Second Thinning Scots Pine Wood Properties in Different Forest Site Types in Estonia

REGINO KASK AND JAAK PIKK

Institute of Forestry and Rural Engineering, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia; e-mail: regino.kask@emu.ee, phone: +372 731 3106

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Abstract

The properties of Scots pine (*Pinus sylvestris*) wood were studied in 27 stands growing on sites of 9 different types in Estonia. Data were collected from 184 trees aged 60-80 years.

Pine wood is the strongest growing on heath and the weakest on raised bogs, its average density being 513-545 kg/m^3 and 414-464 kg/m^3, bending strength 97-100 MPa and 71-83 MPa and compression strength 55-56 MPa and 41-52 MPa, respectively. The heartwood percent is greater in pines grown on more fertile sites. Site type is a highly generalising predictor of strength properties, so site index must also be taken into account. On the contrary, site index may serve as a good predictor of relative strength indicators but only to a limited extent, within the range of adjoining types in the ordination scheme of forest site types.

Key words: Scots pine, site type, site index, heartwood, density, bending strength, compression strength, hardness

Introduction

Differences in properties of Scots pine (*Pinus sylvestris*) wood depending on growth site conditions have been observed for more than a century. The higher the nutrient content of the soil, the better the wood technical properties, other conditions being equal (Hartig1901). According to Jahntov (1913), deterioration in soil conditions leads to decreased wood density and compression strength. Beginning in the late 19th Century, researchers (Schwappach 1897, Omeis 1895, Werberg 1930, Kõresaar 1938) have correlated wood properties with growth site index. One of the best indicators of growth site fertility is site index; however, pine forests of site index 4-5 grow both in peatlands and dry heaths, where nutrition conditions vary widely. The effects of these conditions on wood properties are an issue of interest to today’s theoreticians and practician. Averaged data on wood properties of main tree species have been concentrated into numerous handbooks and catalogues; however, they predominantly deal with mature trees. Fairly frequently, the data available characterise wood strength at breast height alone, disregarding the vertical variation of strength indicators in tree trunks.

Pine is a dominant tree species in Estonia’s forests, taking up 33.6% of the total forest area and 29.1% of the growing stock. The average per-hectare volume was 104 m^3/ha in 1958 and reached 232 m^3/ha in 2006 (Yearbook…2008). Year by year, both wood supply, and demand, primarily for high-quality pine timber, are increasing. Yet the recorded data concerning the quality and properties of Estonian tree species are extremely scarce, and at times controversial.

In Europe, research has been focused on delving deeper into the wood properties of the most widespread tree species and exploring the physiological processes in wood formation (Wilhelmsson *et al*. 2001, Aleinikovas and Grigaliūnas 2006, Jelonek *et al*. 2006, Mandre *et al*. 2007). The structure and properties of wood are affected by genetic, environmental and anthropogenic factors acting during the formation of wood cell and tissue (Lindeberg 2001, Bektas *et al.* 2003). A number of authors (Andrews *et al*. 1999, Finér and Kaunisto 2000) have pointed out differences in the levels of nutrients and other elements found in stemwood, depending on the growth site. And the degree of nutrient retranslocation from senescing sapwood may be influenced by soil nutrient availability.

As early as 1897, Wijkander found that the technical properties of pine wood reach their maximum in annual rings formed at the age of 61-90. For this reason in the last ten years, pine wood properties have been researched in Estonia’s younger, 60-80-year-old pine forests (Pikk *et al*. 2004, Mandre *et al*. 2007, Kask *et al*. 2008). Moreover, a fifth of the pine wood obtained comes from maintenance felling.

The rapidly changing economy, ever-modernising wood processing technology, warming climate, environmental pollution, etc. creates the need for constant regional research at stand, tree, macro- and microlevels. The objective of this paper was to concentrate the research results on pine wood in Estonia and summarize the variation in the properties of wood obtained from the second commercial thinning on the main Scots pine site types.

Materials and methods

The selected pine stands were situated on the most widespread types of pine sites in Estonia (Table 1). The existing classification of Estonian forest site types is from Lõhmus (1984). According to this classification, forests are divided into 22 forest site types. Each site type has as many subtypes as it has neighbouring site types (Lõhmus 1995). The site type index determines the average height of a stand at the age of 50.

Table 1. The number and characteristics of felled sample trees by forest site types

Site type	Site index	Number of sample plots	Tree age	DBH, cm	Height, m	Felled sample trees
Cladonia	3.5	2	81.5	18.9	17.3	12
Calluna	4.0	1	70.0	18.5	15.0	6
Rhodococcum	1.6	5	71.8	20.3	21.3	34
Myrtillus	1.4	10	70.7	24.0	22.7	60
Dry swamp	2.9	2	80.0	21.9	19.0	12
Drained birch fen	3.7	1	70.0	16.6	14.4	8
Drained transitional bog	3.6	2	70.0	20.7	17.7	12
Drained raised bog	5.2	2	88.0	15.0	14.1	24
Raised bog	5.3	2	77.5	14.1	10.9	16

In each of the 27 stands selected, 6-12 sample trees were felled. From these, specimens were prepared in compliance with international standards. More trees were felled in stands with a smaller average breast-height diameter (DBH). According to Saladis and Aleinikovas (2004), no less than six trees must be examined in a single forest stand in order to obtain wood properties with 10% accuracy. Sample blocks for determining wood properties were cut at the height of 1.3m ($h_{1.3}$), at half tree height ($h_{1/2}$) and at three-quarters of tree height ($h_{3/4}$); these stem sections roughly represent the butt log, the second log and the pulpwood, respectively

The following properties were subjected to study: annual ring width, latewood proportion, heartwood percent, oven-dry density, bending strength, compression strength and end-grain surface hardness.

The specimens for determining wood density were prepared in compliance with the requirements of ISO 3130-1975 and ISO 3131-1975. Experiments for determining mechanical properties were prepared and conducted in conformity with ISO standards 3131-1975, 3133-1975, 3787-1976 and 3350-1975. Strength tests were carried out using the universal test press INSTRON 3369.

The WinDENDRO™ software was used to measure annual ring widths and latewood proportions. Oven-dry density was determined in 7,360 specimens upon reaching a constant weight at 103 ƫC.

Seven thousand three hundred and sixty specimens (7,360) were prepared for the tangential static bending strength test and the same number for determining the compression strength parallel to grain. A total of 4,416 experiments were performed to establish the end-grain hardness. The mechanical testing took place with wood moisture content 8±0.5%. In the present paper, all the mechanical properties were reduced to a 12% wood moisture level. Weighted average strength indicators for each stand at three different heights, and then strength indicators were found for all the stemwood. For each site type, the vertical reduction of tree trunk strength properties was calculated in percentages.

Differences in the average wood properties between the site types were estimated using one-way ANOVA. The critical *P*-value was 0.05. Statistical calculations were performed with Excel 2003 (Microsoft Corp., USA). Regression trendlines and R-squared (R^2) were calculated to test the relationships between wood density and site index.

Results

The test results reveal great variations, which were due to the different horizontal and vertical structure of each individual tree trunk. Apart from that, wood formation during the growing season had been influenced by changes in growth conditions (thinning, draining, insect damage).

The weighted average stem strength indicators of the pine forests researched at three different heights were widely divergent (Table 2). The annual ring width increased but all the other strength indicators decreased towards the crown. The decrease was significantly more intensive than from breast height to half tree height than for $h_{3/4}$. Particularly great was the decrease in heartwood proportion in the crown part of the stem. Correlation between the strength indicators given in Table 2 was very strong (R= 0.85-1.00). A remarkable correlation between oven-dry density and site index was found (Figure 1).

The pine latewood at breast height was 30-43%. At half tree trunk height the proportion of latewood was significantly smaller, 22-33%, and, at three-quarters of tree trunk height there is even less latewood, 18-32%.

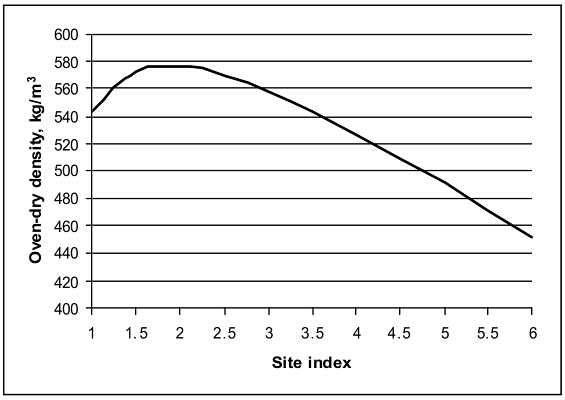

Figure 1. The oven-dry density of pine wood on DBH in different site index classes

Table 2. Wood average properties at three different stem heights and their alteration towards the top (%)

Relative height	Growth ring width, mm	Late-wood, %	Heart-wood, %	Oven-dry density, kg/m³	Bending strength, MPa	Compress-ion strength, MPa	End-grain hardness, MPa
$h_{1.3}$	1.3	40.5	46.4	540.8	104.1	60.2	40.9
$h_{1/2}$	1.9	31.8	19.7	458.2	82.0	50.1	35.9
$h_{3/4}$	2.4	27.7	4.4	434.6	71.8	45.0	34.5
Alteration, %							
$h_{1.3}$…$h_{1/2}$	44.1	-21.5	-25.4	-15.3	-21.2	-16.7	-12.3
$h_{1/2}$…$h_{3/4}$	22.3	-12.8	-77.8	-5.2	-12.5	-10.1	-3.7

An analysis by individual site types revealed significant differences in stemwood strength indicators. Stands growing on fresh and dry soils showed good averages for stem strength indicators. The same indicators, however, were poor for trees growing in swamps and bogs. An exception among the technical properties appeared to be end-grain hardness, which manifested greater variations than the other characteristics; according to our findings, its variations were relatively greater on site types with poorer fertility (Table 3).

Variations in strength indicators between the site types were notable. As could be expected, they were greater in annual ring width and heartwood proportion. As for the other properties, the variations remained within the range of 8.4-10.9%.

The alteration of strength properties along the stem in percent per current metre from breast height to half tree height and then to $h_{3/4}$ also varied widely (Table 4), depending on the site and site index. The percent of per-metre deterioration of the properties up to half tree height was smaller in stands with best site index (up to class 3).

Table 4. The longitudinal decrease of strength properties (percent per meter)

Site type	Site index	Oven-dry density		Bending strength		Compression strength		End-grain hardness	
		$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$	$h_{1.3}$ – $h_{1/2}$	$h_{1/2}$ – $h_{3/4}$
Cladona	3.5	2.8	0.4	3.4	3.1	2.8	3.6	2.4	0.0
Calluna	4.0	3.0	1.8	3.7	4.4	3.5	5.1	2.4	2.2
Rhodococcum	1.6	2.2	1.0	2.4	3.0	2.3	2.1	1.8	0.2
Myrtillus	1.4	1.8	1.1	2.3	2.0	1.6	2.5	1.6	2.6
Dry swamp	2.9	2.3	0.3	2.7	1.9	2.2	0.9	0.9	0.7
Drained birch fen	3.7	0.7	0.0	3.6	1.4	2.1	1.9	1.0	0.9
Drained transitional bog	3.6	1.8	0.0	3.0	0.5	2.0	1.7	1.6	0.0
Drained bog	5.2	3.8	0.0	3.3	5.5	3.4	3.1	1.4	0.2
Raised bog	5.3	5.1	1.3	3.4	10.3	2.4	5.6	2.1	0.0
Average	3.5	2.6	0.7	3.1	3.7	2.5	3.2	1.7	0.7

The relation between longitudinal decrease of bending and compression strength and site index is notable. The relation is weak between decrease of hardness and site index (Figure 2).

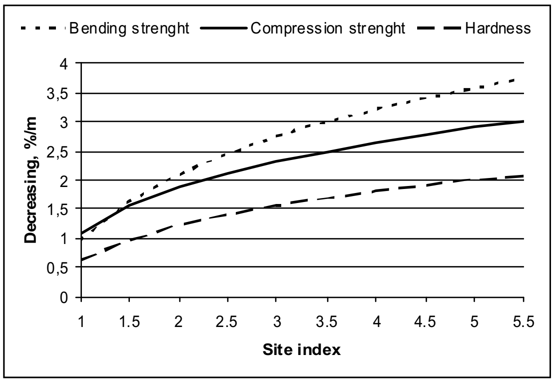

Figure 2. The longitudinal percent-per-meter decreasing of strength properties in different site index classes

Table 3. Pine stem average strength properties and heartwood proportion by different forest site types

Site type	Site index	Stem average						
		Odd, kg/m³	Bs, MPa	Cs, MPa	Egh, MPa	Arw, mm	Lw, %	Hw, %
Cladonia	3.5	513±10	100.2±2.3	54.7±0.9	37.2±1.5	1.15±0.05	33.9±1.2	17.2±3.8
Calluna	4.0	545±12	97.1±4.1	55.7±1.7	36.9±1.7	1.42±0.06	35.8±1.1	14.3±2.1
Rhodococcum	1.6	479±14	86.9±4.3	56.4±2.8	27.1±1.0	1.71±0.08	31.9±1.4	17.3±3.2
Myrtillus	1.4	482±15	89.1±4.4	54.8±3.0	29.7±0.9	1.92±0.08	32.8±1.5	25.2±4.3
Dry swamp	3.3	464±12	80.2±3.0	49.8±1.5	31.9±1.1	1.70±0.05	35.5±1.0	21.5±1.7
Drained birch fen	3.7	446±15	79.3±4.5	48.7±2.3	34.2±1.5	1.65±0.09	35.9±2.0	13.2±2.1
Drained transitional bog	3.6	447±11	83.2±3.7	44.5±1.2	35.2±1.1	1.54±0.12	34.5±1.1	17.4±1.9
Drained raised bog	5.2	450± 8	77.7±2.0	52.1±1.1	34.7±1.4	1.62±0.06	31.3±0.9	10.7±1.7
Raised bog	5.3	414±13	71.6±3.4	41.4±1.8	33.7±1.6	1.54±0.06	27.0±1.1	7.1±1.6
Variation,%		8.4	10.9	10.3	9.9	13.5	8.6	34.1
ANOVA p-value		<0.0001	<0.0001	<0.0001	0.0025	<0.0001	<0.0001	<0.0001

Odd – Oven-dry density, Bs – Bending strength, Cs – Compression strength, Egh – End-grain hardness, Arw – Annual ring width, Lw – Latewood, Hw – Heartwood

Discussion and conclusions

The mechanical properties of wood are strongly correlated with its physical properties, the most important of which are the wood density, latewood proportion in annual ring and annual ring width. However, the great variations in our research results demonstrate that they are insufficient for estimating the mechanical properties of wood where growth rates are the same but growth conditions are different. Maybe consideration must also be given to fibre length, cell wall thickness, growth tensions, the levels of various elements and compounds, *etc.*

In Scots pine, the heartwood differs from sapwood by a number of properties and by chemical composition. Sapwood/heartwood proportions have an effect on technological properties: moisture content, density, shrinkage and water-vapour diffusivity (Allegretti *et al.* 1999). For this reason, heartwood and the phenomenon of its formation has been studied from various aspects (Ogner and Bjorn 1988, Helmisaari and Siltala 1989, Gjerdrum 2003). According to Bamber (1976), the heartwood formation is a developmentally controlled process functioning as a regulator of the amount of sapwood in the trunk, to keep it at the optimal level. According to the so-called "pipe model theory" (Shinozaki *et al*. 1964), the sapwood functions to guarantee the movement of required amounts of nutrients in the stem cross-section as determined by crown size. In this connection, age is the main factor in heartwood formation (Gjerdrum 2003). The correlation between the growth site and the heartwood content is weak (Björklund 1999). Additionally, the variation in the heartwood content between trees within the same DBH-class, growing in the same stand, is higher than the variation between stands.

Among the indicators researched in this paper, the heartwood proportion manifested the greatest variations between the site types as well as within a concrete site type (Table 2). For instance, in one *Myrtillus* site type stand, the heartwood content was 15% while in another it was 30%, although the average breast height diameter and the height of the stands as well as the stand densities were almost identical. If, however, the heartwood percent is the best indicator of tree maturity (Kärenlampi and Riekkinen 2002), and if the heartwood content is as widely varying under similar growth conditions as our findings show, it cannot be the best property to evaluate maturity.

Normally, the heartwood percent is higher under better growing conditions. Thus, our findings have not confirmed the position (Björklund 1999) that the heartwood formation is little affected by where it is grown, and only to a limited extent affected by how it is grown. Additionally, the vertical range of the heartwood may be affected by a number of factors, of which the tree crown appears to be the most important (Jelonek *et al.* 2006).

Sapwood area significantly decreased with decreasing soil moisture. According to some results, the pipe model theory is not valid (Mäkelä and Vanninen 2001). However, according to Rikala (2003) there is no clear evidence that the heartwood proportions of peatland trees are higher than those of trees grown on mineral soil sites. The heartwood percent was the lowest in our bog pine forests, where the soil moisture is high, stand density low and the tree crown volume is relatively big.

Wood density has the greatest influence on mechanical properties. According to Sipi and Rikala (2000), the basic density and amount of heartwood depend, *e.g.*, on geographic location, age and growth rate. At one and the same latewood percent and moisture level the density of the heartwood is usually greater than that of sapwood due to various substances (waxes, resins, tannins, *etc.*) accumulating in heartwood. As a result of the heartwood formation, the density of heartwood rises by 6-8% (Werberg 1930). However, wood density is often different at one and the same latewood percent. For instance, when comparing the density of site index 4 heath pine wood and that of the swamp pine wood of the same site index and latewood percent, the density of the latter was significantly lower (Table 3). It is known that the correlation between the growth site and the latewood content is weak (Björklund 1999). Here, consideration must be given to the effect of growing conditions, primarily the nutritional environment, on the accumulation of the chemical elements, which has been addressed in a number of studies (Helmisaari and Siltala 1989, Ogner and Bjorn 1988, Cave and Walker 1994, Andrews *et al.* 2004). Thus, in Finland the wood density of Scots pine increases from north to south while the opposite is true for spruce (Hakkila 1979, Kärkkäinen 1985).

Owing to variations in wood density, an analogous increase is not observable on the relatively small territory of Estonia. We can only note that the average pine wood oven-dry density in our experiments (471 kg/m^3) was similar to that of southern Finland, 470 kg/m^3 (Hakkila 1979). Surprisingly high is pine wood density in Poland, 540 kg/m^3 at the wood moisture level of 10% (Helinska-Raczkowska and Molinski 2003).

Noteworthy is the dependence of breast-height wood density on site index in some types of growth sites (Figure 1). One can see that due to intensive growth on very fertile sites, wood density there remains lower than on fresh sites with lower fertility. In a stand growing on mineral soils of a high site index

(1a) one can observe lower strength indicators, which is confirmed by data from the literature (Ericson 1960, Björklund and Walfridsson 1993). Hence, the site index is not a good wood oven-dry density predictor. According to our data, the strength of the relationship between stand average density and site index is characterised by determination coefficient R^2= 0.60.

The mechanical properties of softwoods decrease remarkably with increasing growth rate. The growth rate has a large effect on the mechanical properties, which can be accounted for by the affected oven-dry density. In addition to this indirect effect through specific gravity, the growth rate still has an additional effect on the mechanical properties that cannot be explained by oven-dry density (Zhang 1995).

The research results by site types (Table 3) manifest the dependence of mechanical properties (bending and compression strength and hardness) on wood density, while the latter was in turn largely influenced by the amount of latewood contained in the wood. As a rule, when a tree grows the amount of latewood in the annual ring at the same height is greater in each successive year than in the previous year, as a consequence of which the wood of older stems on average is denser and stronger than that of young trees.

The wide variations in the results were due to the heath pine forests, wood density and several strength properties which exceeded the respective indicators for other growth sites, even if the site index was relatively low (3.5-4). As another exception, Veermets (1960) points out the alvar pine forests, the wood compression strength which does not depend on wood density, as it does on sites of other types.

The strength properties of wood on sites of dry mineral soil types were better than on fresh soil sites. Peat soils, however, exhibited better wood strength properties on drained, more fertile sites. The strength properties of pine wood were clearly poorer on our low-fertility wet sites, as in Finland (Rikala 2003).

Site type is a highly generalising predictor of strength properties, so site index must also be taken into account. Site index may serve as a good predictor of wood relative strength indicators but only to a limited extent, within the range of adjoining types in the chart of ordinated forest site types.

The formation of wood properties is influenced by a number of silvicultural measures. Draining reduces basic density and the latewood proportion (Rikala 2003). In Estonia, such an effect is observable only in post-draining years, when draining results reduced the basic density and the latewood proportion. Later, the effect is opposite: the latewood proportion and the density increase and ultimately good results are achieved, as in Russia (Perelygin and Ugolev 1971).

Of mechanical properties, variations are the greatest in end-grain surface hardness. Hardness is highly dependent on grain direction. The strength of the radial and tangential surface is directly connected with the end-grain surface. For example, according to Mihailit□enko and Sadovnit□i (1983), end-grain strength exceeds tangential and radial surface hardness by 40%. According to Holmberg (2000), the hardness value of a radial surface, *i.e.* when load is applied in tangential direction, is about half the end-grain surface hardness.

In this research, greater variations in end-grain surface hardness were manifested in wood grown on more fertile sites, where, due to the greater width of annual rings, the test press ball might hit only early- or latewood. Accordingly, a smaller or greater result was obtained. The hardness of a wood end-grain surface with narrower annual rings therefore manifested less variation and was often greater than the average. With particularly wide annual rings, the probability of the ball hitting early wood was greater and the test result was therefore smaller.

The decrease in pine wood density and strength properties towards the tree-top has been widely covered in the literature (Veermets 1960, Sipi and Rikala 2000, Repola 2006). According to Repola (2006), the difference in wood density between the butt and the top in Scots pine stems is more than 100 kg/m^3. In this study, wood density in Scots pine decreased from $h_{1.3}$ to $h_{3/4}$, and the difference in wood density in pine stems was over 106 kg/m^3. This result is in agreement with previous studies (Hakkila 1966, Björklund 1984, Repola 2006).

In stands of site index 1 and 2 wood density and strength properties decreased towards the top by 1-2% per metre, whereas in stands of site index 5 the wood density and bending strength on average decreased by 3.5% per metre. On poorer sites, the reduction in compression strength and end-grain surface hardness towards the top was less intensive (3%). The extent of deterioration in the properties of wood obtained from tree stems depending on the site index is characterised in Figure 2. Of mechanical properties, bending strength had the strongest correlation with site index (R^2=0.75).

The longitudinal percent-per-metre reduction of bending strength, compression strength and end-grain surface hardness in tree stem is smaller on more fertile sites.

As early as in 1897, Wijkander in Sweden investigated pine technical properties at the heights of 1, 3, 10 and 12 m and ascertained that compression strength drops by 1.6% per current metre within the range of 1-3 metres, by 1.7% at 3-10 metres and by 1.2%

at 10-12 metres. The overall decrease from 1 to 12 metres was 16%. Apparently, the test material was obtained from a relatively fertile site type.

We have to take into account that the site index is determined based on age and height. The stands studied were of relatively similar ages, falling within one age group. In a sense, therefore, the site indexes given in the figures also indicate the different heights of the stands. The tree height, in turn, determines the variation of strength properties in the lower half of the stem. The longer the stem, the less the variance in strength properties of its timber.

In Estonia, the second thinning Scots pine wood is the strongest growing on heath and the weakest on raised bogs, its average density being 513-545 kg/m^3 and 414-464 kg/m^3, bending strength 97-100 MPa and 71-83 MPa and compression strength 55-56 MPa and 41-52 MPa, respectively.

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ТЕХНИЧЕСКИЕ СВОЙСТВА СОСНОВОЙ ДРЕВЕСИНЫ СРЕДНЕВОЗРАСТНОГО ДРЕВОСТОЯ В СВЯЗИ С УСЛОВИЯМИ МЕСТОПРОИЗРАСТАНИЯ В ЭСТОНИИ

Р. Каск и Я. Пикк

Резюме

Свойства древесины сосны (*Pinus sylvestris*) исследовали в 27 древостоях 9-ти типов местопроизрастания леса. Всего было взято 184 модельные деревья возрастом 60-80 лет. На срубленных деревьях выпиливались 3 пробные кряжи: на высоте груди, на середине высоты ствола и на высоте ствола 3/4.

Выяснилось, что наилучшими техническими показателями древесина сосны отличается на верещатниках и более низкими показателями - на верховом болоте. Средняя плотность соответственно была 513-545 кг/м^3 и 414-464 кг/м^3. Сопротивление на статический изгиб в тангентальном направлении соответственно было 97-100 МПа и 71-83 МПа и сопротивление на сжатие вдоль волокон соответственно 55-56 МПа и 41-52 МПа. Процент ядра в стволе наибольший у сосны, растущей на плодородных почвах.

При оценке технических свойств древесины основным определяющим показателем является тип местопроизрастания. Бонитет также может служить хорошим индикатором твердости древесины, однако ограниченно, только в отношении подобных типов местопроизрастания.

Технические свойства (изгиб, сжатие, твердость) от высоты груди до середины высоты ствола уменьшаются меньше в древостоях, растущих на плодородных почвах.

Ключевые слова: сосна обыкновенная, тип местопроизрастания, класс бонитета, ядро, плотность, изгиб, сжатие, твердость