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Selected physical and mechanical properties of Scots pine (*Pinus sylvestris* L.) wood from stands of younger age classes as criteria for rational utilization of timber

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Abstract

The aim of this study was to assess the quality of Scots pine (*Pinus sylvestris* L.) wood depending on the age of trees, forest site conditions and social class of tree position in the stand. Analyses were based on the determination of specific density and static bending strength, as well as the strength quality coefficient. It was to determine changes in physical and mechanical properties of timber depending on tree age as well as growth conditions reflected in the forest site such as fresh mixed coniferous forests and fresh mixed broadleaved forests. Experimental plots were established in 6 localities with 30, 40 and 60-year-old trees. In each of the stands, a 1-hectare experimental plot was established. Based on the measured DBH and tree height, dimensions of three mean sample trees were calculated, while the classification of social class of tree position in the stand developed by Kraft (1884) was also applied. Analyses were conducted on wood samples with 12 % moisture content. Strength tests on wood samples were performed on an Instron 33RH204 universal strength testing machine. A detailed analysis showed properties of pine wood are improved with an increase of tree age in both forest sites. Statistically significant differences were observed for wood density and static bending strength. More advantageous properties were observed for wood of pines from the less fertile forest site, i.e., fresh mixed coniferous forests. Density and static bending strength were markedly determined by tree age and growth conditions. The static bending strength quality coefficient from pines growing in the fresh mixed coniferous forests increased between 30 and 40 years, similarly as it was for the fresh mixed broadleaved forests, while between 40 and 60 years, it deteriorated for the fresh mixed coniferous forests. Wood density from the fresh mixed coniferous forests was by 3 % to 7 % greater than pines growing in fresh mixed broadleaved forests. In turn, static bending strength of wood from pines growing in fresh mixed coniferous forests was by 4 % to 10 % greater than trees from the fresh mixed broadleaved forests.

Keywords: Scots pine, wood properties, forest site, Poland

Introduction

An increase in economic value generated by the product depends not only on its quantity, but primarily on its quality. Production yield as well as final quality of timber are dependent on several factors, including, e.g., genetic variation. Genetic conditions may be crucial for the quality and value of produced timber, thus literature on the subject increasingly often focuses on these factors (Zabel 1971, Persson et al. 1995, Allona et al. 1998, Fujimoto et al. 2006, Kumar et al. 2006). Despite intensive research the problem of localization and identification of genes responsible for xylem formation has not been fully explained. Scots pine covers almost the entire territory of Poland and it is one of the main forest-forming species in our country. It forms plant associations, the so-called pure pine forests, such as for example the plant community (*Pinetum*) found on soils ranging from weak to fertile soils, e.g., swamps or peatland (Seneta and Dolatowski 2008). In contrast to the lowlands, in the Sudeten Foothills and the Carpathian Foothills, Scots pine is not a popular species. It remains a valuable source of timber for the domestic wood industry (Białobok et al. 1993). Most Polish forests originate from artificial regeneration through sowing or planting. The Durowo Forest District administers 16.4 thousand hectares, of which 69 % area (10,414.27 ha) are forest sites with the predominance of broadleaved species, while 31 % of the productive area (4,685.22 ha) comprise forests with the predominance of coniferous species (Thomas-Trybus 2014, Lasy Państwowe 2016). The fresh mixed broadleaved forests cover 4,954.69 ha, accounting for 32.9 %, while fresh mixed coniferous forests cover 3,754.00 ha, i.e., 24.9 % area of the forest district. Each year artificial regeneration covers 123 ha. Silvicultural measures, such as early cleaning, are performed annually in 70 ha, late cleaning in 180 ha, early thinning in 180 ha and late thinning in 800 ha. In the Durowo Forest District, the area of seed stands is 177.98 ha, from which seeding material is collected in the form of seeds.

The final outputs of timber production are also determined by traits resulting to a greater or lesser extent from growth and development conditions as well as human activity (Prescher and Stähl 1986). In turn, these factors together with tree genotype are of paramount importance for xylem formation, while from the point of view of forest management and potential utilization of timber they determine its quality and value (Brüchert et al. 2000, Jelonek et al. 2006, 2010, Tomczak et al. 2008). Xylem itself is to a varied extent optimized in terms of served functions, tree growth conditions and strategies facilitating its survival. The traits characteristic to trees includes, e.g., a complex chemical composition and anatomic structure specific to individual tree species, which in turn directly modifies physical and mechanical properties of wood. Even within one species difference may be found in wood structure and properties, e.g., depending on the geographic location (Fabijanowski 1961), forest site (Pazdrowski and Spława-Neyman 1996, 1997), tree age and social position in the stand (Pazdrowski and Spława-Neyman 1993, Fabisiak 2005).

The aim of this study was to assess quality of Scots pine (*Pinus sylvestris* L.) wood depending on tree age, forest site conditions and social tree position in the stand. The evaluation was based on the determination and comparison of basic density, static bending strength and the coefficient of strength quality.

Material and methods

Analyses were conducted on wood of pines growing in two forest site types: fresh mixed coniferous forests and fresh mixed broadleaved forests.

Experimental site areas were in 6 localities of Scots pine (*Pinus sylvestris* L.), within the natural distribution range of this forest-forming species in Europe. All the areas were selected in the Durowo Forest District (Figure 1), administered by the Regional Directorate of the State Forests in Piła, Poland. The experimental areas were average in terms of their quality. The stands growing there were 30, 40 and 60 years old. A description of the experimental plots is given in Table 1. Biometric characteristics of selected trees are presented in Table 2 for the fresh mixed coniferous forests and in Table 3 for the fresh mixed broadleaved forests.

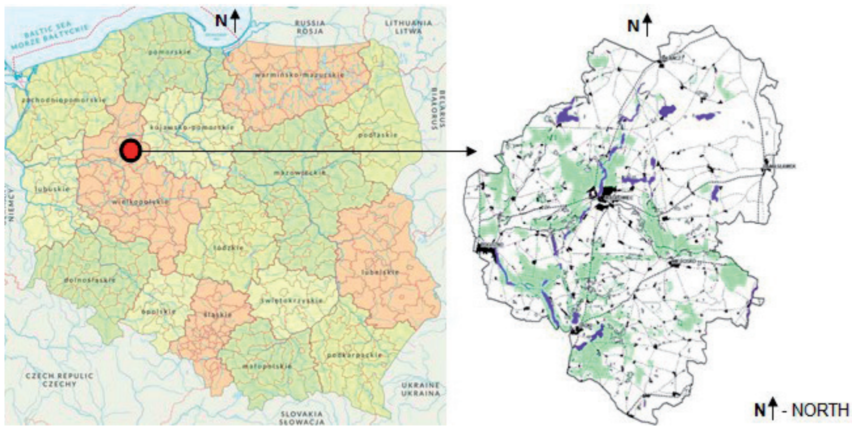

Figure 1. The Durowo Forest District (Narożny 2014)

Table 1. Characteristics of stands, in which the experimental plots were established

	Fresh mixed coniferous forests			Fresh mixed broadleaved forests		
Age, years	30	40	60	30	40	60
Average DBH, cm	19	27	31	19	26	33
Average height, m	17	25	25	18	24	27
Stocking	0.7	0.8	0.7	0.8	0.8	0.6
Thinning stand, m^3/ha	142	355	336	174	339	271
Estimated index soil habitat	16	23	22	24	30	28

Table 2. Characteristics of mean sample trees grown in the fresh mixed coniferous forests

Characteristics	Kraft's classes	Tree age, years		
		30	40	60
DBH, cm	1	17	24	34
	2	14	17	28
	3	12	14	22
Height, m	1	16.6	21.5	26.5
	2	16.4	19.5	26.3
	3	16.2	16.8	24.9
Crown length, m	1	6.3	6.3	8.1
	2	5.3	4.9	7.0
	3	5.3	3.6	6.7
Maximum diameter of the crown, m	1	2.9	3.7	4.3
	2	2.2	2.5	3.8
	3	2.1	1.9	3.5

Table 3. Characteristics of mean sample trees grown in the fresh mixed broadleaved forests

Characteristics	Kraft's classes	Tree age, years		
		30	40	60
DBH, cm	1	15	23	33
	2	11	19	25
	3	9	15	21
Height, m	1	14.5	20.8	25.4
	2	12.9	20.5	23.5
	3	12.5	18.3	21.8
Crown length, m	1	6.1	6.3	8.5
	2	4.2	7.0	6.3
	3	4.1	6.7	5.6
Maximum diameter of the crown, m	1	2.2	3.1	3.9
	2	1.8	2.9	3.8
	3	1.4	2.1	2.9

In each stand, 1-hectare experimental areas were established, in which in all tree measurements diameters were taken at breast height and heights in proportion to the frequency in 1-cm diameter subclasses. Based on the recorded results, diameters at breast height and tree height were calculated using the Urich I diameter class method (Grochowski 1973) for three model trees. When identifying model trees and the social class of tree position, the Kraft method (1884) was applied. Pine trees representing the first classes were selected, i.e., predominant, dominant, and codominant trees, as those constituting the main stand. Pines with a healthy, straight stem and a symmetrical, well-developed crown were selected for felling. A total of 18 model trees were selected and felled. From the felled trees blocks were cut out, whose bottom ends were located at a height of 1.30 m, while the upper ends at 2.30 m of the stem. Blocks collected from stems of model trees were used to prepare wood samples for analyses of selected physical and mechanical properties (Figure 2).

Wood density and moisture content were determined for samples of 20 × 20 × 30 mm. In turn, static bending strength was determined on samples of 20 × 20 × 300 mm. Analyses were conducted on wood samples at 12 % moisture content stored in climatic chambers. Wood strength parameters were determined using an Instron 33RH204 testing machine with load capacity of maximum 50 kN (accurate to 0.01 MPa).

The coefficient of strength quality at static bending was determined by referring wood strength to its density using the formula:

$$J = \frac{-Rg_{12}}{\rho_{12}} \cdot 100[\text{km}]$$

where: J is the coefficient of strength quality [km], Rg_{12} is the static bending strength of wood at 12 % moisture content [MPa], ρ_{12} is wood density at 12 % moisture content [kg/m^3].

Coefficient of strength quality (J) is also called strength/weight ratio (which is represented in kilometres).

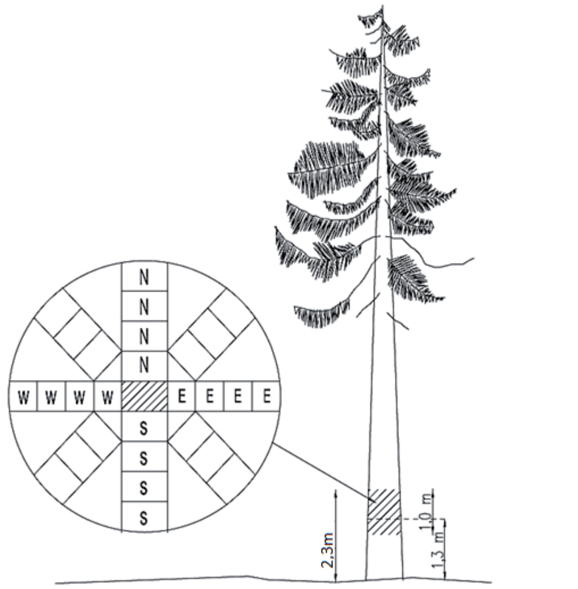

Figure 2. A scheme of sample collection from the model trees

This feature may be expressed as breaking length, which means the length of a wood lath measuring 1 × 1 cm that will be destroyed under its own weight (Kokociński 2004).

The empirical material was statistically analyzed using Statistica 12.0 software package (StatSoft 2013).

Results

This study presents an analysis of the age effect (30, 40, 60 years) on the variation of physical and mechanical wood properties, density, static bending strength and coefficient of strength quality at bending. The analyses also included growth conditions of stands expressed by forest site type, i.e., fresh mixed coniferous and fresh mixed broadleaved forests. Statistical characteristics for physical and mechanical properties as well as their interdependency were calculated using Statistica 12.0 software package. To determine the significance of differences in analyzed traits between individual age intervals, Tukey's Honestly Significant Difference Test was applied (Glen 2016).

In the wood samples of trees from the fresh mixed coniferous forests, the (mean) density was observed to increase with age. The highest mean wood density was found in trees aged 60 years (614.35 kg/m^3), while it was lowest in 30-year-old pines (487.73 kg/m^3). The coefficient of variation (CV) for this property showed a downward trend with tree age (Table 4). Tukey's Honestly Significant Difference Test showed differences in pine wood density between the tree age intervals (Figure 3, Table 5). In all age groups of the fresh mixed broadleaved forests, an average xylem density was also observed to increase with age. The greatest density was recorded for the wood samples of 60-year-old trees (597.99 kg/m^3), while it was lowest in 30-year-old trees (454.55 kg/m^3). The CV also decreased with an increase in tree age (Table 6).

Table 4. Statistical characteristics of wood density in trees grown in the fresh mixed coniferous forests

Statistical characteristics	Tree age, years		
	30	40	60
	Number of samples		
	110	154	130
Mean, kg/m³	487.72	513.09	614.35
Median, kg/m³	486.00	505.00	607.00
Minimum, kg/m³	404.00	397.00	551.00
Maximum, kg/m³	610.00	638.00	706.00
Variance	2251.89	2276.81	1618.32
Standard deviation	47.45	47.72	40.23
Coefficient of variation, %	9.73	9.29	6.55
Standard error	± 4.52	± 3.85	± 3.53

Statistically significant differences in wood density were recorded between the age intervals (Figure 4, Table 7). Differences in wood density were also observed depending on growth conditions. Values for this property were higher in pines growing in the fresh mixed coniferous forests when compared to pines growing in the fresh mixed broadleaved forests (Tables 5 and 6). Static bending strength of pine wood increased with tree age. The lowest mean value of this property was recorded in the 30-year-old stand (74.28 MPa), while it was highest in the 60-year-old (93.85 MPa). The CV showed a downward trend with tree age (Table 8). Statistically significant differences in static bending strength of pine wood were recorded between all age intervals (Figure 5, Table 9).

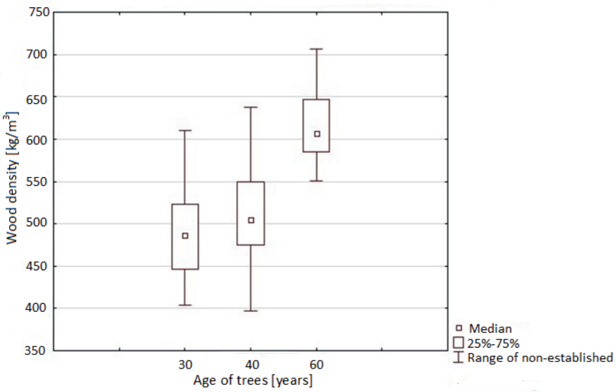

Figure 3. The dependence of wood density on the age of trees grown in the fresh mixed coniferous forests

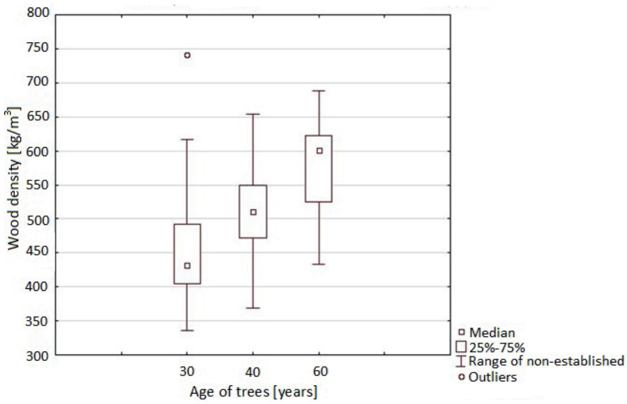

Figure 4. The dependence of wood density on the age of trees growing in the fresh mixed broadleaved forests

Table 5. Probability values, *p*, for Tukey's HSD test for wood density in trees in individual age intervals grown in the fresh mixed coniferous forests

Age, years	30	40	60
30		0.0001	< 0.0001
40	0.0001		< 0.0001
60	< 0.0001	< 0.0001	

Obtained results are significant at the significance level $p < 0.05$.

Table 7. Probability values, *p*, for Tukey's HSD test for wood density in trees in individual age intervals grown in the fresh mixed broadleaved forests

Age, years	30	40	60
30		< 0.0001	< 0.0001
40	< 0.0001		< 0.0001
60	< 0.0001	< 0.0001	

Obtained results are significant at the significance level $p < 0.05$.

Table 6. Statistical characteristics of wood density in trees grown in the fresh mixed broadleaved forests

Statistical characteristics	Tree age, years		
	30	40	60
	Number of samples		
	112	149	162
Mean, kg/m³	454.55	513.23	597.99
Median, kg/m³	432.50	510.00	600.50
Minimum, kg/m³	336.00	369.00	434.00
Maximum, kg/m³	742.00	654.00	689.00
Variance	4341.82	3010.41	3527.78
Standard deviation	65.89	54.87	59.39
Coefficient of variation, %	14.49	10.69	10.24
Standard error	± 6.23	± 4.49	± 4.67

Table 8. Statistical characteristics for static bending strength of wood from trees grown in the fresh mixed coniferous forests

Statistical characteristics	Tree age, years		
	30	40	60
	Number of samples		
	110	154	130
Mean, MPa	74.28	84.27	93.85
Median, MPa	74.25	84.25	93.85
Minimum, MPa	43.20	59.50	64.10
Maximum, MPa	100.80	117.60	119.60
Variance	143.47	111.92	109.45
Standard deviation	11.98	10.58	10.46
Coefficient of variation, %	16.13	12.55	11.15
Standard error	± 1.14	± 0.85	± 0.92

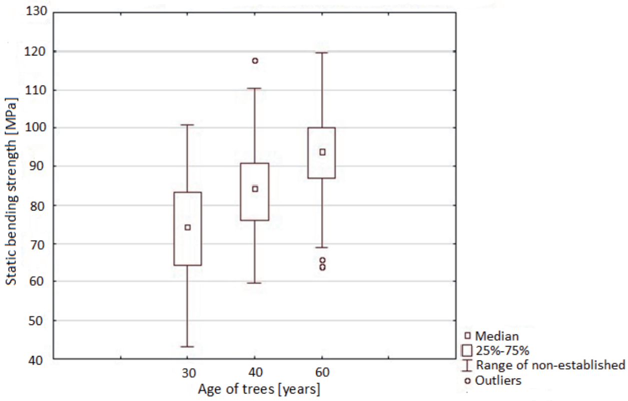

Figure 5. The dependence of static bending strength of wood on the age of trees grown in the fresh mixed coniferous forests

Table 9. Probability values, *p*, for Tukey's HSD test for static bending strength of wood from trees in individual age intervals grown in the fresh mixed coniferous forests

Age, years	30	40	60
30		< 0.0001	< 0.0001
40	< 0.0001		< 0.0001
60	< 0.0001	< 0.0001	

Obtained results are significant at the significance level $p < 0.05$.

In all age intervals of pine stands growing in the fresh mixed broadleaved forests, the mean static bending strength of wood was also observed to increase with tree age. The greatest mean value of this property was found in 60-year-old trees (90.08 MPa), while it was lowest in 30-year-old trees (66.75 MPa). The CV decreased with an increase in tree age (Table 10).

Statistic differences in static bending strength were observed between the tree age intervals (Figure 6, Table 11). Analyses showed higher values of wood strength for pines grown in the fresh mixed coniferous forests comparing to the ones from the fresh mixed broadleaved forests (Tables 8 and 10). There are differences of the coefficient of strength quality for trees between 30-, 40- and 60-year-old in the fresh mixed coniferous forests. The highest values were recorded in 40-year-old (16.53 km), and the lowest in 30-year-old trees (15.31 km).

Statistically significant differences in the coefficient of strength quality were found between 30- and 40-year-old, and between 40- and 60-year-old trees. No statistically significant differences were observed between the coefficient of strength quality of 30- and 60-year-old trees (Figure 7, Table 13). The coefficient of strength quality at static bending in the fresh mixed broadleaved forests showed an upward trend with age. The lowest value was recorded in 30-year-old wood (14.82 km), while it was highest in 60-year-old wood (15.54 km) (Table 14). Variation in the coefficient of strength quality decreases with tree age (Table 12).

Table 10. Statistical characteristics for static bending strength of wood from trees grown in the fresh mixed broadleaved forests

Statistical characteristics	Tree age, years		
	30	40	60
	Number of samples		
	112	149	162
Mean, MPa	66.75	78.28	90.08
Median, MPa	64.55	77.30	88.50
Minimum, MPa	39.60	48.50	65.00
Maximum, MPa	99.20	110.10	117.50
Variance	134.37	143.79	165.44
Standard deviation	11.59	11.99	12.86
Coefficient of variation, %	17.37	15.32	14.28
Standard error	1.09	0.98	1.01

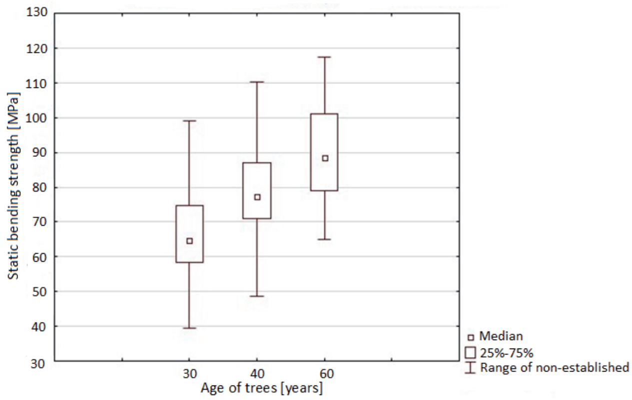

Figure 6. The dependence of static bending strength of wood on the age of trees grown in the fresh mixed broadleaved forests

Table 11. Probability values, *p*, for Tukey's HSD test for static bending strength in individual age intervals grown in the fresh mixed broadleaved forests

Age, years	30	40	60
30		< 0.0001	< 0.0001
40	< 0.0001		< 0.0001
60	< 0.0001	< 0.0001	

Obtained results are significant at the significance level $p < 0.05$.

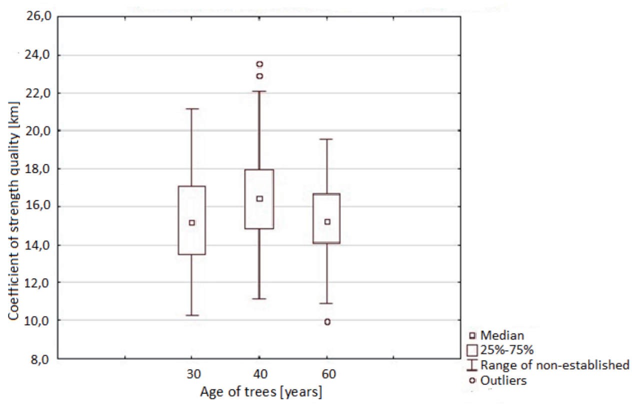

Figure 7. The dependence of strength quality coefficient on the age of trees grown in the fresh mixed coniferous forests

Statistically significant differences in mean values of the coefficient of strength quality were observed between 30- and 60-year-old wood. No statistically significant differences were recorded between the other age intervals (Figure 8, Table 15).

In fresh mixed coniferous forests, the highest mean coefficients of strength quality were found in wood samples of 40-year-old trees, while in wood of trees from the fresh mixed broadleaved forests, the coefficient values increased in tested wood samples with tree age.

Table 12. Statistical characteristics of the coefficient of strength quality for trees grown in the fresh mixed coniferous forests

Statistical characteristics	Tree age, years		
	30	40	60
	Number of samples		
	110	154	130
Mean, km	15.31	16.52	15.33
Median, km	15.16	16.44	15.20
Minimum, km	10.27	11.15	9.95
Maximum, km	21.14	23.54	19.56
Variance	6.61	5.29	3.48
Standard deviation	2.57	2.30	1.87
Coefficient of variation, %	16.79	13.91	12.18
Standard error	± 0.24	± 0.18	± 0.16

Table 13. Probability values, *p*, for Tukey's HSD test for the coefficient of strength quality for wood of trees in individual age intervals grown in the fresh mixed coniferous forests

Age, years	30	40	60
30		0.0002	0.9986
40	0.0002		< 0.0001
60	0.9986	< 0.0001	

Obtained results are significant at the significance level $p < 0.05$.

Table 14. Statistical characteristics for the coefficient of strength quality for wood of trees growing in the fresh mixed broadleaved forests

Measures of position and scatter	Tree age, years		
	30	40	60
	Number of samples		
	112	149	162
Mean, km	14.82	15.36	15.54
Median, km	14.40	15.17	15.75
Minimum, km	8.07	9.07	10.73
Maximum, km	21.80	25.54	19.40
Variance	5.87	6.62	2.44
Standard deviation	2.42	2.57	1.56
Coefficient of variation, %	16.35	16.76	10.05
Standard error	0.23	0.21	0.12

Table 15. Probability values, *p*, for Tukey's HSD test for the coefficient of strength quality for wood of trees in individual age intervals grown in the fresh mixed broadleaved forest

Age, years	30	40	60
30		0.1317	0.0327
40	0.1317		0.7803
60	0.0327	0.7803	

Obtained results are significant at the significance level $p < 0.05$.

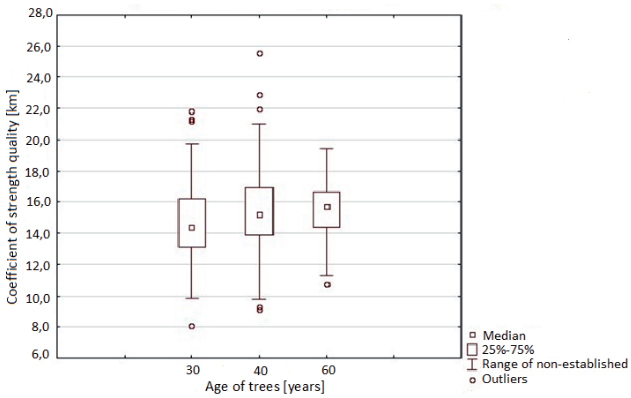

Figure 8. The dependence of strength quality coefficient on the age of trees grown in the fresh mixed broadleaved forests

Discussion

The aim of this study was to analyses fluctuations of density, static bending strength and the coefficient of strength quality at static bending in wood, depending on age and growth conditions, which in this study was expressed for the forest site. In the researched age intervals of 30, 40 and 60 years in trees growing in fresh mixed coniferous forests, mean wood density was observed to increase with tree age. Variation in this physical trait, irrespective of growth conditions (fresh mixed coniferous forest vs. fresh mixed broadleaved forest), changed with age, as indicated by the coefficients of variation. It needs to be highlighted xylem of Scots pine trees growing in the fresh mixed coniferous forest was characterized by a greater compactness compared to trees growing in the more fertile forest site type, i.e., fresh mixed broadleaved forests. Static bending strength of pine wood from trees of both forest sites increased with tree age, with the slightly higher values of this trait of trees from the more fertile site. Irrespective of the forest site, values of the CV in relation to that property decreased with tree age. A lesser variability of this trait was observed in wood of trees from the fresh mixed coniferous forests than from the fresh mixed broadleaved forests, particularly in the age intervals of 40 and 60 years. The coefficient of strength quality at bending in fresh mixed coniferous forests remained within the interval from 15.31 km to 16.52 km, while in trees from fresh mixed broadleaved forests ranged from 14.82 km to 15.54 km, respectively. Greater variation of the coefficient was observed in the 30-year-old trees, while it was lowest in the older trees.

Based on density we may characterize wood in terms of its mechanical properties as well as appraise timber in terms of its utility value (Krzysik 1978, Paschalis 1980, Kollmann and Cöte 1984, Spława-Neyman and Pazdrowski 1999, Witkowska 1999, Witkowska and Lachowicz 2013). Many authors have reported a marked relationship between wood density and its mechanical properties, owing to which this physical property may be an indicator of wood technical quality (Pazdrowski 1988, Saranpää 2003). We need to highlight here extensive wood applications, e.g., in engineering and building structures, in which wooden structural elements are frequently subjected to static and dynamic bending loads. For that, it is essential to determine and analyse static and dynamic bending strength of wood (Kollmann and Cöte 1984, Pazdrowski and Spława-Neyman 1997, Jelonek et al. 2010, Tomczak and Jelonek 2013). Density and static bending strength were markedly determined by tree age and growth conditions expressed in terms of forest site. Optimal forest site conditions for Scots pine (the fresh mixed coniferous forests) guarantee greater wood density and strength than excessively fertile sites (the fresh mixed broadleaved forests).

Relatively low values of wood density, static bending strength as well as greater variability in properties of 30-year-old pines seem to be the effect of several factors, among which an important role is probably played by the chemical structure as well as microstructure of xylem, i.e., cell walls. The share of juvenile wood in stems of younger (30-year-old) pines is greater than in older trees, which affects values of wood properties. Closer to the stem pith and closer to the crown the angles of fibril helices in tracheid walls are less steep, cellulose content is lower, shrinkage during drying is stronger, pure density of wood is lower and the length of anatomical elements is smaller, so this wood is referred to as juvenile wood (Hejnowicz 2012). This type of wood is formed during the first 10–20 years of tree growth.

Results recorded show that wood harvested during intermediate cutting in pine stands of middle age classes, i.e., 40- and 60-year-old, exhibits appropriate properties classifying it for use in various lines of the wood industry. Tested wood from the 40- and 60-year-old trees showed satisfactory values of selected physical and mechanical properties. At the same time, it needs to be stressed these analyses do not definitely clarify the problem either from the scientific or practical point of view. It is advisable to conduct further research aiming at the identification of the greatest possible number of factors modifying properties of the xylem.

Conclusions

1. Density and static bending strength of wood were markedly dependent on the age of trees and growth conditions reflected for the forest site.
2. Analyzed xylem properties increased with the age of trees growing in both studied forest sites.
3. The static bending strength quality coefficient of wood from pines growing in the fresh mixed coniferous forests increased with tree age within the period from 30 to 40 years, while in the case of the fresh mixed broadleaved forests, this strength quality coefficient increased with tree age within the period from 40 to 60 years.
4. More advantageous wood properties were found in pines growing under conditions optimal for this species, i.e., fresh mixed coniferous forests.
5. Wood density from pines in the fresh mixed coniferous forests was greater than that of trees growing in the fresh mixed broadleaved forests.
6. Static bending strength in trees from the fresh mixed coniferous forests was greater than that of trees from the fresh mixed broadleaved forests.

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