VARIATION OF BASIC DENSITY AND BRINELL HARDNESS WITHIN MATURE FINNISH *BETULA PENDULA* AND *B. PUBESCENS* STEMS

Henrik Heräjärvi

Research Scientist
Finnish Forest Research Institute
Joensuu Research Centre
P.O. Box 68
FIN-80101 Joensuu, Finland

(Received November 2001)

ABSTRACT

The objective of this study was to analyze the variation in basic density between different horizontal and vertical locations within mature Finnish *Betula pendula* and *B. pubescens* stems. In addition, the dependence of Brinell hardness in radial direction, which is of importance especially for the parquetry, veneer, and plywood industries, on the basic density was investigated. Furthermore, the sources of error in the Brinell hardness test according to EN 1534 were analyzed. Both basic density and Brinell hardness were measured from small, defect-free specimens. The average basic density of *B. pendula* and *B. pubescens* were 512 kg/m^3 and 478 kg/m^3, respectively. Concerning both birch species, wood material near the pith was clearly less dense than near the surface of the stem. The average Brinell hardness of *B. pendula* specimens was 23.4 MPa, and that of *B. pubescens* specimens was 20.5 MPa. Brinell hardness was found to be positively correlated with basic density. Therefore, the assumption that Brinell hardness varies within a birch stem similarly to basic density is confirmed. The test method according to the EN 1534 standard was found to be precise enough but unnecessarily laborious for hardness tests. Finally, an alternative method is suggested for determining Brinell hardness on an industrial scale.

Keywords: Basic density, Brinell hardness, *Betula pendula, Betula pubescens,* furnishing, parquet, veneer, plywood.

INTRODUCTION

The quality of wood can be characterized by a number of different properties, depending on their importance to the end-use of the product. Density, which denotes the weight of the wood substance contained in a unit volume, is an important quality indicator for basically all uses of wood. Density depends primarily on the ratio between the volume of the cell walls and the volumes of the intracellular and intercellular spaces, since the specific gravity of the cell wall substance is practically constant (Hakkila 1966).

Several different ways to define density are used in literature. Usually, however, the dry-matter weight of a wood specimen is compared to its volume. The definition of volume, on the other hand, varies depending on whether it has been measured from an oven-dry specimen or from a specimen with certain moisture content. If the volume of a specimen is measured when its moisture content is above the fiber saturation point, the term basic density of wood is used for the density value obtained (e.g., Hakkila 1966; Wagenführ and Schreiber 1989).

Density is correlated with the mechanical properties of wood. Hence, the variation of the density of the wood material can be used for indirect description of strength for different tree species, or fractions of wood from different locations within a single stem. For instance, in waferboard manufacturing, tree species of different densities are mixed together in order to obtain maximum internal bond strength and bending strength for the product (Gertjejansen and Hedquist 1982; Pagano and Gertjejansen 1989).

Weight, which is a direct derivative of density, influences especially the usability of the wood material for different purposes. It is of special importance in transporting vehicles such as aircraft and ships, considering both their construction and load-bearing capacity. Heavier materials are more expensive to transport, in particular by air or sea. On the other hand, the density of wood plays a significant role in industrial timber and wood chip scaling.

B. pendula wood material has often been observed to be denser than *B. pubescens* wood (e.g., Kujala 1946; Hakkila 1966, 1979; Velling 1979; Wagenführ and Schreiber 1989; Verkasalo 1998). Kujala (1946) observed a considerable increment of 200 kg/m^3 in the density of birch wood from the pith to the surface. Similar observations, even if not as considerable as Kujala's (1946), were presented in the studies by Jalava (1945), Hakkila (1966), Tamminen (1970); and Verkasalo (1998). Vertically, the variation of density is smaller; however, the density decreases from the stump to the top of a birch tree (Jalava 1945; Kujala 1946; Hakkila 1966; Tamminen 1970; Velling 1979; Verkasalo 1998). It has also been shown that birch produces denser wood as the tree ages (Hakkila 1979; Bhat 1980; Verkasalo 1998). Bearing in mind the high correlation between density and mechanical and physical properties of wood, it appears that the variation of density within a stem may have significance also for different end-uses of birch products.

The hardness of wood is often considered an operational or a practical property rather than an individual mechanical property. This is affected by the fact that hardness is actually derived from several different forces, such as friction, shearing and compressive forces appearing during the test (Kollmann and Côté 1968). The varying definitions for hardness can be roughly summarized as follows: hardness is the ability of a material to resist an intrusion by an external object. As for wood, the definition, however, leaves many possibilities for clarifications. In fact, the value of hardness is, more than any other mechanical property, dependent on the testing conditions and methods used (e.g., Kúdela 1998). For instance, even a 4–5 times higher hardness was observed for latewood than for earlywood in Lassila's (1926) studies on Finnish softwoods. Therefore, when testing hardness, it is essential to focus the measurements on either earlywood or latewood, or at least report if the results represent both earlywood and latewood. According to Lassila (1926), the hardness of wood is dependent on 1) the amount of force used, 2) tree species, 3) the internal structure of wood, 4) the position of tested surface (radial, axial, or tangential), 5) the moisture content of wood, 6) the temperature of wood, 7) the weight of wood. The first mentioned, however, should not influence the results, as far as current expectations for an objective measurement method are considered. Lassila (1926) also, surprisingly, mentioned that density itself obviously has not as clear a correlation with hardness as "what could be expected."

Dunham et al. (1999) investigated the effects of the growth rate on the strength properties of sawed beams of cultivated *Betula pendula*. They found a relatively high correlation ($r^2 = 0.45$) between the density and hardness of birch wood.

In Europe, the most widely used method for determining the hardness of wood material is the Brinell test, whereas in North and South American studies the most commonly used method is the Janka test (e.g., Siimes and Liiri 1952; Niemz and Stübi 2000). In the Brinell test according to EN 1534, a constant force and predetermined time are used to indent a round steel ball with a certain diameter into the specimen, after which the size of the residual indentation on the face of the specimen is measured. In the Janka test, on the other hand, a round steel ball is indented into the specimen by half of its diameter, and the force required directly gives the hardness in N/mm^2. The Janka method is not widely accepted in Europe since there is a considerable possibility of failure due to the cell-wall compression (Niemz and Stübi 2000).

Schwab (1990) compared different methods for determining the hardness of solid wood, and concluded that the Brinell test gives the most reliable results. The justification for the argument was that in the Brinell test only, the variation of the wood material in two different directions is, at least somehow, taken into consideration. Earlier, Kontinen and Nyman (1977) compared two different methods for determining the Brinell hardness. First, they calculated the results using the depth of the residual indentation formed on the specimen. Second, the results were calculated by using the diameter of the indentation. The hardness values obtained by measuring the diameter were ca. 60–160% higher than those obtained by measuring the depth of the indentation. This was due to reverting of the indentation after the load had been removed. Therefore, Kontinen and Nyman (1977) concluded that using the depth of the indentation is a better and more accurate method. Similar conclusions were published by Niemz and Stübi (2000). Jalava (1945) used "the combined Brinell-Janka test," where a steel ball with an area of 1 cm^2 was indented into wood until the depth of its radius by using a constant speed of 0.8 mm/s, and the force needed for the procedure was measured. This method was actually very similar to the traditional Janka hardness method.

The hardness of wood is of importance in plank floorings and facing furniture veneers, as well as kitchen and office furnishing. In addition, hardness is the most important characteristic for wood intended for parquet manufacturing (e.g., Lutz 1977). Birch wood material is in keeping with all these end-uses due to its mechanical strength, as well as homogeneity of appearance and color. So far, no results have been published regarding the variation of hardness within birch stems. Furthermore, few studies have been published either for softwoods or hardwoods, where the current standard EN 1534 was used.

The objective of this article was, first, to detect the variation of basic density within mature *Betula pendula* and *Betula pubescens* stems, as well as the possibilities to predict it on the basis of location parameters. Second, the dependence of Brinell hardness measured according to EN 1534 on the basic density was studied.

MATERIALS AND METHODS

Two different lots of specimens were prepared: one for the basic density tests (lot 1, 6304 specimens) and another for the Brinell hardness tests (lot 2, 650 specimens). The basic density of the specimens, however, was measured from both lots. Thus, the dependence of Brinell hardness on basic density could be detected from lot 2, and then generalized into lot 1. With a larger number of specimens, lot 1 was used to detect the horizontal and vertical variation of basic density within birch trees. Only defect-free specimens were allowed for both lots 1 and 2.

The specimens originated from 89 *Betula pendula* (age 60–141) and 171 *Betula pubescens* (age 60–120) stems sampled from 21 stands altogether, which were located in southern, central, and eastern Finland (61–65° N, 24–31° E). All *B. pendula* trees grew on fertile mineral soils (*Oxalis-Myrtillus* type (OMT) and *Myrtillus* type (MT)). Seventy-nine of the *B. pubescens* trees were located on drained peatlands (herb-rich drained peatland forest (Rhtkg) and *Vaccinium myrtillus* drained peatland forest type 1 (Mtkg)) and 92 on mineral soils (OMT, MT).

The material for the basic density tests was prepared from discs, which were systematically cut from the heights of 0, 4, 8, 12, and 16 meters of each tree. From smaller trees, however, the highest disc obtained was from 12, or in some cases from 8 meters. The discs were sawed into ca. 20 × 20 × 40-mm specimens, as shown in Fig. 1. Each specimen was coded by stand number, sample tree number, and vertical and horizontal location within the sample tree.

Basic density was determined for both lots of specimen as follows:

$$D = M_0 / V_g \qquad (1)$$

where D denotes the basic density (g/cm^3) of the specimen, M_0 denotes the dry-matter weight of the specimen (g), and V_g denotes the green volume of specimen, i.e., the volume (cm^3) when the moisture content of wood is above the fiber saturation point. For further calculations, the density values were transformed into kg/m^3.

The Brinell hardness specimens were prepared of lumber pieces sawed pith-centrally into 25-mm fresh thickness. The saw logs, on the other hand, represented the entire tree from the base up to the stem diameter of 12 cm. The location of the specimen in each lumber piece was

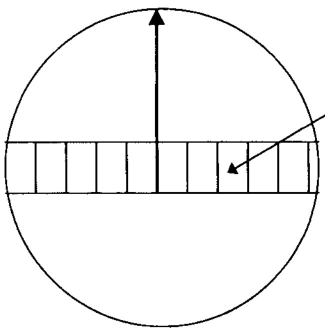

FIG. 1. Alignment of the basic density specimens within the sample disc. Positioning arrow was parallel in all discs within individual tree; thus density specimens from different heights were located parallel, as well.

determined so that the test could be performed exactly into radial direction, into defect-free wood, and the first contact surface being earlywood. As shown in the literature, the test for Brinell hardness is highly dependent on the location of the test point regarding earlywood and latewood (e.g., Lassila 1926). Birch wood being in question, however, the latewood rings are very narrow compared to the earlywood rings, thus, hardly affecting the overall properties of wood.

All specimens within a single tree were tested in parallel direction. The minimum thickness allowed for the specimens after planing the surface was 18 mm, the minimum length in parallel to grain direction was 100 mm, and the minimum width in tangential direction was 100 mm. In practice, most of the specimens were larger than the above-mentioned minimum dimensions. The moisture content of the specimens at the moment of hardness test was determined according to the following formula:

$$MC = ((M_l - M_0)/M_0) \times 100 \quad (2)$$

where MC denotes the moisture content of the specimen during the Brinell hardness test (percentage of water weight of the specimen dry-matter weight), M_l is the weight of the specimen at the moment of testing (g), and M_0 is the dry-matter weight of the specimen (g).

The Brinell hardness was tested according to EN 1534 in the wood laboratory of the University of Joensuu. The machine used was FMT-Mec100 by Matertest Ltd. In the laboratory, a constant relative humidity of 65% ± 3%, and temperature of 20°C ± 2°C were maintained, in conditions where the equilibrium moisture content (EMC) of wood ends up close to 12%. Before testing, the specimens were conditioned in the test laboratory at least for four weeks.

In the Brinell hardness test according to EN 1534, a constant force of 1 kN was used, and the diameter of the residual indentation on the face of the test specimen was measured with an accuracy of ± 0.1 mm two times, at right angles to each other. A break period of 3 min was taken between the removal of the load and the moment of measurement. This break is due to the possible reverting of the indentation after the load has been removed. An electronic calliper was used for the diameter measurements. Diameters were measured both parallel and perpendicular to the grain in order to take into account the inhomogeneous structure of wood in different dimensions. The mean value of the two diameter measurements was used in calculating the result:

$$HB = \frac{2 \times F}{\pi \times D\left[D - \left(D^2 - d^2\right)^{1/2}\right]} \quad (3)$$

where HB is the Brinell hardness in MPa (= N/mm^2), π is the pi factor ($\approx$ 3.14), F is the nominal force in newtons, D is the diameter of the steel ball in millimeters (10 mm), and d is the mean diameter of the residual indentation in millimeters.

In addition to the mean value and outermost values, the characteristic value for Brinell hardness was calculated by the formula (EN 1534):

$$X_k = m - (t_{05} \times s) \quad (4)$$

where X_k is the characteristic value for the Brinell hardness in MPa, m is the mean value of the sample, t_{05} is the student coefficient for a one sided 5% liability (=1.645 for the lot sizes tested), and s is the standard deviation of the studied lot.

The basic density variations being in question, the differences between the sites and birch species were, first, tested using analysis of variance. For the further tests, the observations were grouped in accordance with the results of the above-mentioned tests. The dependence of the basic density on location parameters, as well as on average annual ring width at a 1.3-meter height, was studied using regression analysis. In addition, mean values for the variation of basic density from the pith to the surface were calculated for the heights of 0, 4, 8, 12, and 16 meters, and in order to illustrate the variations, smoothed as continuous lines using spline-function. The dependence of Brinell hardness on the basic density was studied by linear regression analysis.

The Brinell hardness test method is often characterized by uncertainty or even unreliability. In particular, the manual measurement of the diameter of the residual indentation is considered a highly error-susceptible phase of the test (e.g., Kontinen and Nyman 1977; Niemz and Stübi 2000). Measuring the diameter precisely, particularly in parallel to the grain direction, was found difficult also in this study. Therefore, a magnifying glass and coloring the surrounding, i.e., the non-pressed surface of the specimen, by a graphite crayon were used to increase the accuracy of measurements.

The possible sources of error, which are related to the test method, were also intensively evaluated during the analysis of the results. First, the possible systematic error, as well as the size of the error in individual measurements caused by the manually used calliper, was studied. For this reason, the depth of the residual indentation was measured automatically by the test machine. The depth-measurement started when the nominal value of force directed towards the steel ball exceeded 5 N in the beginning of the test. The maximum depth value observed during the test was recorded. As a result of the two measurements, the correlation could be calculated between the depth of the indentation measured by the machine and the diameter of the indentation measured manually. Second, in order to assess the magnitude of the within-specimen variation in Brinell hardness, a sample of 50 specimens was tested by making two adjacent indentations close to each other in one specimen.

RESULTS

Basic density

The differences between the specimens from different sites and birch species were studied by using the non-parametric Mann-Whitney U–test. Considering *B. pendula* trees, the average basic density differed both from *B. pubescens* grown on mineral soil ($p = 0.000$, $Z = -21.694$), and from *B. pubescens* grown on peatland ($p = 0.000$, $Z = -18.187$). On the other hand, no difference was observed in the test between the average basic density of *B. pubescens* trees grown on mineral soil compared to the trees of the same species grown on peatland ($p = 0.978$, $Z = 0.027$). Based on this evaluation, in further calculations *B. pubescens* trees were not grouped according to the site; only the two birch species were studied separately.

B. pendula being in question, the average basic density of the wood material was 512 kgm^{-3}, and *B. pubescens* 478 kgm^{-3}, respectively (Table 1).

Linear regression models were constructed to predict the variation of the basic density in different horizontal and vertical locations of the stem. In addition, the effect of average growth ring width on the basic density was studied. The models are presented in Table 2. Despite the statistical significance of the models, their usability is not very high due to the possible large variation (for both species ca. $\pm$ 80 kg/m^3 above or below the predicted value) shown in unstandardized residuals (Fig. 2). According to the regres-

TABLE 1. *Mean values, standard deviations, and the observed outermost values for basic density (kg/m^3) of the specimens of mature Finnish birch.*

Species	Number of specimens	Mean	Std. Deviation	Minimum	Maximum
	Basic density, kg/m^3				
B. pendula	2564	512	42	411	653
B. pubescens	3740	478	31	392	579
Total	6304	492	40	392	653

TABLE 2. *Models for predicting the variation of basic density (kg/m³) within mature birch stems by species.*

Model (species)	Variable	Unstandardized coefficients (B) and standard errors (S.E.)			
		B	S.E.	t	p
1					
(*B. pendula*)					
RMSE: 0.036	Intercept	479.997	5.387	89.098	0.000
R^2: 0.265	X_1	94.286	4.635	20.343	0.000
Sig. 0.000	X_2	-37.327	4.473	-8.345	0.000
N: 2564	X_3	-3.458	2.802	-1.234	0.217
2					
(*B. pubescens*)					
RMSE: 0.029	Intercept	474.557	3.210	147.835	0.000
R^2: 0.151	X_1	51.135	3.078	16.613	0.000
Sig. 0.000	X_2	4.244	2.704	1.570	0.117
N: 3740	X_3	-14.677	1.635	-8.976	0.000

X_1: Relative distance from the pith, % from the radius of tree at given height.
X_2: Relative distance from the stump, % from the total height of tree.
X_3: Average annual ring width at 1.3-m height, mm.

sion analysis, however, *B. pendula* basic density was more dependent on the vertical location than that of *B. pubescens*. This was undoubtedly affected by the clearly divergent horizontal density structure of *B. pendula* wood at stump height compared to the above-stump heights. Subsequently, excluding the stump height, the average horizontal variation of the basic density of *B. pendula* wood seemed very similar at different heights of the tree (Fig. 3). The mean values of *B. pubescens* stems indicated, on the other hand, that the average basic density more likely increases from the stump upwards (Fig. 4). The absolute vertical variations of *B. pubescens* were, nevertheless, smaller than those of *B. pendula*. Considering both birch species, the wood material near the pith was clearly lighter than near the surface of the stem. An interesting finding was that near the stump height of both birch species, the average basic density of the outermost specimen (distance more than 100 mm from the pith) was somewhat smaller than within the distance of 50–100 mm from the pith. This may be affected by the divergent grain orientation near the

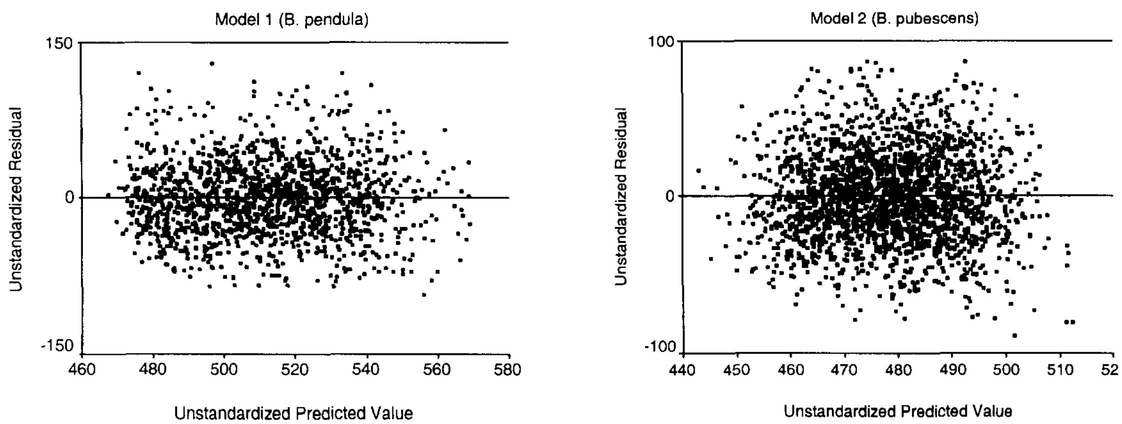

FIG. 2. The unstandardized residuals for models 1 and 2 indicated equal validity of the models throughout the density range of the material.

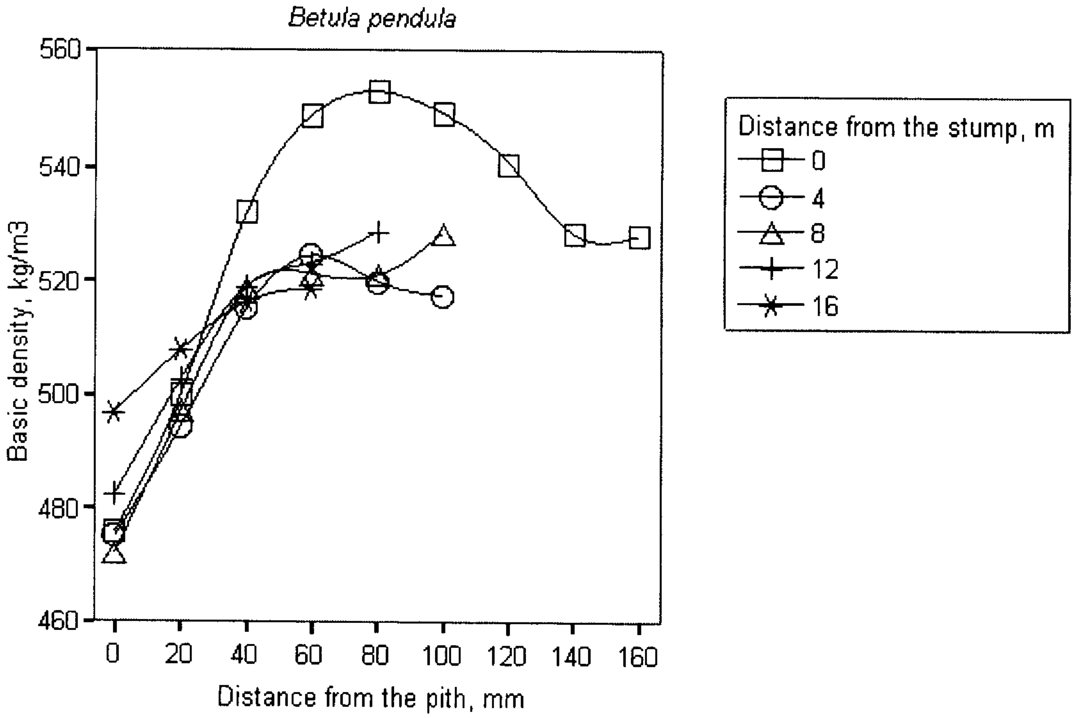

FIG. 3. Variation of basic density of *Betula pendula* at different heights from the pith to the surface.

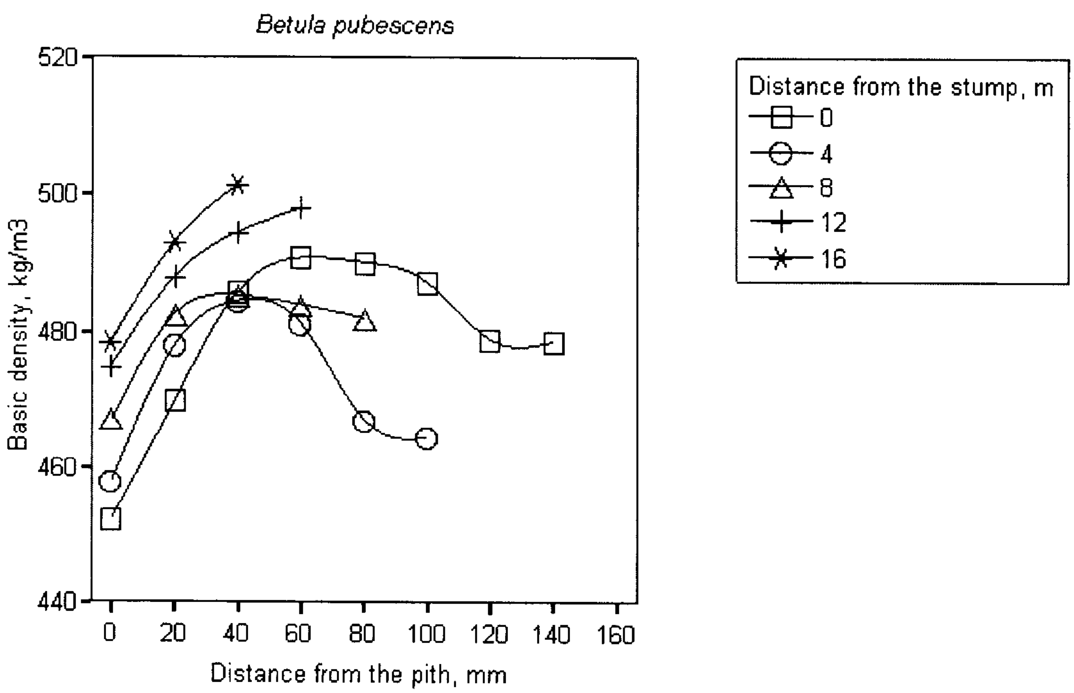

FIG. 4. Variation of basic density of *Betula pubescens* at different heights from the pith to the surface.

stump caused by butt swelling or a buttressed base.

In addition to the location parameters, the basic density of *B. pubescens* wood material was clearly dependent on the average growth rate of a tree at a 1.3-meter height, whereas no such dependence was observed for *B. pendula*.

Brinell hardness

At the moment of testing, the EMC of the Brinell hardness specimens varied between 9.76% and 13.66% (mean 11.76%). No correlation between basic density and EMC was observed. The two-tailed Pearson correlation coefficient (0.893) between the depth of the residual indentation of the steel ball measured by the machine and the diameter of the residual indentation measured manually, was highly significant, which can be seen from the scatter plot in Fig. 5, as well. No systematic over- or underestimate could be seen either. This reflects that no considerable revert of the indentation occurred during the waiting period of 3 min from the removal of the load to the moment of measurement. Hence, both measurement practices can be considered equally reliable.

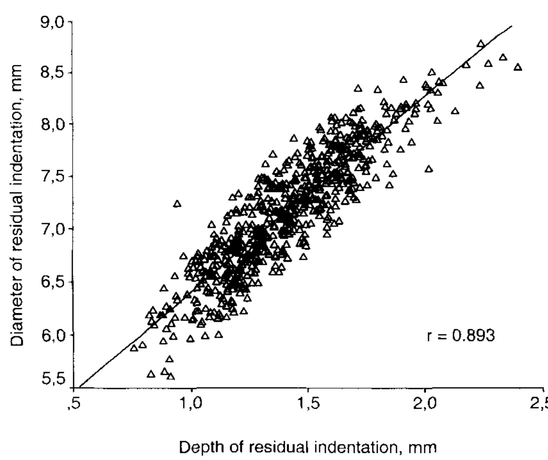

FIG. 5. Correlation between the depth of residual indentation measured by the machine and the diameter (mean value of the measurements perpendicular and parallel to the grain) of the residual indentation measured manually during the Brinell hardness tests.

The reliability of the results of Brinell hardness was also studied by assessing the degree of variation between the two tests within one specimen. Considering the sample of 50 specimens, which were tested by two adjacent indentations, the average difference between the two results for Brinell hardness was 6.6% (min 0.2%, max 18.0%). According to this evaluation, the results for the rest of the specimens tested with one indentation only were trustworthy.

The average Brinell hardnesses of all *B. pendula* and *B. pubescens* specimens were 23.4 MPa and 20.5 Mpa, respectively. The means and characteristic values, as well as the outermost observations for radial Brinell hardness of defect-free wood of Finnish birch species, are presented in Table 3.

The dependence of Brinell hardness on the basic density was evident. Based on the results, the Brinell hardness of birch wood is at its highest (approximately 35 MPa for *B. pendula* and 30 MPa for *B. pubescens*) where the basic density of wood is high, i.e., generally near the surface of the stem and near the stump. Respectively, Brinell hardness is at its lowest (ca. 15 MPa for both birch species) where the basic density is low, i.e., generally near the pith and in the upper parts of the stem.

The linear regression models for predicting the Brinell hardness are shown in Table 4, and the unstandardized residual plots for the two models in Fig. 6.

DISCUSSION

The objective of this article was to analyze the variation of basic density (kg/m^3) between the different horizontal and vertical locations of mature Finnish *Betula pendula* and *B. pubescens* stems. In addition, the dependence of Brinell hardness (MPa) of birch wood on the basic density was investigated. The sources of error in the Brinell hardness test according to EN 1534 were also analyzed. Both basic density and Brinell hardness were measured from small, defect-free specimens. The annual rings of birch wood consist mainly of earlywood, which, therefore, largely defines the mechanical properties of

TABLE 3. *Number of specimens measured (N), means, standard deviations, the observed outermost values, and characteristic values for the Brinell hardness of mature Finnish birch.*

Species	N	Mean	Std. Deviation	Min	Max	Characteristic value
	Brinell hardness, MPa					
B. pendula	261	23.37	4.40	13.31	37.38	16.13
B. pubescens	358	20.53	3.81	12.49	32.92	14.26
Total	619	21.73	4.30	12.49	37.38	14.66

birch. Hence, the Brinell hardness tests were focused on earlywood, which makes the results best applicable for practical purposes. In practice, due to the knots, decay or, for example, irregular grain structure, characteristic values for the entire stem are likely to be somewhat lower than those observed in these measurements.

There is probably variation on the density or hardness results between the separate sample stands. Except for the birch species, this variation was not analyzed in this study. The results thus characterize the entire wood flow procured to the wood processing industry, while the applicability of the results relates to the planning of end-uses, as well as sawing, veneering, or other processing of the separate sections of birch stems. The possible differences between separate stands cannot be detected on the basis of the results.

Significant differences for the basic density between the two birch species were found. In general, the average values of *B. pendula* were a little higher than those published previously (e.g., Hakkila 1966, 1979; Velling 1979). However, the results of Verkasalo (1998) were very similar to the results of this study, excluding that Verkasalo (1998) found that density values differ between *B. pubescens* stems grown on mineral soil and on peatland. In this study, the densities between trees grown at the two sites did not differ. On the other hand, while the raw material properties of young birch stands inevitably reflect on the continuously increasing utilization of birch wood from thinning forests for both the mechanical and chemical wood industry, it is notable that the average basic density of younger, both naturally born birch trees (e.g., Hakkila 1966; Verkasalo 1998), and, in particular, planted birch trees (Velling 1979; Verkasalo 1998) is remarkably lower than that of mature trees. Considering *B. pendula,* the average growth rate at the 1.3-meter height did not have a significant effect on the basic density of the wood material, whereas *B. pubescens* density was more clearly dependent on the growth rate. This may

TABLE 4. *Models for predicting the Brinell hardness (MPa) of mature Finnish* Betula pendula *and* B. pubescens *on the basis of basic density of wood material.*

Model (species)	Variable	Unstandardized coefficients (B) and standard errors (S.E.)			
		B	S.E.	t	p-value
3					
(*B. pendula*)					
RMSE: 2.7715	Intercept	-35.297	3.054	-11.556	0.000
R^2: 0.620	X_1	116.447	6.046	19.261	0.000
Sig. 0.000					
N: 229					
4					
(*B. pubescens*)					
RMSE: 2.6166	Intercept	-29.304	2.454	-11.944	0.000
R^2: 0.544	X_1	104.182	5.118	20.358	0.000
Sig. 0.000					
N: 349					

X_1: Basic density (kg/m^3) of the specimen.

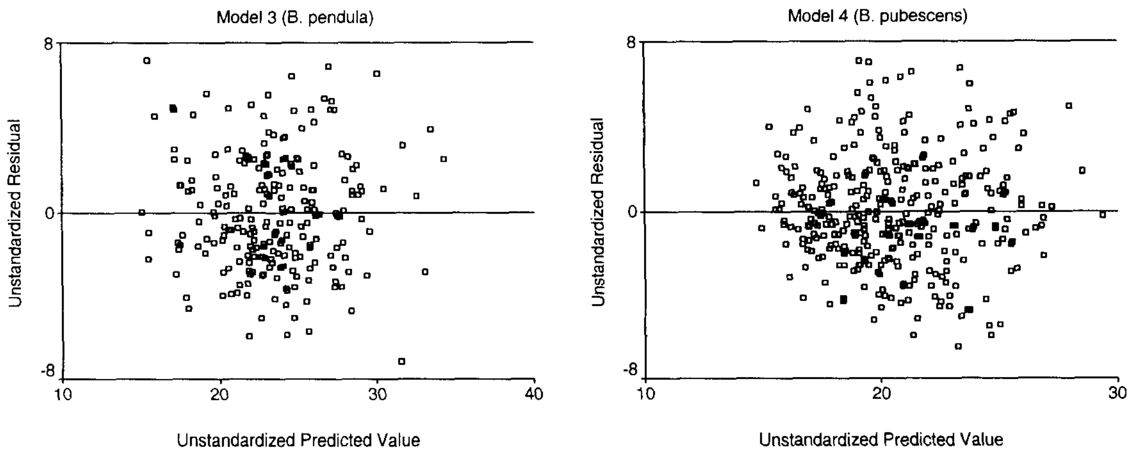

FIG. 6. The unstandardized residuals for models 3 and 4 indicated equal validity of the models throughout the hardness range of the material.

be a positive matter, remembering the abovementioned density differences between planted and natural *B. pendula* trees, as well as the expanding utilization of birch from cultivated forests.

The results concerning the horizontal and vertical variation of basic density were generally consistent with the results of Hakkila (1966). Some dissimilarities were observed, for instance, in the vertical variation of *B. pubescens* wood density. In this study, the average basic density from the stump upwards slightly increased, whereas Hakkila (1966) observed a slight decrease in the respective examination. In both studies, nevertheless, the vertical variation of basic density concerning *B. pubescens* wood material was insignificantly small from the practical point of view.

The horizontal variation of the basic density at stump height was unexpected for both birch species. Near the pith, the density was at its lowest level, then gradually increased toward the surface; but near the surface, it surprisingly began decreasing again. The same phenomenon was also observed at four-meter height in *B. pubescens*. At the stump height, a logical explanation for the decrease of density near the surface of the stem would be the abnormal grain orientation caused by butt swelling. However, this is not probable anymore at a four-meter height.

No publications were found in which exactly the same method (EN 1534) for measuring the Brinell hardness of untreated birch wood was used. Möller and Otranen (1999), however, measured the hardness of heat-treated birch wood using the same method, and noticed that heat-treatment does not influence the perpendicular to the grain Brinell hardness of wood. In the parquetry industry, the same method is commonly used in quality control and testing of new products. Unfortunately, these results are not published. In the studies by Kontinen and Nyman (1977) and Niemz and Stübi (2000) on wood-based panels and boards, however, the test method differed only slightly from EN 1534.

Despite the comprehensive conditioning of the specimens in standard environmental conditions (20°C, 65% RH), the difference in EMC between the driest and the moistest specimens during the test was still almost 4%. At least for particleboards (Niemz and Stübi 2000), such variation influences by several percent units the hardness result. Undoubtedly, the increment of moisture content decreases the Brinell hardness of solid wood, as well. However, Brinell hardness was highly correlated with the basic density, which was also noticed by Kučera (1984). Therefore, the assumption that Brinell hardness varies within the birch stem in a similar way as the basic density does is reasonable. No correlation was observed between the basic density and EMC of the specimens.

The Brinell hardness test method was found fairly reliable, but very laborious. According to the evaluations of the possible errors caused by manual measurement of indentation on the face of the specimen, no systematic error was found. Both under- and overestimates occurred, but generally, the deviations were small. Considering the hardness testing of wood, the reason for the manual measurement of the diameter of the indentation in two perpendicular directions is stated by the inhomogeneous structure of wood in axial, radial, and tangential directions. Kontinen and Nyman (1977) studied the hardness of wood-based panels and found significant differences between the hardness results depending on whether the diameter or the depth of the residual indentation was used in calculations. The reason for this was the resilient behavior of the materials tested: the indentation reverted after the load had been removed. In this study, both measurement methods were found reliable and no significant differences were observed. It is evident, however, that the speed of the revert of the indentation depends not only on whether the material is solid wood or wood based panel, but considering solid wood, also on the elastic properties of the tree species in question.

As a conclusion, if solid wood is studied, the only way to obtain information on the anisotropic behavior of wood in axial, radial or tangential directions during the hardness test is to measure the diameter of the indentation manually two times at right angles to each other. For practical uses, however, such accuracy is not usually needed. Hence, when testing solid wood, and when the hardness value itself is of more interest than the anisotropic structure of wood, the depth of the indentation (or the diameter, calculated on the basis of the depth) can be used for determining hardness. Similarly, if the material is very elastic, as is the case with some wood-based panels, the depth measurement is a more exact method (Niemz and Stübi 2000). The advantage obtained by using the depth measurement would be the considerably lowered time consumption, while all variables could be measured automatically.

ACKNOWLEDGMENTS

The author would like to thank Mr. Hannu Koivunen from the Finnish Forest Research Institute, Joensuu Research Centre, and Mr. Tapani Orttenvuori from Muhos Research Station, for comprehensive laboratory measurements, Professor Erkki Verkasalo from Joensuu Research Centre for invaluable comments on the manuscript, Ms Anne-Marita Järviluoto for revising the language, and finally, the Academy of Finland, as well as Metla, for funding the research.

REFERENCES

Bhat, K. M. 1980. Variation in structure and selected properties of Finnish birch wood. I. Interrelationships of some structural features, basic density and shrinkage. Silva Fenn. 14:384–396.

Dunham, R. A., A. D. Cameron, and J. A. Petty. 1999. The effect of growth rate on the strength properties of sawn beams of silver birch (*Betula pendula* Roth). Scand. J. For. Res. 14:18–26.

EN 1534: 2000 E. Wood and parquet flooring—Determination of resistance to indentation (Brinell)—Test method. European Standard CEN 2000. 10 pp.

Gertjejansen, R., and D. Hedquist. 1982. Influence of paper birch on the properties of aspen waferboard: a mill trial. Forest Prod. J. 32(11/12):33–34.

Hakkila, P. 1966. Investigations on the basic density of Finnish pine, spruce and birch wood. Comm. Inst. For. Fenn. 61(5):1–98.

———. 1979. Wood density survey and dry weight tables for pine, spruce and birch stems in Finland. Comm. Inst. For. Fenn. 96(3):1–59.

Jalava, M. 1945. Strength properties of Finnish pine, spruce, birch and aspen. Comm. Inst. For. Fenn. 33(3): 1–66. (In Finnish with English summary).

Kollman, F. F. P. and W. A. Côté. 1968. Principles of wood science and technology. Volume 1. Solid wood. Springer Verlag. Berlin – Heidelberg – New York. 592 pp.

Kontinen, P., and C. Nyman. 1977. Hardness of wood-based panel products and their coating and overlays. Paper and Timber 9/1977 (In Finnish with English summary).

Kučera, B. 1984. Bjørkevirkets mekaniske, teknologiske og fysiske egenskaper. Norges landbruksvitenskapelige forskningsråd, Slutrapport nr. 500. 21 p. (In Norwegian).

Kúdela, J. 1998. Analysis of wood hardness. Pages 199–203 *in* S. Kurjatko, and J. Kúdela, eds., Proc. Seminar on Wood Structure and Properties '98. Arbora Publishers, Zvolen, Slovakia.

Kujala, V. 1946. Some recent research data on birches. Comm. Inst. For. Fenn. 34(1):1–36. (In Finnish with English summary).

LASSILA, I. 1926. The mechanico-technical properties of wood. Their study and its objects. Reprinted from Acta For. Fenn. 186 pp. (In Finnish with English summary).

LUTZ, J. F. 1977. Wood veneer: Log selection, cutting, and drying. USDA, Tech. Bull. No. 1577. 137 pp.

MÖLLER, K., AND L. OTRANEN. 1999. Heat treatment of timber. Publications of the Institute of Environmental Technology. Nr. 4. Mikkeli 1999. 115 pp. (In Finnish).

NIEMZ, P., AND T. STÜBI. 2000. Investigations of hardness measurements on wood based materials using a new universal measurement system. Pages 51–61 *in* S. E. Stanzl, and A. Reiterer eds. Proc. of the Int. Symposium on Wood Machining, Properties of Wood and Wood Composites Related to Wood Machining. Vienna, Austria, 27.29.9.2000.

PAGANO, K., AND R. GERTJEJANSEN. 1989. The effect of mixing high and low density hardwoods on bond development in waferboard. Forest Prod. J. 39(2):45–48.

SCHWAB. E. 1990. Die Härte von Laubhölzern für die Parkettherstellung. Holz Roh-Werkst 48(2):47–51. (In German).

SIIMES, F. E., AND O. LIIRI. 1952. Investigations of the strength properties of wood I. Tests on small clear specimens of Finnish pine (*Pinus sylvestris*). Technical Research Centre of Finland VTT, Report 103. 88 p. (In Finnish with English summary).

TAMMINEN, Z. 1970. Moisture content, density, and other properties of wood and bark. III Birch. Rapp. Instn. Virkeslärä Skoghögsk. 63: 1–99. (In Swedish with English summary).

VELLING, P. 1979. Wood density in two *Betula pendula* Roth progeny trials. Folia For. 416:1–24. (In Finnish with English summary).

VERKASALO, E. 1998. Raudus- ja hieskoivun laatu puuaineen tiheyden perusteella arvioituna. [Quality of European silver and white birch evaluated on the basis of wood density]. *In* P. Niemistö, and T. Väärä. eds. Rauduskoivu tänään–ja tulevaisuudessa, Tutkimuspäivä Tampereella 12.3.1997. Finnish Forest Research Institute. Research notes 668:127–140. (In Finnish).

WAGENFÜHR, R., AND C. SCHREIBER. 1989. Holzatlas. 3. Auflage. VEB Fachbuchverlag Leipzig. 720 pp.