 92 MPa).

Going from the pith to the to the side of the trunk in all origins, the static bending strength increases (Fig. 6). The highest values in the perimeter zone are related to the smaller graininess and higher density of wood in this zone, which directly affects durability (Krzysik, 1978). The origin of Bliżyn and Nowe Ramuki reached the highest values of bending strength from the northern side, while in the case of the provenance of the Rycerka Praszywka II it was oposite and the highest values occurred from the southern side. This difference is difficult to explain by the influence of tree growth conditions (on the experimental surface of LZD

Głuchów they were identical for all origins). Most likely these differences result from genetic conditions. In addition, again, the origin of Bliżyn also in terms of bending strength was distinguished by very high variability, the south reaching even 37%.

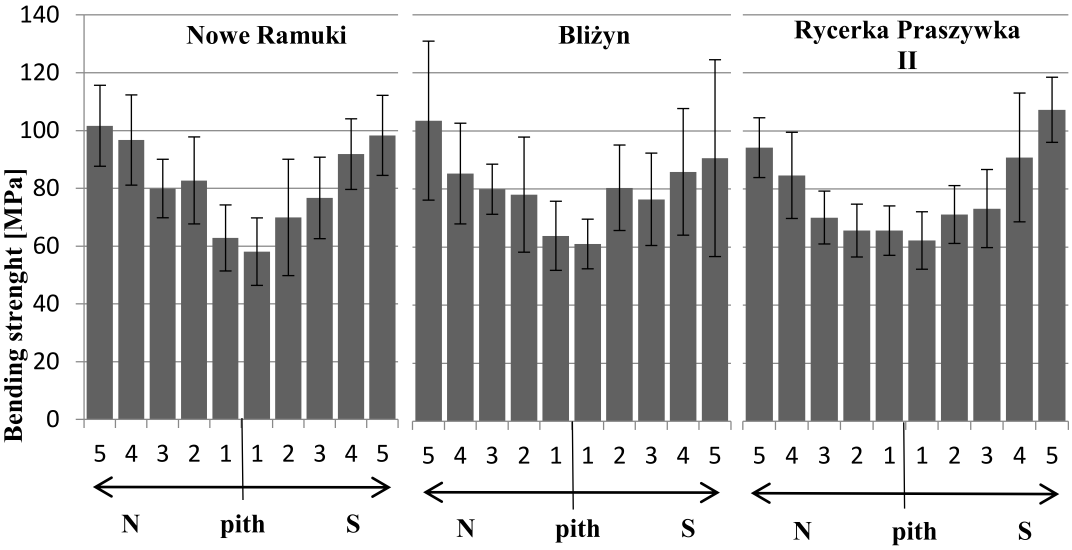

Figure 6. The average variability of bending strength of wood at the cross-section of the trunk (Norway spruce wood) on the N-S axis.

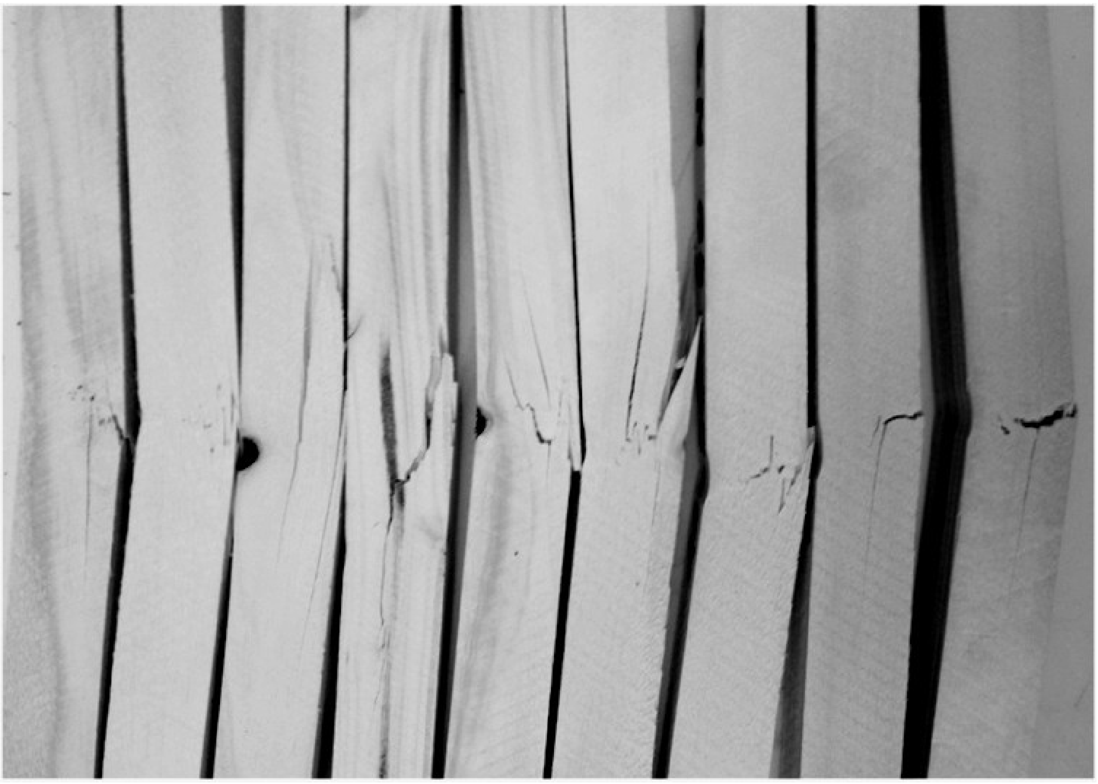

Figure 7. Sample failures samples from the breast part of tree No. 11-20-40 - origin of Bliżyn.

Regardless of origin in most of the samples tested (especially in the perimeter zone), as a result of breaking according to ASTM D 143-94: 2000 classification, splintering / brash tension occurred (Fig.7). According to predictions in the area of the pith (juvenile wood), where the density and strength were lower, a dominant simple / cross-grain tension shear was observed.

Regardless of the origin, the correlation relationships between the selected wood characteristics tested were generally similar (Fig 8 and 9). However, the coefficients of parametric simple correlation equations and determination coefficients were significantly different. The strongest dependence of static modulus of elasticity and bending strength on the density of wood was observed in the Bliżyn (the correlation coefficient was equal to both properties). In other origins, these compounds were characterized by a much lower correlation but still significant. For the Nowe Ramuki provenance level of 0.5 (for both properties) and for the Rycerka, Praszywka II origin 0.6 - for static modulus of elasticity and 0.7 - for bending. The attention is also drawn to the much lower value of the directional coefficients of linear correlation for the origin of Nowe Ramuki and Rycerka Parszywka II in comparison to the origin of Bliżyn.

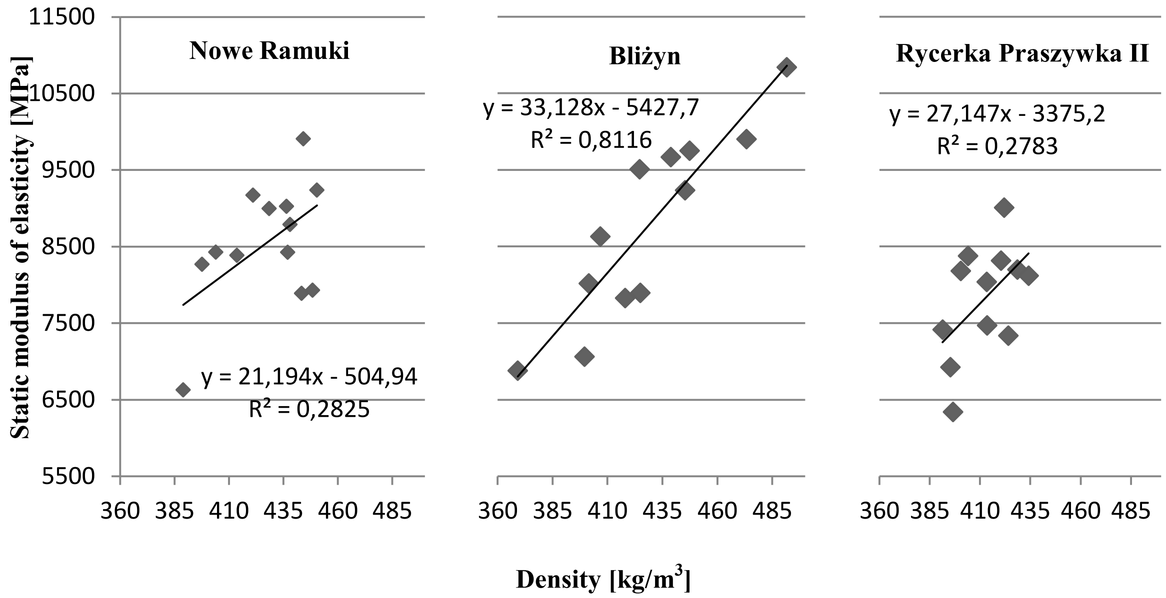

Figure 8. Dependence of wood density on static modulus of elasticity of wood.

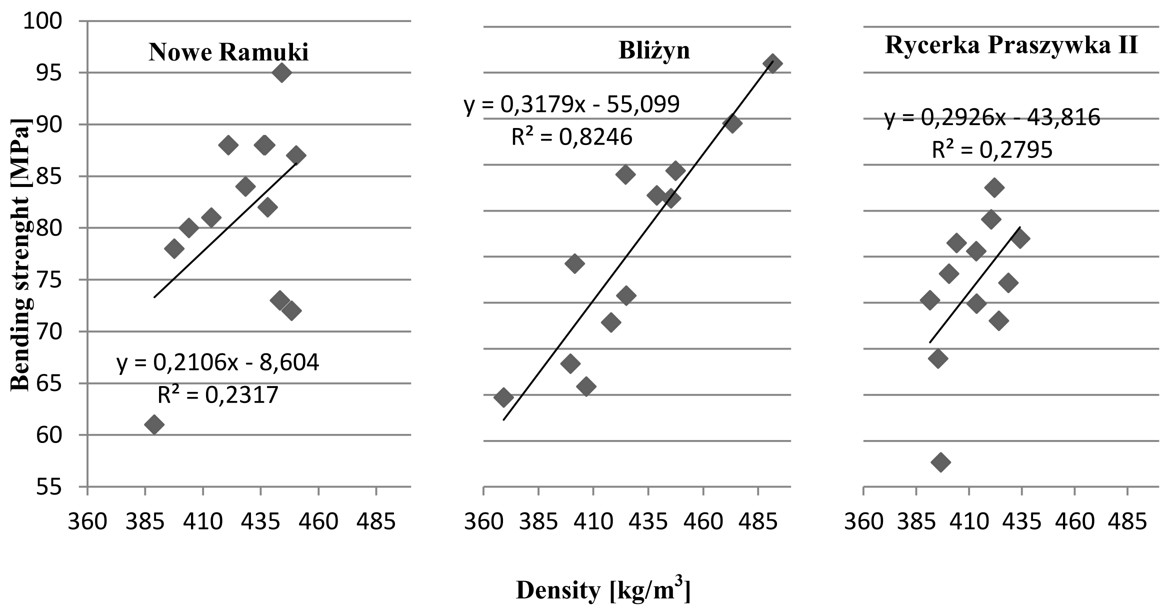

Figure 9. Dependence of wood density on bending strength of wood.

CONCLUSIONS

On the basis of investigations carried out on spruce air-dry wood of three genetic origins (Bliżyn, Nowe Ramuki, Rycerka Praszywka II) from the surface of the Forest Experimental Plant Rogów in the Forestry Głuchów, the following conclusions were made:

1. The density of wood grows from the pith to the side of the trunk, especially in the periphery region. The density distribution of different origins in the N and S directions does not show significant differences.
2. The speed of sound transitions from the southern side is slightly higher than on the northern side, however, it does not differ significantly between origins. All origins were characterized by similarly low wave velocity in the area of the pith.
3. The modulus of wood elasticity is clearly increasing from the pith to the trunk circumference in all origins. In general, the modulus of elasticity assumes an average higher value from the south side of the trunks.
4. Resistance to static bending of wood also grows from the pith to the circumference. The Bliżyn and Nowe Ramuki provenances reached the highest values of bending strength from the north, while in the case of provenance Rycerka Praszywka II was the other way, the highest values were from the southern side, which is most likely the result of genetic determinants.
5. The nature of the failures of the tested samples depends mainly on their original location in the trunk (it does not depend on origin). In the area near the pith, simple / cross-graintence dominates and in the remaining splintering / brash tension).
6. Depending on the origin, the density of wood determines the value of modulus of elasticity and static bending strength to varying degrees. The strongest relationships between these traits were found for the origin of Bliżyn.
7. The origin closest to the research area - Bliżyn - reached the highest average values in all studied traits and was characterized by the highest variability of the studied properties.

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Streszczenie: *Zmienność promieniowa wybranych właściwości fizycznych i mechanicznych drewna świerkowego* (*Picea abies* (L.) H. Karst) *z powierzchni proweniencyjnej w Głuchowie*. Ze względu na szerokie występowanie świerk pospolity wykazuje znaczną zmienność genetyczną, która może przekładać się również na cechy i właściwości tworzonego drewna, decydujące o przydatności surowca do różnych celów przemysłowych. Badanie przeprowadzono na drewnie pozyskanym z 40-o letniego, litego drzewostanu świerkowego z powierzchni doświadczalnej Leśnego Zakładu Doświadczalnego Rogów w Leśnictwie Głuchów. Poszczególne drzewa, wzrastające w tych samych warunkach, różniły się pochodzeniem. W niniejszej pracy analizowano trzy pochodzenia: po jednym z północnej, centralnej i południowej części Polski, a mianowicie: Nowe Ramuki, Bliżyn i Rycerka Praszywka II. Drewno świerkowe z pochodzenia Bliżyn, leżącego najbliżej proweniencyjnej powierzchni badawczej w Głuchowie, osiągnęło najwyższe średnie wartości we wszystkich badanych cechach (gęstości, prędkości fal ultradźwiękowych, dynamicznego i statycznego modułu sprężystości oraz wytrzymałości na zginanie statyczne)a także charakteryzowało się największą zmiennością tych cech. Niezależnie od pochodzenia wymienione wyżej cechy drewna wykazywały wyraźną tendencję wzrostową idąc od rdzenia do obwodu pnia.

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