Variations in and Models for Brinell Hardness of Scots Pine Wood from Finland and Sweden

MIKA GREKIN AND ERKKI VERKASALO*

Finnish Forest Research Institute, Eastern Finland Regional Unit, P.O. Box 68, FI-80101 Joensuu, Finland. Tel. +358 50 391 3020, email: erkki.verkasalo@metla.fi

* *Corresponding author*

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Abstract

Variations in Brinell hardness of Scots pine wood from mature mineral soil stands in five regions in Finland and Sweden were studied by means of linear mixed models. Hardness was studied from planed tangential surfaces of the specimens, i.e., the force acted in radial direction. One model consisted of only readily available background variables, whereas, in the other model wood density was included as an independent variable. Geographical origin, as well as the longitudinal and radial location of the specimens within a tree was significantly affecting hardness. In addition, if the indentation was placed on latewood section the hardness was clearly higher compared to earlywood and combined earlywood and latewood. With the best fit model approx. 50% of the hardness variation could be described. Wood density was the most important variable affecting hardness and simple linear relationship was found between hardness and wood density. Hardness values based on the diameters of the residual indentations and the initial depths of the indentations were compared, and the differences between these two, as well as the possible sources of error were discussed.

Key words: Brinell hardness, linear mixed model, *Pinus sylvestris* L., Scots pine, wood quality

Introduction

Scots pine (*Pinus sylvestris* L.) wood tends to have large variations in material properties related to silviculture and growth region. With regard to mechanical properties, in general, wood is highly anisotropic material at any structural level. On the macroscopic scale, variability in mechanical properties mainly can be attributed to slope of grain and wood density (Kollmann and Côté 1968, Dinwoodie 1975, Bodig and Jayne 1982). As it is well known, the basic density of Scots pine wood from the north differs radically from the wood with a more southerly origin (e.g. Hakkila 1979, Kellomäki 1979, Björklund and Walfridsson 1993). As most of the strength properties are proportionate to wood density (Wangaard 1950, Kollmann and Cōté 1968), also the mechanical properties of Scots pine wood vary with varying origin. In addition to the geographical variation, the basic density increases from the pith to bark, and decreases from the butt towards the top of the tree (e.g. Hakkila 1966, Uusvaara 1974), causing the similar change in the mechanical properties.

The hardness of the surface greatly affects the machinability of wood. It is also of high importance in plank floorings and facing furniture veneers, as well as in kitchen and office furnishing (Heräjärvi 2004). In addition, hardness is the most important characteristic for wood intended for parquet manufacturing (Lutz 1977, Niemz and Stübi 2000), affecting the resistance against scratching, wearing, and abrasion. Hardness can actually be derived from several different forces, such as friction, shearing, and compressive forces (Kollmann and Cōté 1968); Therefore, the hardness of wood is often considered as an operational or a practical property rather than and individual mechanical property (Heräjärvi 2004).

In the typical tests of hardness a hard tool of known geometry is forced into the body, and the hardness is defined as the ratio of the applied force to the size of the indentation (Doyle and Walker 1985). With elastic materials the hardness is determined under load as there will be little or no permanent deformation, whereas with plastic materials the size of the permanent indentation is measured (Tabor 1951). In Europe, the most widely used hardness determination method is the Brinell test, whereas, predominantly in North and South America the most commonly used method is the Janka test. The Janka method has not been accepted in Europe since there is a considerable possibility of failure due to the cell wall compression (Niemz and Stübi 2000). In addition, the depth of indentation determined by the Brinell method is thought to have fewer side effects than the Janka method (Bektas et al. 2001). Schwab (1990) concluded that the method according to Brinell is the most suited method for solid wood.

In this study, the principal aim was to map the levels of and variations in the Brinell hardness of Scots pine wood grown in mineral soil stands in different regions in Finland and Sweden. One aim of the project was to compare different regions; the average values and variations, as well as relationships between the hardness and wood density. Furthermore, linear mixed model analyses were executed to find out the background variables affecting the Brinell hardness of Scots pine wood.

Materials and methods

Empirical materials

Tree, log, and wood samples from sixty mature Scots pine dominated stands growing on mineral soils were collected in three regions in Finland (northern, south-eastern, and central inland) and two regions in Sweden (south-central and southern), 12 stands from each (Figure 1), to cover the geographical spread for latitude and altitude, accordingly, the climate for effective temperature sum. For the sake of clarity in the statistical analyses, the regions were numbered in ascending order starting from the northernmost region: 1 = Northern Finland (NF), 2 = Central Inland Finland (CIF), 3 = South-eastern Finland (SEF), 4 = South-central Sweden (SCS), 5 = Southern Sweden (SS). In each region, the stands were selected randomly to represent different forest sites and age classes of mature stands. In Finland, the sampling was based on the sample plot network of the 8th (in the north) and 9th (in the south) National Forest Inventory (NFI); and in Sweden, on the records of the landowner, Sveaskog Ltd. In each stand, three Scots pine trees covering the diameter range of conventional saw log and small-diameter log trees (DBH>14cm) were felled for sampling, the total sample being 180 trees. At first, a circular experimental plot was randomly placed on each stand; thereafter the DBH of each Scots pine tree on the plot was measured. The averaged values from two measurements perpendicular to each other were used. Then, separately on each plot (stand), all the trees with the DBH exceeding 14 cm were put in ascending order based on the DBH, and the sample trees were evenly selected from the DBH series. More detailed descriptions of regions and sample trees are given in Tables 1 and 2.

From each sample tree, 70-cm bolts were cut from the sections of butt log, middle log, and top log (at 2, 6, and 10 meter heights, respectively) (Figure 2). Based on the average tree heights, the bolts from 10m height were considered to represent the top log section of

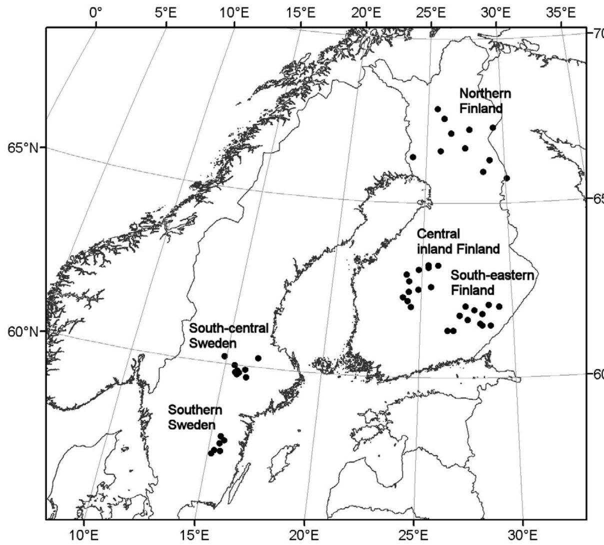

Figure 1. Location of the sample of the 60 stands in the five regions in Finland and Sweden: Northern Finland (region 1), Central Inland Finland (region 2), South-eastern Finland (region 3), South-central Sweden (region 4), Southern Sweden (region 5). Map: Nivala V. and Lukkarinen A., Metla

Table 1. Basic climatic characteristics of sample plots in different regions. N/A=no information available

Region	Elevation m			Effective temperature sum dd			Annual precipitation sum mm		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1 NF	215	130	280	816	714	923	515	475	565
2 CIF	160	110	205	1102	1031	1194	575	535	605
3 SEF	110	85	125	1227	1175	1285	595	590	605
4 SCS	130	80	200	1233	1163	1282	*N/A*	*N/A*	*N/A*
5 SS	170	145	190	1313	1293	1329	*N/A*	*N/A*	*N/A*

Table 2. Basic description of sample trees in different regions

Region	DBH over bark cm			Height m			Lower limit of live crown, m			Age years		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
1 NF	23.8	15.0	31.1	16.5	10.1	22.2	9.6	4.3	17.0	173	67	295
2 CIF	28.7	18.7	41.4	22.5	15.8	29.3	14.1	6.7	19.3	129	94	178
3 SEF	28.7	17.1	42.6	23.5	16.4	29.8	14.0	5.4	19.0	97	61	155
4 SCS	29.4	18.0	39.9	22.6	16.5	30.0	13.4	8.1	19.3	108	90	130
5 SS	32.3	20.5	42.9	23.7	16.0	33.1	14.7	7.4	23.5	124	73	178

the trees in the most northerly region. The same definition for the top logs was then used in all regions, respectively. The bolts were sawn through-and-through into approx. 30-mm thick boards, and the boards were slowly dried at room temperature. The boards were numbered ascending from the pith outwards, so that the 0-board was the middle, pith enclosed core board, the 1-boards were the first boards outwards from both sides of the pith, etc. The 1-, 2-, and 3-boards were further processed into approx. 100 x 150 x 30 mm specimens (N=875).

Brinell hardness

The Brinell hardness was measured perpendicular to grain from the specimens according to the European standard EN1534 (2000) with a FMT-MEC 100 kN material testing apparatus. Before measurements, the specimens were conditioned to constant mass at the temperature of 20 °C and RH of 65% that equals to the approximate MC of 12%. In each specimen, one to three hardness measurements (total N=2,151) were executed along the radius of the stem on the planed outer face of the board (on tangential surface) and the measurements were averaged for each specimen (wood specimens A, N=875). The points for indentation were randomly positioned to avoid any irregularities (knots and other defects) and the type of wood (earlywood, latewood or both) was recorded. After hardness measurements the air-dry density ρ_{0,w_A} of each specimen was determined. In addition, smaller clear wood specimens were produced surrounding randomly selected points of indentation for determination of local air-dry and basic densities (ρ_{0,w_B} and ρ_{0,g_B}), as well as the exact moisture content (w) of wood (wood specimens B, N=841) (Figure 2).

In the Brinell hardness test according to EN1534 (2000), a steel ball (diameter 10mm) is impressed into a material with a force increasing at such rate, that the nominal value of 1 kN is reached after 15 seconds.

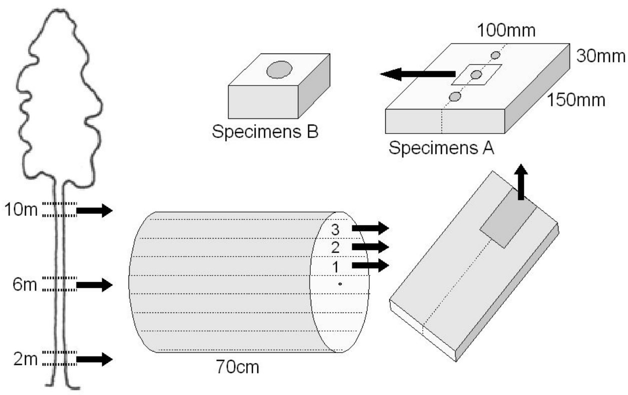

Figure 2. Preparation of the wood specimens A and B

After maintaining the force for 25 seconds the indenter is withdrawn. The size of the residual impression is measured after the recovery period of at least 3 minutes. Normally, the Brinell hardness should be calculated on the basis of the two orthogonal diameters, one along the grain, and another across the grain, of the residual indentations (EN1534 2000, Kúdela 1998). Due to major occurrence of the phenomenon called "sinking in", i.e. the elliptical indentations in the fibre direction (Doyle and Walker 1985), in this study the hardness calculations were based only on the residual indentation diameters measured across the grain, i.e. in tangential direction. In addition, complementary hardness values were calculated on the basis of the initial depths of the indentations measured by the material testing apparatus itself. The following formulae were used for calculating the hardness values in MPa (or N/mm²):

$$HB = \frac{F}{\pi D h} = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)}, \quad (1)$$

where F is the force used (N), D is the diameter of the indenter (mm), h is the initial depth of the indentation (mm), and d is the diameter of the residual indentation (mm).

Statistical analyses

At first, the hardness results based on the residual diameters (HB_d) and the initial depths of the indentations (HB_h) were compared. For wood hardness and density, the conventional statistics (averages and standard deviations) were calculated. Simple one-way ANOVA were executed to compare different regions, heights etc. and pair-wise LSD comparisons were included to find the significant differences between the individual factors at 0.05 level. In addition, the variations in hardness values were studied by means of linear mixed models. By these models, the dependence of Brinell hardness on the selected background variables. Two basic-types of models were fitted: one where only readily available explanatory variables describing the geographical origin, site, location in the tree *etc*. were used (type A models), and another where more detailed independent variables, such as wood density, were used (type B models). To ensure the fit of each model built, the residuals were examined as a function of predicted values, and the normal distribution of residuals was checked as well. For each model, the coefficient of determination was calculated by squaring the correlation coefficient between measured values and fixed predicted values. The relationships between Brinell hardness and basic and air dry density, as well as moisture content, were studied more thoroughly with wood specimens B. The statistical analyses were executed with the PASW Statistics 17.0 software.

Results and discussion

Wood specimens A

Based on the paired samples t-test, the HB_d and HB_h values differed significantly from each other (t = 32.30, df = 869, P < 0.001). Compared to the diameter-based values (HB_d), the depth-based values (HB_h) tend to be overestimates rather systematically (Table 3, Figure 3). In addition, different regional differences were found in the average hardness values depending on the values (HB_d or HB_h) to be compared (Table 3). Considering the averages of HB_d, the lowest value was found in region 1 (14.9 MPa) and the highest in regions 2 and 4 (16.9 MPa), whereas the average of HB_h ranged from 19.0 MPa in regions 1 and 4 to 21.4 MPa in region 2. The coefficient of variation ranged by region from 19% to 21% for HB_d and from 23% to 27% for HB_h, respectively. On average, the depth based hardness values were approx. 25% higher compared to diameter based ones in regions 1, 2 and 3, whereas, in regions 4 and 5, the difference was as low as 15%. In other words, the relationship between HB_d and HB_h was different in different regions; the correlation coefficient between the two variables ranged from 0.706 to 0.935 in regions 5 and 1, respectively. The relationship between HB_h and HB_d was found to be heteroscedastic: the higher the hardness the bigger also the variation between the two hardness determination methods (Figure 3).

There are several possible sources of error in the different procedures of measuring hardness of wood surfaces. In fact, the value of hardness is, more than any other mechanical property, dependent on the testing conditions and methods used (Doyle and Walker 1985, Kúdela 1998, Niemz and Stübi 2000, Hirata et al. 2001). As a conclusion, hardness values measured using different methods and set-ups of the selected method are usually significantly different and cannot be used interchangeably (Kontinen and Nyman 1977, Kúdela 1998). According to Doyle and Walker (1985), for example, with a spherical indenter the geometry of the indenter changes as a function of the depth of the indentation. Due to this fact, a deep indentation could not be considered as a magnified version of a shallow one; That is, the Brinell hardness is dependent on the depth of the indentation.

Table 3. Average values and standard deviations (in parentheses) of air-dry density (ρ, kg/m^3) and diameter and depth based Brinell hardness values (HB_d and HB_h, MPa) in different regions in wood specimens A. N = number of measurements

Region	$\rho_{0,\omega}$	HB_d	HB_h	N
1 NF	492 (46)	14.9 (2.86)	19.0 (5.07)	131
2 CIF	521 (57)	16.9 (3.31)	21.4 (5.33)	144
3 SEF	522 (57)	16.7 (3.56)	20.9 (5.49)	221
4 SCS	523 (51)	16.9 (3.42)	19.0 (4.47)	178
5 SS	543 (57)	16.7 (3.35)	19.2 (4.32)	196

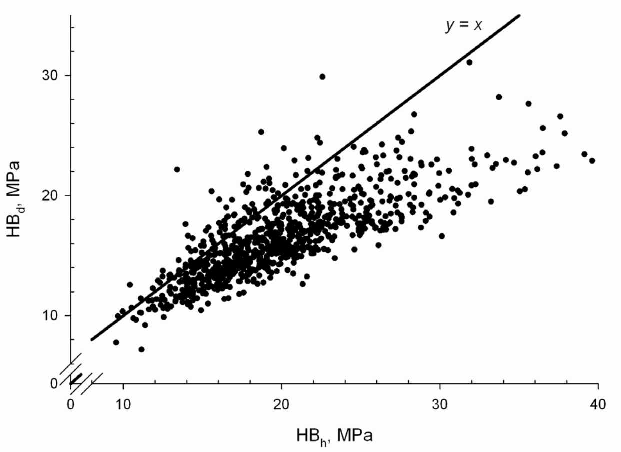

Figure 3. Relationship between Brinell hardness values (MPa) based on initial depths of the indentations (on x-axis) and the diameters of the residual indentations (on y-axis) in wood specimens A (N=875)

In an earlier study by Kontinen and Nyman (1977), diameter based Brinell hardness values of wood panels (plywood, particle board, and fibreboard) were found to be approx. 1.5 to 2.5 times higher compared to depth based values. On the other hand, Heräjärvi (2004) found no differences between the diameter and depth based Brinell hardness values for birch wood. In this study, even if the diameters along the grain were ignored due to the "sinking in", the across-grain boundaries of the indentations were, as well, found to be rather imprecise caused by the same phenomenon. In general, the "sinking in" leads to exaggerated dimensions of the permanent indentation (Doyle and Walker 1985), i.e. the geometry of the indentation do not precisely match the geometry of the indenter, and the areas of the indentations are to be bigger compared to what could be expected from the size of the steel ball impressed. Therefore, "sinking in" probably caused the lower averages of the diameter based hardness *(HB_d)* values compared to the depth based ones (HB_h). The relatively high load used in this study caused rather abrupt indentations with no or only minor recovery. Values of HB_d take into account only the plastic deformation, whereas the HB_h values represent elastic and plastic deformations both. As the former were lower compared to the latter ones, the magnitude of elastic deformation and recovery was negligible compared to the effect of "sinking in".

In addition to the inaccuracy caused by "sinking in", the heteroscedastic relationship between the diameter and depth based hardness values (Figure 3) can be explained by the used measuring procedures. The diameters of the recovered indentations were measured manually after the impression, whereas the depths were acquired from the testing apparatus and they were actually measured during the impression. Firstly, as the size of the indentation decreases (hardness increases), the relative proportion of measuring error in diameter increases, and, as a consequence, the variation in hardness also increases. Secondly, the diameter to depth ratio of the indentation decreases with increasing depth until the depth of half of the indenter diameter is reached, and vice versa. Therefore, the accuracy of the diameter measurements is the more crucial the smaller the indentation, that is, higher the hardness. That causes the variation of diameter and depth based hardness values to increase with increasing hardness.

Schwab (1990) found Brinell hardness values measured with 1.0 kN to be approx. 6-20% higher compared to 500 N based values. The relatively high load used in this study (1.0 kN) caused some problems in comparing the measurements. With relatively low wood density, the indentations showed a clear fracture of the surface, or collapse of wood tissue under the surface of the specimen. In specimens with higher wood density such phenomena were not so evident. Therefore, the executed measurements represent the overall mechanical behaviour of wood under a certain load, including surface hardness and resistance to compression and shear, rather than "true" hardness values of Scots pine wood. Diameter based hardness better describes the performance of wood in different end uses (flooring, panelling etc.). Therefore, and despite the above discussed findings, the further analyses were executed only to the hardness values based on the diameters of the residual indentations (HB_d), as stated in the standard EN 1534 (2000).

The region had a significant effect on HB_d (one-way ANOVA; $F = 9.255$, $df = 4$, $P < 0.001$). By region, the average hardness varied from 14.9 MPa in region 1 to 16.9 MPa in regions 2 and 4, respectively. Based on the pair-wise LSD comparisons, the region 1 differed significantly from all other regions, and no differences were found between the other four regions. The hardness values varied with varying height position within a tree (one-way ANOVA; $F = 78.245$, $df = 2$, $P < 0.001$) and significant differences were found between all heights (2 m, 6 m, and 10 m). The distance from the pith, i.e. board number, significantly affected hardness (one-way ANOVA; $F = 43.850$, $df = 2$, $P < 0.001$); Significant differences were found between boards 1 and 2, as well as between boards 1 and 3, respectively. The type of wood also affected significantly (one-way ANOVA; $F = 14.491$, $P < 0.001$), as the hardness values on latewood sections differed from the ones on earlywood and combined early- and latewood. On the other hand, earlywood and combined earlywood and latewood did not differ significantly from each other.

Considering the type A models, the best fit of the mixed model ($R^2 = 0.279$) describing the variation of HB_d was achieved with the following model structure:

$$HB_d = \mu + reg + hgt + board + early/late + diam + tree + \varepsilon \quad (2)$$

where μ is the constant average term ($F = 577.119$, $P < 0.001$), *reg* is the region shown in Figure 1 ($F = 8.296$, $P < 0.001$), *hgt* is the height position within a tree ($F = 76.866$, $P < 0.001$), *board* is the board number, i.e. the radial location of the specimen within a tree cross-section ($F = 43.164$, $P < 0.001$), *early/late* tells whether the specimen is of earlywood, latewood, or both ($F = 12.629$, $P < 0.001$), and *diam* is the tree diameter over bark at a given height ($F = 6.876$, $P = 0.009$). In addition to residual term ε, a tree level random effect (*tree*) was included. *Reg*, *hgt*, *board*, and *early/late* were treated as factors and *diam* as covariate. A slightly lower R^2 value was achieved if the average annual temperature sum was included in the model instead of region.

According to the pair-wise comparisons executed to the mixed model shown in Eq. 2, the hardness was significantly lower in northern Finland (region 1) compared to the other regions, but no significant differences were found between the regions 2–5. The hardness decreased with increasing height position within the tree from approx. 19.0 MPa at 2m height to 15.7 MPa at 10-meter height, respectively, and all heights (2 m, 6 m, and 10 m) differed significantly from each other. Moving from the pith outwards the hardness increased, but statistically significant differences were only found between boards 1 and 2, as well as boards 1 and 3. The average hardness was 16.0, 17.7, and 17.8 MPa in boards 1, 2, and 3, respectively. When the indentation was positioned in the latewood sections the average hardness was higher (18.7 MPa) compared to the earlywood (16.2 MPa) or combined earlywood and latewood (16.7 MPa), and all these three differed significantly from each other. An inverse relationship was found between the tree diameter at given height and the hardness of wood. Of the total random variation approx. 24% was covered by the tree level random effect and the residuals accounted for the rest.

The factors included into the model (Eq. 2) more or less describe the variation in wood density, and, thereby, in hardness. As was previously mentioned, the results obtained using different set-ups of the measurements are not necessarily comparable. However, Jalava (1945), as well as Siimes and Liiri (1952) found similar differences in the average hardness of Scots pine wood from different locations in Finland, as wood hardness in northern Finland differed from more southerly origin. On the other hand, Hirata et al. (2001) found hardness to be significantly higher in latewood than in earlywood due to the differences in densities.

With the air-dry density of the specimens included as an independent variable, the best-fit of the type B mixed model (R^2 = 0.500) was achieved with the following model structure:

$$HB_d = \mu + \rho_{0,\omega\_A} + reg + hgt + board + early/late + tree + \varepsilon, \quad (3)$$

where μ is the constant average term (F = 2.310, P = 0.129), ρ_{0,ω_A} is the air-dry density of the specimen (F = 372.298, P < 0.001), *reg* is the region as shown in Figure 1 (F = 5.921, P < 0.001), *hgt* is the height position within a tree (F = 5.616, P = 0.004), *board* is the board number, i.e. the radial location of the specimen within a tree cross-section (F = 11.288, P < 0.001) and *early/late* tells whether the specimen is of earlywood, latewood, or both (F = 10.674, P < 0.001). ρ_{0,ω_A} was treated as covariate, and *reg, hgt, board,* and *early/late* as factors. In addition to the residual term ε, a tree level random effect was included in the model, even though it was statistically insignificant.

The air-dry density had a strong positive effect on hardness. After the effect of density had been removed, based on the pair-wise comparisons on the mixed model shown in Eq. 3, region 1, as well as region 5, differed significantly from regions 2 and 4 both. The average hardness values were 16.6MPa in regions 1 and 5 and 17.5 MPa and 17.6 MPa in regions 2 and 4, respectively. Again, with the effect of density removed, the average HB_d values at 2 m (17.5 MPa) and 10-meter heights (16.7 MPa) differed significantly from each other; At 6-meter height the average was 17.2 MPa. Between different positions within a cross section, only the averages in boards 1 and 3 significantly differed from each other; the average values were 16.7 MPa, 17.6 MPa, and 17.1 MPa in boards 1, 2, and 3, respectively. Hardness of latewood sections was significantly higher compared to earlywood or combined earlywood and latewood, but between the two latter no significant differences were found.

Despite the fact that density was included as an independent variable, all independent variables presented in type A model except stem diameter were included also in the type B model. In other words, after the effect of density had been removed, some variation still could be explained by the geographical origin and longitudinal and radial location of the specimen within a tree. The region affects hardness most probably via varying average annual ring width, which was not measured, whereas height position within a tree and board number from the pith describe the curvature of the annual rings in the specimens.

Wood specimens B

The moisture content of the specimens (ω) ranged from 9.6% to 13.3%, average being 11.2% and standard deviation 0.5%-points. No significant correlation was found between the moisture content and hardness HB_d. As the specimens were stored in constant conditions between indentations and the determination of moisture content ω, the results may be generalized to represent also the moisture content of the wood specimens A. In earlier studies a clear decrease in wood hardness with increasing moisture content has been reported (e.g. Kollmann and Côté 1968, Niemz and Stübi 2000); In this study, the moisture content range of the specimens was not broad enough to find out such relationship.

The averages of the local air-dry and basic density (ρ_{0,ω_B} and ρ_{0,γ_B}) were 516 kg/m³ and 420 kg/m³ and the respective standard deviations 57 kg/m³ and 45 kg/m³. The air-dry densities of wood specimens A and B significantly correlated with each other (r = 0.872, P < 0.01). The correlation coefficient between local density and hardness was 0.710 (P < 0.01) for air-dry and 0.651 (P < 0.01) for basic density, respectively. A clear linear relationship was found between density and hardness (Figure 4); Approx. 49% of the hardness variation could be described using air-dry density and approx. 46% with basic density, respectively. Simple power and logarithmic functions were also evaluated, but no improvements were achieved compared to linear ones. Compared to earlier studies on tangential (Blomberg et al. 2005) and radial (Holmberg 2000) surfaces clearly lower explanatory power of density was observed (Table 4). This is probably due to inaccuracy caused by “sinking in” discussed earlier. In addition, the 1.0 kN force used for indentations was, most probably, too high for such material with fairly low average density and relatively large density variations between and within (earlywood and latewood) specimens. The parameter estimates of a simple logarithmic function between density and hardness calculated in this study deviated from the results in the literature (Table 4, Figure 4). Regression parameters according to Blomberg et al. (2005), especially, would overestimate hardness in this very material. The differences are most likely due to different set-ups of

$\ln HB = \ln a + b \ln \rho$

Table 4. Parameter estimates and coefficients of determination for function $\ln HB = \ln a + b \ln \rho$ describing hardness (HB, kg/mm²) to density (ρ, kg/m³) relationship in this study (specimens B) and in the literature

Source	ln a	b	R^2	Density range, kg/m³	Notes
This study	-8.2	1.40	0.51	360–720	ω =11.2%
Blomberg et al. 2005	-12.1	2.07	0.89	Average 460	ω =12.6%
Holmberg 2000			0.77	350–680	ω ≈12%, radial surface
Kollmann and Côté 1968	-12.9	2.14		200–1000	Several European species, oven-dry density

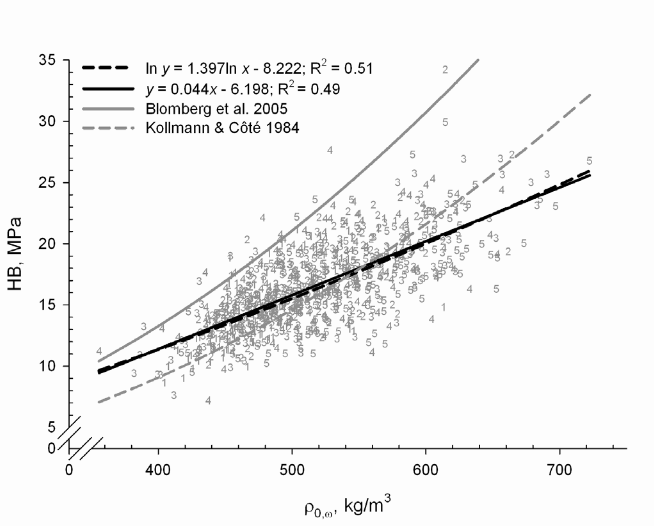

Figure 4. Brinell hardness as a function of air-dry density in different regions (numbers) in wood specimens B (N=841). Equations and corresponding R^2 values of linear (solid black line) and logarithmic (dashed black line) regression functions are shown. Regressions according to Blomberg et al. (2005) (solid grey line) and Kollmann and Côté (1984) (dashed grey line) are also shown (Table 4)

the hardness determination, as well as differences in the materials used.

If the type B mixed model (Eq. 3) was fitted to the data from wood specimens B a R^2 value of 0.534 was achieved. All the fixed variables in the equation were statistically significant at 0.05 level, whereas, only residuals were significantly accounting for the random variation. No differences were found in the interpretation of the variables affecting hardness compared to what was discussed earlier considering the wood specimens A. The slightly better R^2 value was probably due to the local density as an independent variable; in wood specimens A, knots and other defects were more probable to be present and affect the density of the specimens.

Conclusions

A heteroscedastic relationship between hardness values based on the diameter of residual indentations and initial depths of the indentations was observed. “Sinking in” significantly affected the accuracy of the diameter measurements. In addition, compared to possible elastic recovery of the indentations the magnitude of “sinking in” was clearly higher. On average, the diameter based hardness of Scots pine wood from the north was significantly lower compared to more southerly origin. In addition, hardness decreased with increasing height position within a tree and increased from the pith outwards. A clear linear relationship between hardness and wood density was observed; with the density included, approx. 50% of the hardness variation could be described. After the effect of density had been removed, some variation still could be explained by the geographical origin and the location of the specimen within a tree. Compared to the results in the literature, relatively low explanatory power of wood density was observed. This was probably due to inaccuracy caused by “sinking in”, as well as major deformation and collapse of wood tissue observed in specimens with relatively low wood density.

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ВАРИАЦИИ ТВЕРДОСТИ ПО БРИНЕЛЛЮ ДРЕВЕСИНЫ СОСНЫ ОБЫКНОВЕННОЙ В ФИНЛяНДИИ И ШВЕЦИИ И СООТВЕТСТВУЮЩИЕ МОДЕЛИ

М. Грекин и Э. Веркасало

Резюме

С помощью линейных смешанной статистических моделей были изучены вариации твердости по Бринеллю древесины сосны обыкновенной из спелых древостоев на минеральных почвах в пяти регионах Финляндии и Швеции. Твердость изучалась на строганных тангенциальных поверхностях образцов, т.е. усилие было приложено в радиальном направлении. Одна модель состояла исключительно из уже имеющихся основных переменных, в то время как во вторую модель в качестве независимой переменной была включена плотность древесины. Значительное влияние на твердость оказывало территориальное происхождение, а также продольное и радиальное положение образцов в стволе. Кроме того, если отпечаток приходился на участок поздней древесины, то твердость была явно выше по сравнению с ранней древесиной и с сочетанием ранней и поздней древесины. При применении подобранной модели можно описать приблизительно 50% вариаций твердости. Плотность древесины была самой важной переменной, влияющей на твердость, и между твердостью и плотностью древесины была обнаружена простая линейная зависимость. Сравнивались значения твердости, основанные на диаметрах остаточных отпечатков и начальных глубинах отпечатков. Обсуждалась разница между этими двумя значениями, а также возможные источники ошибок.

Ключевые слова: твердость древесины по Бринеллю, линейная смешанная статистических модель, *Pinus sylvestris* L., сосна обыкновенная, качество древесины