Influence of Density and Equilibrium Moisture Content on the Hardness Anisotropy of Wood

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Abstract

The aim of this study was to investigate the anisotropic characteristics of Brinell hardness for six species (softwood, Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook.], Red pine [*Pinus koraiensis* Sieb. et Zucc.], Mongolian scotch pine [*Pinus sylvestris* L. var. *mongolica* Litv.]; hardwood, Manchurian walnut [*Juglans mandshurica* Maxim.], Asian white birch [*Betula platyphylla* Suk.], Mongolian oak [*Quercus mongolica* Fisch. et Turcz.]) with the equilibrium moisture content (EMC) obtained at four relative humidity (RH) levels (20°C; 50%, 65%, 85%, and 95% RH). The results showed that the cross section of specimens presented higher Brinell hardness and lower elastic recovery than those tested on radial and tangential surfaces. Ovendried density was significantly positively correlated with Brinell hardness. With the exception of softwood on a tangential surface ($r = 0.02$), there was a statistically significant positive correlation of elastic recovery against ovendried density (at the 0.01 level). We found that a general increase in EMC significantly lowered the Brinell hardness for six species, irrespective of grain orientation. The decreased extent of relative Brinell hardness (HB/HB_0) was highest for cross section samples, compared with radial and tangential surfaces. For three softwood species, the decreased extent of HB/HB_0 on the radial surface was higher than that on the tangential surface, whereas the opposite relationship was found in three hardwood species. The results indicated that rays were probably the main factor controlling transverse anisotropy in hardwood, while the interaction of earlywood and latewood was more important for softwood. In addition, elastic recovery anisotropy was probably owing to different failure behavior in three directions, and it was difficult to establish a direct influence of EMC on elastic recovery.

Wood is described as an anisotropic natural material with unique and independent mechanical properties in three mutually perpendicular axes: longitudinal, radial, and tangential. The latter two are identified as transverse direction (Forest Products Laboratory 1987). The hardness of a wood species is a key measurement of its commercial application, such as use in flooring or furniture, and especially for civil engineering for joint use in the transverse direction.

To evaluate the hardness anisotropy of wood, many studies have examined the hardness values for the longitudinal or transverse direction, respectively, but few studies provide a detailed comparison of the three grain orientations (Kollmann and Côte 1968, Bodig and Jayne 1982, Holmberg 2000). Wood is substantially harder on the cross section (i.e., when loading in the longitudinal direction) than on radial and tangential surfaces (Bodig and Jayne 1982). Holmberg (2000) tested the hardness values of Scots pine (*Pinus sylvestris* L.) and found that the hardness on the radial surface was about half of that on the cross section. The hardness on the radial surface for most wood species is higher than on the tangential surface, and the reinforcement of latewood causes greater hardness on the radial surface (Hirata et al. 2001, Heräjärvi 2004).

A high density of wood is often correlated with good mechanical properties. Several authors have reported

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positive linear relationships between hardness and wood density (Forest Products Laboratory 1987, Niemz and Stübi 2000, Saranpää and Repola 2000, Hirata et al. 2001, Heräjärvi 2004). Holmberg (2000) studied the effect of grain direction on wood density–dependent hardness and found that the coefficient of regression between wood density and hardness on the cross section was significantly lower than that on the radial surface. Until now, comprehensive data sets of the relationships between wood density and anisotropic hardness have been lacking for most wood species.

Wood by nature is hygroscopic, which describes the mechanical and physical properties of wood, as hardness and anisotropic swelling are affected by the moisture in the cell wall. Because wood in many applications is exposed to varying climatic conditions, the relationships between its mechanical properties and equilibrium moisture content (EMC) are of particular interest for commercial purposes. For example, the EMC below the fiber saturation point has a negative effect on mechanical properties (Forest Products Laboratory 1987, Skaar 1988, Siau 1995, Niemz and Stübi 2000, Ozyhar et al. 2012). The influence of EMC on hardness in the longitudinal direction was investigated (Wang and Wang 1999, Niemz and Stübi 2000), but the behavior in the perpendicular to the grain directions has been only rarely studied.

In this work, hardness and elastic recovery measurements were carried out in six species. To understand the ovendried density and moisture-dependent hardness anisotropy, this study examined the effects of ovendried density and EMC on hardness on the cross section, radial, and tangential surfaces. Moreover, the decrease in hardness with increasing EMC for the six species was evaluated.

Materials and Methods

Materials

Samples from three softwood species, Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.), Red pine (*Pinus koraiensis* Sieb. et Zucc.), and Mongolian scotch pine (*Pinus sylvestris* L. var. *mongolica* Litv.), and three hardwood species, Manchurian walnut (*Juglans mandshurica* Maxim.), Asian white birch (*Betula platyphylla* Suk.), and Mongolian oak (*Quercus mongolica* Fisch. et Turcz.), with dimensions of 20 (longitudinal) by 20 (radial) by 20 (tangential) mm were tested in this study. The average raw density, determined by the ratio of mass and volume at a temperature of 20°C and a relative humidity (RH) of 65 percent, amounted to 394, 456, 509, 529, 568, and 749 kg/m^3, respectively. All species originated from China. For each species, specimens with longitudinal (L), radial (R), and tangential (T) grain orientations were cut from the heartwood part of a tree. All tests performed in this research were carried out on carefully selected clear wood specimens.

Moisture conditioning

For each species, 75 specimens were divided into five groups with 15 samples per EMC; four groups were conditioned in climatic chambers at 50, 65, 85, and 95 percent RH, respectively, and a temperature of 20°C until EMC was reached. For the calculation of the EMC (Eq. 1), the mass of the samples was determined at 20°C and 50, 65, 85, and 95 percent RH (M_w) and oven-dry (M_0):

$$EMC = \Big((M_W - M_0)/M_0\Big) \times 100\% \qquad (1)$$

The corresponding EMC is shown in Table 1.

Furthermore, 103°C ovendried samples were also prepared using the fifth group items, and the ovendried density (dry mass on dry volume) was calculated and is presented in Table 2.

Anatomical studies

Specimens for anatomical studies were cut into clear blocks (10 [L] by 10 [R] by 10 [T] mm) after Brinell hardness measurement with a razor blade and then softened in water at 80°C for 5 hours. Thereafter, 15-µm cross sections were cut on a sliding microtome and stained with 1 percent aqueous safranin for microscopic examination under a light microscope (Olympus BX51, Japan) at ×40 magnification. Fifty measurements of the width of the growth rings and of earlywood were made on the cross section. In addition, 50 measurements of the wood rays content were calculated by the dot–grid integrating eyepiece technique (Quirk 1975).

Brinell hardness and elastic recovery measurements

Hardness measurement standards may be difficult to apply in the same way for wood materials, and variations in the experimental setup may be required (Hirata et al. 2001). Such adaptations are necessary because the density profile of wood materials is nonhomogenous, and this can have a significant influence on hardness measurement. There are at least two standards for wood, which are referred to as a Brinell hardness—EN 1534 (European Committee for Standardization [CEN] 2000) and JIS Z 2101 (Japanese Standards Association [JSA] 1994) (Hirata et al. 2001, Rautkari et al. 2011). However, the measured parameters and properties can be different for the two methods. In the JIS Z 2101 (JSA 1994) standard, a steel ball diameter of 10 mm is pressed into the wood surface to a certain depth (1/π mm), and the applied force is measured. At that point, the surface properties of wood are obtained. Using the standard specified in EN 1534 (CEN 2000), the load is constant and the diameter of the indentation is measured. Because of the different penetration depth of the steel ball used in the EN 1534 (CEN 2000) test, the properties of the bulk wood can be evaluated rather than the surface properties. Another commonly used method to measure the hardness of wood materials is the so-called Janka test. In the Janka test, a steel ball 11.284 mm in diameter is indented into a test piece to the depth of the hemisphere, and the hardness value is measured as the maximum force recorded during the test. The Janka test is not widely accepted in Europe, because there is a considerable possibility of failure owing to cell wall compression, and because of the more reliable results of the Brinell test compared with those of the Janka test (Schwab 1990, Niemz and Stübi 2000, Hirata et al. 2001, Heräjärvi 2004, Lykidis et al. 2015).

In this study, the Brinell hardness was measured according to EN 1534 (CEN 2000) with a minor modification described by Niemz and Stübi (2000). The tests were performed using a Zwick Z100 (Zwick GmbH & Co. KG, Ulm, Germany) universal testing machine equipped with a 100-kN load cell (with an accuracy of

Table 1.—Equilibrium moisture content (EMC) of six species.

	Species	EMC, mean (SD) (%)			
		50% RH	65% RH	85% RH	95% RH
Softwood	Chinese fir	10.0 (2.9)	11.2 (2.5)	13.7 (3.4)	17.3 (2.7)
	Red pine	9.8 (2.6)	11.6 (2.5)	15.5 (3.3)	19.4 (4.0)
	Mongolian scotch pine	10.5 (1.8)	12.9 (2.4)	16.8 (1.2)	20.1 (0.8)
Hardwood	Manchurian walnut	9.4 (1.4)	12.5 (3.3)	14.8 (3.1)	17.1 (2.2)
	Asian white birch	9.5 (2.8)	11.6 (3.8)	14.6 (6.2)	18.6 (6.3)
	Mongolian oak	9.6 (2.1)	11.5 (3.6)	13.7 (3.3)	16.8 (1.0)

0.01 N). A 10-mm steel ball with an accuracy of 0.001 mm was applied on the cross section (i.e., longitudinal direction), radial surface (i.e., tangential direction), and tangential surface (i.e., radial direction), respectively. The force increased at such a rate that a nominal value of 500 N was reached after 15 seconds; the force was maintained for 25 seconds and then released over 15 seconds. Instead of measuring the diameter of the indentation manually as defined in EN 1534 (CEN 2000), a transducer was used to register the depth (with a high accuracy of 0.001 mm) of the ball from the first touch on the surface of the test object until the end of the release phase. The unloading processes are shown schematically in Figure 1. Brinell hardness (*HB*, N/mm^2) was defined according to Equation 2:

$$HB = \frac{F}{D \times \pi \times h} \quad (2)$$

where F is the maximum force (N), D is the diameter of steel ball (mm), and h is the depth of the indentation between the wood surface and the lowest point of the steel ball circumference (mm).

Another important parameter obtained in this study was the final depth, h_f, which provides the depth of indentation after ''immediate'' recovery when the load was removed. The elastic recovery (ε_e) was calculated using Equation 3.

$$\varepsilon_e = \frac{h - h_f}{h} \times 100\% \quad (3)$$

The recovery does not affect the actual hardness value in this case but provides valuable information on wood behavior under load. With a higher recovery percentage, a smaller part of the deformation in the hardness test is considered permanent. The final hardness values were calculated as the average of 15 specimens per grain orientation with one indentation on six sides of each sample. For the multiple comparison of *HB* in orthotropic grain orientations and at different RH levels, Duncan's multiple range test for variable was used with SPSS Statistics 17.0 software.

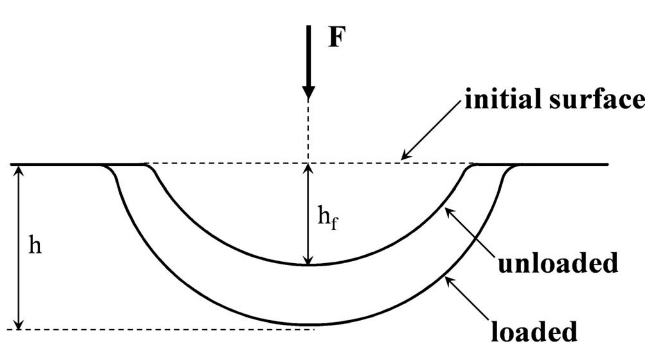

Figure 1.—Schematic illustration of the unloading process showing parameters characterizing the contact geometry.

Results and Discussion

Influence of ovendried density on wood Brinell hardness and elastic recovery

The average ovendried density, Brinell hardness, and elastic recovery in three grain orientations of six species are presented in Table 2. For each species, Brinell hardness on the cross section was statistically significantly higher than that on the radial and tangential surfaces based on Duncan's multiple range test. The differences of wood mechanical behavior between the longitudinal and transverse directions could be related to variation in anatomical structure (Holmberg 2000, Keunecke et al. 2009, Salmén and Burgert 2009, Bader et al. 2012). Tracheids, vessels, and fibers are strictly aligned in the longitudinal direction, which provides mechanical integrity to counteract longitudinal force for the highest hardness in the cross section samples (Forest Products Laboratory 1987, Holmberg 2000).

For the three hardwood species, Duncan's multiple range test showed that the Brinell hardness on the tangential surface, with the exception of Manchurian walnut, was statistically significantly higher than that on the radial surface. An opposite trend was found for Red pine and Mongolian scotch pine, as the Brinell hardness on the radial surface was higher than that on the tangential surface, although there was no statistical difference in the transverse direction for Red pine. In hardwood, ray tissue can influence transverse anisotropy, ray cells act as stiffening ribs in the radial direction, and large and particularly compactly shaped bundles might increase the hardness on the tangential surface (Schniewind 1959, Burgert et al. 1999, Smith et al. 2003, Mishnaevsky and Qing 2008, de Borst and Bader 2014). The test for Brinell hardness is highly dependent on the location of the test point in earlywood and latewood. The steel ball probably more easily penetrates the earlywood areas of Manchurian walnut because of its high average ring width (3.3 mm) and earlywood fraction in growth rings (80.9%; Table 3), which results in no significant difference in hardness on the radial and tangential surfaces. Softwood has a lower ray content of about 5 to 7 percent by volume (Table 3), so these rays may have less of an effect on hardness. However, the different cell arrangements in radial and tangential directions probably had an influence on transverse anisotropy in softwood. More importantly, the local density gradient is far higher between earlywood and latewood, and the transverse anisotropy of softwood can be reasonably explained by the

Table 2.—Brinell hardness of six species under ovendried condition.[a]

	Species	Ovendried density (kg/m^3)	*HB*, mean (SD) (N/mm^2)			ε_e, mean (SD) (%)		
			Cross section	Radial surface	Tangential surface	Cross section	Radial surface	Tangential surface
Softwood	Chinese fir	369 (30)	52.6 (16.8) A	11.4 (3.5) B	12.6 (3.3) B	18.6 (5.1) a	24.1 (3.9) b	22.7 (8.3) b
	Red pine	434 (14)	56.6 (7.0) A	13.3 (2.0) B	11.8 (1.9) B	20.0 (3.0) a	31.1 (2.9) b	27.3 (4.4) c
	Mongolian scotch pine	481 (11)	68.9 (14.4) A	19.3 (3.5) B	16.3 (6.6) C	25.6 (6.0) a	31.9 (4.7) b	26.3 (8.9) a
Hardwood	Manchurian walnut	491 (22)	68.8 (11.4) A	17.4 (1.6) B	20.2 (3.5) B	20.3 (3.6) a	28.0 (3.5) b	26.5 (3.9) b
	Asian white birch	549 (12)	78.1 (6.3) A	17.6 (1.5) B	23.3 (2.1) C	23.7 (1.7) a	35.3 (1.6) b	29.6 (2.0) c
	Mongolian oak	707 (29)	102.3 (13.8) A	29.6 (2.8) B	35.2 (4.7) C	31.5 (2.7) a	36.3 (3.2) b	36.6 (6.3) b

[a] *HB* = Brinell hardness; ε_e = elastic recovery. The same letter in the same row indicates that there is no statistical difference; a different letter indicates significant differences at $P < 0.05$. Uppercase letters (A, B, C) indicate results of Duncan's multiple range test for the variable in *HB*; lowercase letters (a, b, c) indicate results of Duncan's multiple range test for the variable in ε_e.

earlywood–latewood interaction (Kifetew 1999, Hirata et al. 2001, Heräjärvi 2004). Hardness is obviously higher in latewood than in earlywood because of the differences in their local density. Latewood acts as ''reinforcement'' and probably resists compression to a greater extent on the radial surface than on the tangential surface, resulting in greater hardness values for the radial surface (Hirata et al. 2001, Hofstetter et al. 2007, Bader et al. 2012). The lack of significant difference in hardness for radial and tangential surfaces of Chinese fir and Red pine was probably owing to the gradual transition from earlywood to latewood or the higher earlywood fraction in the growth ring (Table 3), although further investigation would be necessary to confirm such an effect of earlywood–latewood transitions or earlywood fraction.

The elastic recovery on the cross section was lowest for all species in this study, and this difference was statistically significant (Table 2). The difference in elastic recovery in the longitudinal and transverse directions may be explained by the stored elastic energy in wood (Salmén and Burgert 2009, Engelund and Svensson 2011). Cellulose microfibril, which acts as an elastic body in the cell wall, can be compressed during hardness tests in the longitudinal direction (Dinwoodie 1968, Forest Products Laboratory 1987, Engelund and Svensson 2011). Moreover, the compression induces mainly irreversible cell wall buckling (especially along microfibril cracks), whereas this buckling is rare in the transverse direction (Dinwoodie 1968, Ljungdahl et al. 2006, Hofstetter et al. 2007, Bader et al. 2012, de Borst and Bader 2014). Therefore, elastic recovery in the transverse direction was statistically significantly higher than that in the longitudinal direction.

An increase in elastic recovery with increasing Brinell hardness was obtained in both softwood and hardwood regardless of grain orientations (Table 2). This result was consistent with previous studies (Rautkari et al. 2011). However, when evaluating all species, the correlation between Brinell hardness and elastic recovery was not found. This difference in findings may result from the distinct anatomical characteristics of softwood and hardwood.

In order to analyze the effects of ovendried density on Brinell hardness and elastic recovery for softwood or hardwood, the one-way analysis of variance (ANOVA) was carried out. As can be seen in Figure 2, Brinell hardness tended to increase as the ovendried density increased in softwood as well as hardwood, and ANOVA showed statistical significance at the 0.01 level. Similar results were reported by Holmberg (2000) and Heräjärvi (2004). For softwood, the Brinell hardness showed moderate correlation ($r = 0.57$) on the tangential surface and strong correlation ($r = 0.85$) on the radial surface against ovendried density. In the case of hardwood Brinell hardness, a strong correlation ($r = 0.88$ to 0.94) against ovendried density was observed. The results are likely explained by the variation in ovendried density. The mechanical properties of wood depend on the thickness of the cell walls, which governs wood density (Kollmann and Côte 1968, Stamm 1968, Forest Products Laboratory 1987, Bader et al. 2012). With the exception the tangential surface of softwood ($r = 0.02$), a statistically significant (at the 0.01 level) positive correlation of elastic recovery against ovendried density was observed and is shown in Figures 2d through 2f. The structural arrangement of the cell wall can be viewed as a fiber composite system by cellulose microfibril and

Table 3.—Extractives and microstructure properties of six species.

Parameter	Softwood, mean (SD)			Hardwood, mean (SD)		
	Red pine	Chinese fir	Mongolian scotch pine	Manchurian walnut	Asian white birch	Mongolian oak
Extractives content (%)[a]	6.5	6.2	6.1	10.1	5.2	10.1
Rays content (%)	5.5 (26.5)	6.1 (9.7)	4.4 (17.3)	13.8 (15.4)	14.4 (24.3)	26.4 (32.2)
Average ring width (mm)	1.3 (21.2)	4.0 (42.3)	3.4 (15.1)	3.3 (17.4)	1.8 (11.2)	2.0 (17.4)
Earlywood fraction in growth ring (%)	73.1 (17.8)	85.4 (30.6)	68.9 (12.7)	80.9 (26.3)	85.7 (29.1)	25.3 (20.0)
Earlywood–latewood transitions in softwood/pore distribution in hardwood	Gradual transition	Gradual transition	Abrupt transition	Semi-ring porous	Diffuse porous	Ring porous

[a] Data from Cheng (1985).

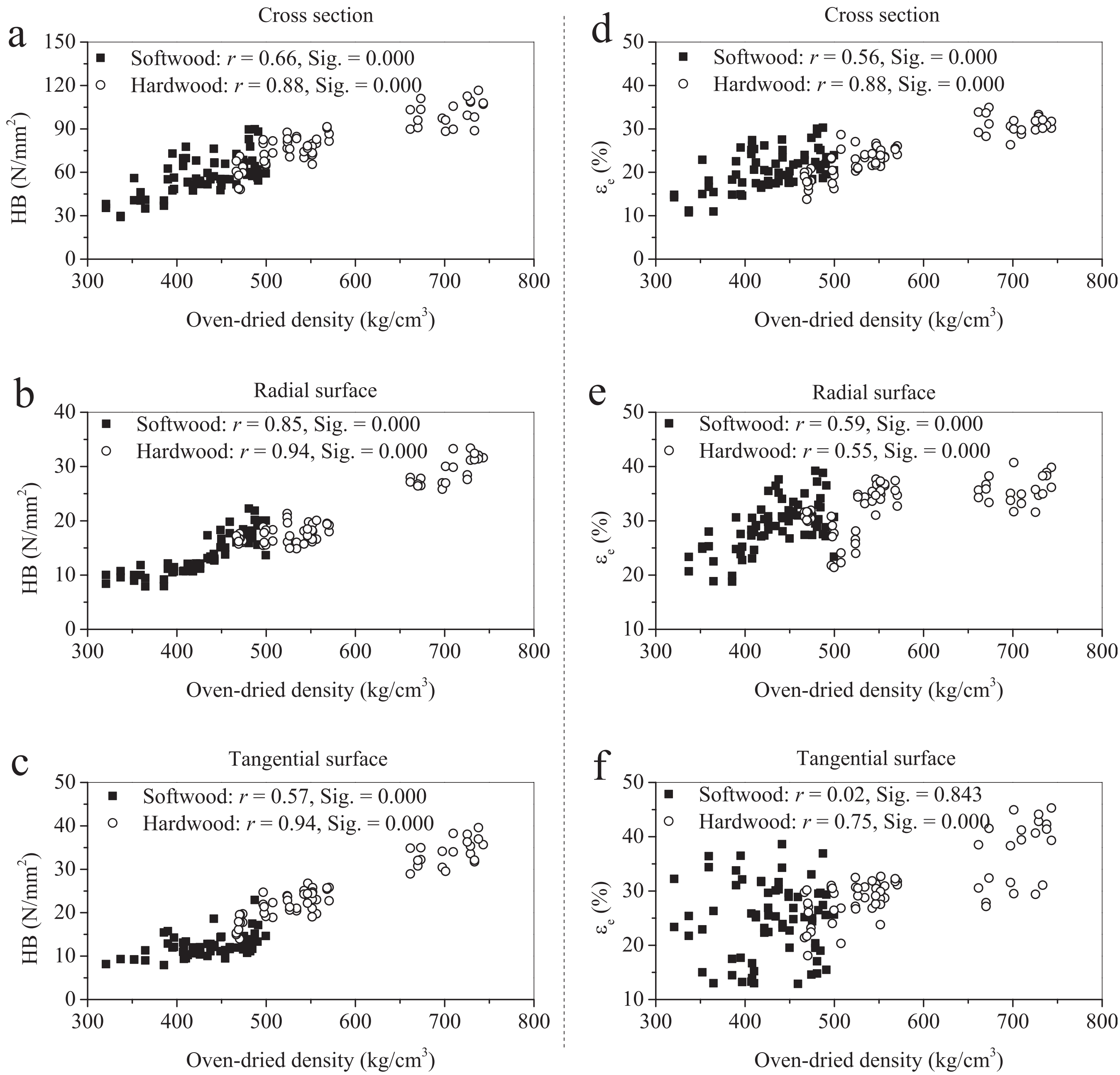

Figure 2.—Correlation analyses of ovendried density and HB *(a, b, c) or* ε_e *(d, e, f) on cross section (a, d), radial (b, e), and tangential (c, f) surfaces.* HB = *Brinell hardness;* ε_e = *elastic recovery;* r = *correlation coefficient.*

hemicellulose–lignin matrix (Abe and Yamamoto 2006, Mishnaevsky and Qing 2008). Cellulose microfibril acts as an elastic body and dominates the elastic properties in the longitudinal direction (Engelund and Svensson 2011). The thicker the cell wall, the higher the density and the higher the amount of cellulose in a given volume (Kollmann and Côte 1968, Stamm 1968, Smith et al. 2003), resulting in higher elastic recovery. The tangential surface of softwood exhibited highly scattered data in elastic recovery (Fig. 2f), probably because the elastic recovery was dependent on penetration position of the steel ball (in earlywood or latewood area) and on the local density and failure behavior of the cell when the load was applied to the tangential surface.

EMC of wood

Figure 3 shows the EMC of six species at 20°C and 50, 65, 85 and 95 percent RH. An increasing trend for the EMC with increasing RH was observed in all species. For given RH conditions, the EMC varied among different species, and the degree of variance increased with increased RH. The changing ranges of EMC among six species at 50, 65, 85, and 95 percent RH were 9.4 to 10.5, 11.2 to 12.9, 13.7 to 16.8, and 16.8 to 20.1 percent, respectively. The overall EMC of softwood was higher than that of hardwood at each RH level.

Under the same constant climate, hemicellulose content is the key factor in wood hygroscopicity to explain varied EMC among different species (Skaar 1988, Siau 1995).

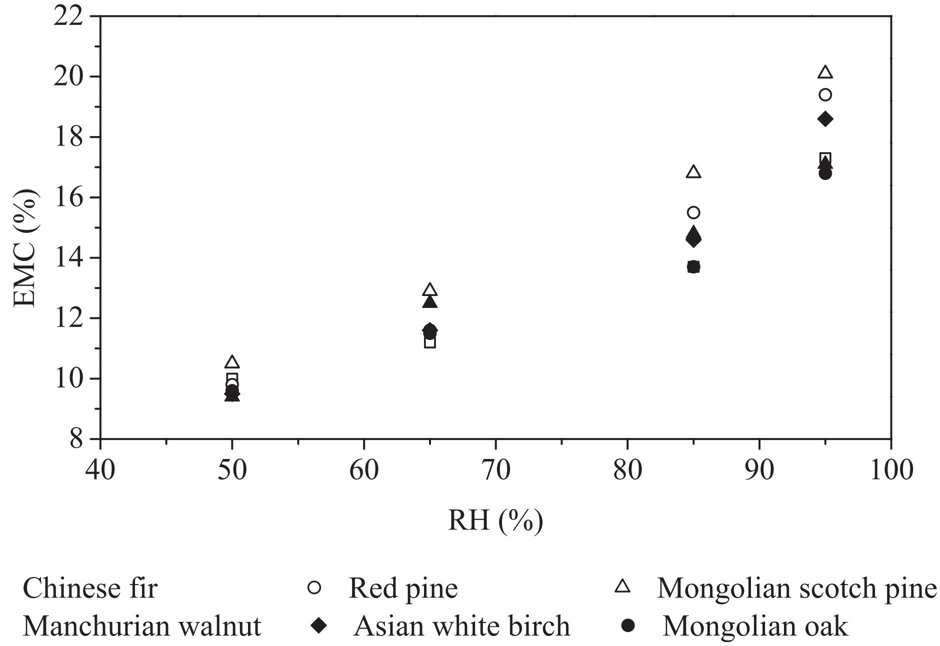

Figure 3.—Equilibrium moisture content (EMC) of six species at 20°C and 50, 65, 85, and 95 percent relative humidity (RH).

Because extractives cause bulking action, whereby the extractive substance within the cell wall precludes moisture from occupying the same space, the difference in extractive content of the six species (Table 3) may explain the larger variance of EMC in the upper range of RH (Wangaard and Granados 1967, Nzokou and Kamdem 2004). In addition, Wang (1986) reported that the EMC of softwood with dark heartwood (such as Chinese fir, Red pine, Mongolian scotch pine) is always higher than that of semi-ring or ring porous hardwood with dark heartwood (Manchurian walnut, Mongolian oak).

Influence of moisture content on wood Brinell hardness and elastic recovery

In order to clarify the effects of EMC on the decreased Brinell hardness in the three grain orientations, a new parameter, the relative Brinell hardness HB/HB_0 (where the HB_0 is defined as the value at ovendried condition), is introduced in this article. For the range of EMC investigated in this study, a general increase in EMC significantly lowered the Brinell hardness for the six species according to Duncan's multiple range test, irrespective of grain orientation (Fig. 4). It is well known that water is a plasticizing agent for wood, and the replacement of hydrogen bonding within the amorphous polymers by water–carbohydrate links with the penetration of water can enhance the flexibility of the polymer networks and facilitate the deflection of wood during loading (Skaar 1988, Smith et al. 2003, Salmén and Burgert 2009, Engelund et al. 2013). In addition, cell wall swelling can exert a negative effect where fewer cell wall substances per unit area are available to resist the load (Skaar 1988, Kaboorani et al. 2013, Kulasinski et al. 2015). Water induces the swelling of the cell wall, while the amount of substances (i.e., the polymers in the cell wall) remains unchanged. When water penetrates the cell wall, the cell wall is composed of substances, void, and water, but only substances and void when it is dried. Therefore, the increasing water results in a decrease in the fraction of substances making up the cell wall. As a result, wood with a higher moisture content is characterized by a lower hardness. On the cross section, the aforementioned plasticization effect accelerates sliding between longitudinal cellulose molecules during loading. Furthermore, the viscous response of the middle lamella with a high moisture content aggravated the adjacent cell wall slippage (Skaar 1988, Kaboorani et al. 2013). This could explain why the Brinell hardness on the cross section decreased as EMC increased. In the transverse direction, the effect of hemicellulose is more pronounced than cellulose and lignin (Bergander and Salmén 2002, Salmén 2004, Mishnaevsky and Qing 2008). This suggests that hardness reduction on radial and tangential surfaces caused by increasing the EMC may be a result of the hygroscopicity and expansion of hemicellulose.

The data in Figure 4 suggest that the decreased extent of HB/HB_0 on the cross section was obviously higher than that on both radial and tangential surfaces for all six species. Comparing the decreased extent of HB/HB_0 between radial and tangential surfaces, softwood and hardwood showed an opposite trend. As discussed above, rays are not a key factor controlling transverse anisotropy for softwood, but available evidence suggests that it is an important factor for hardwood (Skaar 1988, Ljungdahl et al. 2006, de Borst and Bader 2014). Water can facilitate the cell wall buckling of rays, making it easier for the loading on the tangential surface as tracheids do for the longitudinal direction. Therefore, to a certain extent, rays contribute to the greater decreased extent of HB/HB_0 on the tangential surface for the three hardwood species. However, for the three softwood species, compared with the radial surface, a less decreased extent of HB/HB_0 on the tangential surface was found. Earlywood–latewood interaction may explain transverse anisotropy, especially in softwood (Skaar 1988). Wu and Wilson (1967) found a general pattern of variation in lignin content with maximum amounts in earlywood and minimum amounts in

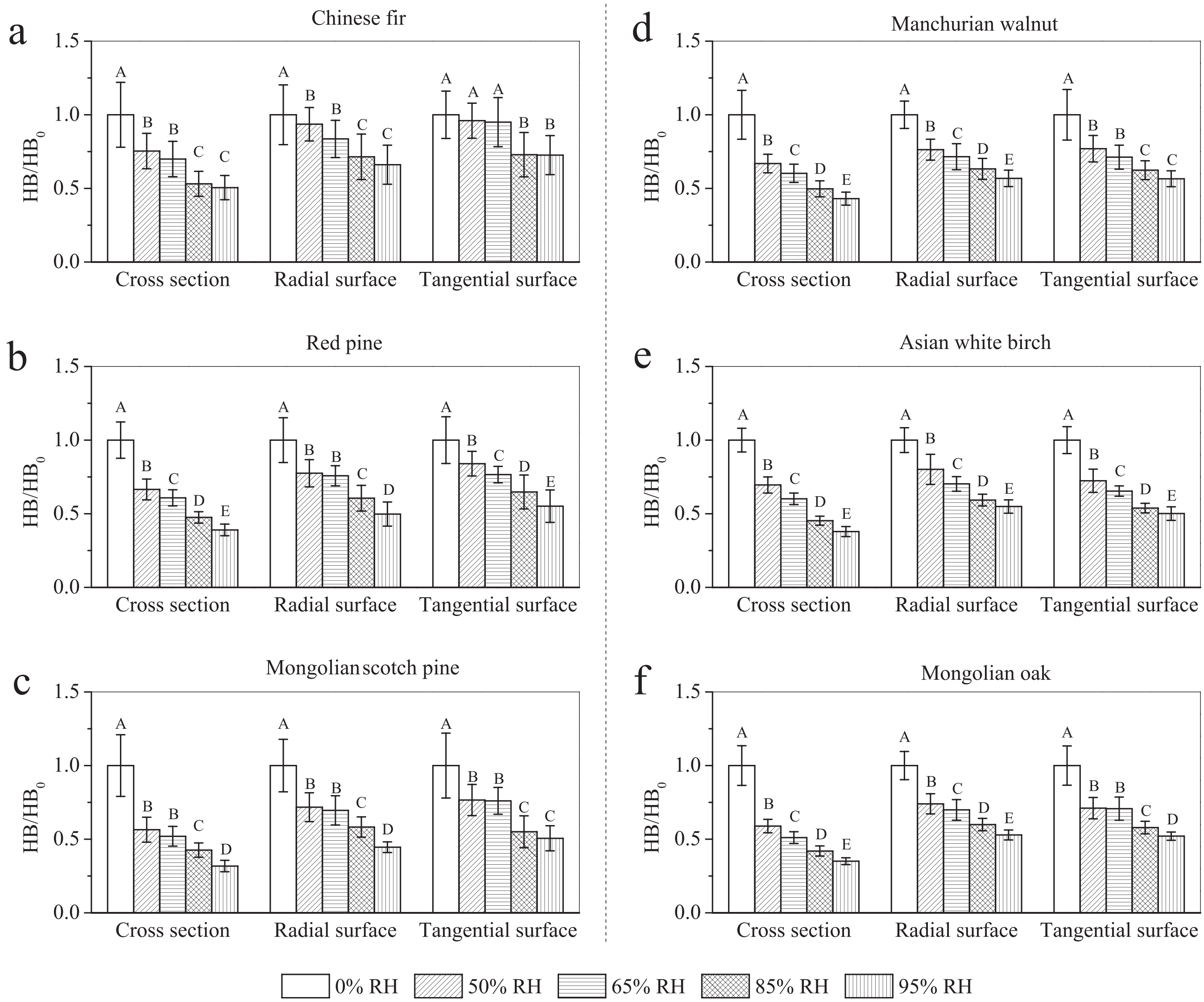

Figure 4.—Moisture-dependent HB/HB_0 *of softwood (a, b, c) and hardwood (d, e, f) species in orthotropic grain orientation.* HB/HB_0 *= relative Brinell hardness, where* HB *is the Brinell hardness of ovendried and wet wood, respectively; and* HB_0 *is the Brinell hardness at ovendried condition. The same letter in the same surface indicates that there is no statistical difference; a different letter indicates significant differences at* $P < 0.05$ *(Duncan's multiple range test).*

latewood. Conversely, cellulose is at its maximum in latewood and its minimum in earlywood (Hale and Clermont 1963). Therefore, latewood may present slightly better hygroscopicity. More importantly, the ''reinforcement'' effect provided by latewood on radial surfaces was weakened when water penetrated the cell wall, resulting in greater decreases in HB/HB_0 on the radial surface for the three softwood species.

The effects of EMC on elastic recovery in the three grain orientations for six species are shown in Figure 5. In general, similar to the results with the ovendried samples, the elastic recovery on the radial surface was highest, followed by the tangential surface and the cross section at different RH levels. For Brinell hardness tests on the cross section, the force probably caused wood fiber, vessel, or tracheid distortion, severe crinkles, or even separation (Wilkins 1986, Smith et al. 2003). Because the elastic properties are controlled by the lengthening and/or the rotation of covalent and hydrogen bonds, when the covalent and hydrogen bonds of cellulose microfibrils break, it causes the lowest elastic recovery in the longitudinal direction (Engelund and Svensson 2011, Engelund and Salmén 2012). In addition, owing to the different damage mechanisms between the longitudinal and transverse directions, the diversity of elastic recovery in the transverse direction could be explained by earlywood–latewood interaction. The cell wall of earlywood is much thinner than that of latewood, and the crystallinity degree of cellulose in latewood is higher than that in earlywood (Bader et al. 2012, de Borst and Bader 2014), suggesting higher elastic energy in latewood. Furthermore, the aforementioned ''reinforcement'' effect provided by the latewood probably leads to higher elastic recovery on the radial surface. However, when load was applied on the tangential surface, failure started in the weakest earlywood layer and progressed sequentially to several other earlywood layers, or the stiffer

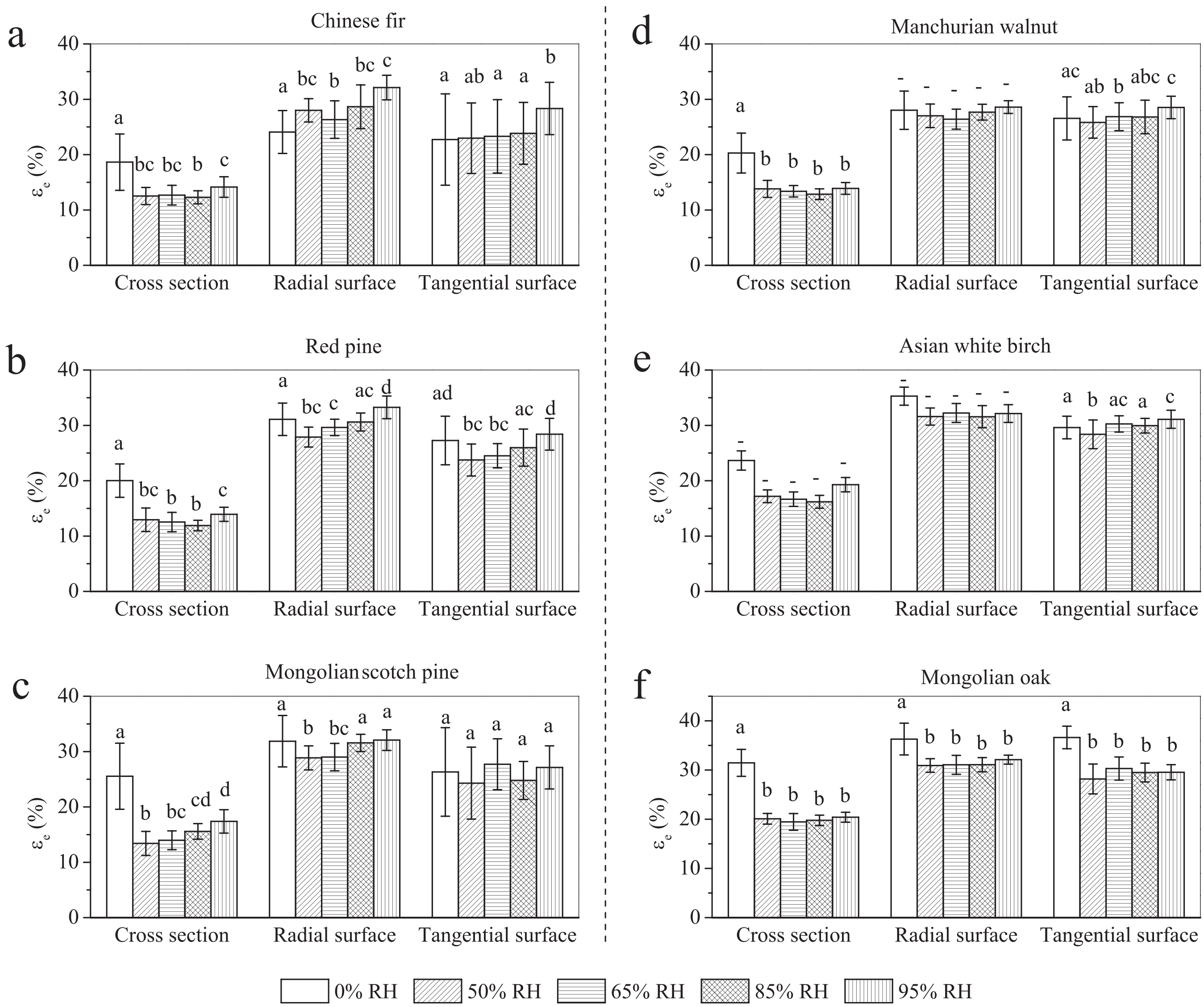

Figure 5.—Influence of equilibrium moisture content on elastic recovery (ε_e) in orthotropic grain orientations for softwood (a, b, c) and hardwood (d, e, f) species. The same letter in the same surface indicates that there is no statistical difference; a different letter indicates significant differences at $P < 0.05$ (Duncan's multiple range test); and a dash indicates no significant difference in F test, and Duncan test is not required.

latewood layers collapsed (Tabarsa and Chui 2001, Smith et al. 2003, Ljungdahl et al. 2006), resulting in lower elastic recovery.

As seen in Figure 5, the elastic recovery in three grain orientations was virtually unchanged with increasing EMC for the three hardwood species, but for the three softwood species, the elastic recovery changed slightly as EMC increased. Duncan's multiple range test shows that EMC had a complex effect on elastic recovery. The anatomical structure (such as fiber morphology and arrangement of fiber) or fracture behavior during hardness measurement may play a role in elastic recovery. Therefore, it was difficult to establish a direct influence of EMC on elastic recovery.

Conclusions

This study focused on examining the anisotropic characteristics of Brinell hardness for six species with EMC obtained at different RH levels (20°C; 50%, 65%, 85%, and 95% RH). The effects of ovendried density and EMC on wood Brinell hardness and elastic recovery were analyzed in three grain orientations, respectively. The decreased extents of relative Brinell hardness (HB/HB_0) in orthotropic directions with increasing EMC were compared. The following main conclusions were drawn.

1. In three grain orientations, Brinell hardness tended to increase with the increased ovendried density, and the correlations were significant at the 0.01 level for softwood and hardwood. Concerning the correlation of elastic recovery against density, with the exception of softwood on the tangential surface ($r = 0.02$), a statistically significant positive correlation against ovendried density (at the 0.01 level) was observed.
2. For the range of EMC investigated in this study, a general increase in EMC significantly lowered the Brinell hardness for six species as measured by the

Duncan's multiple range test, irrespective of grain orientations. For all six species, the decreased extent of HB/HB_0 on the cross section was obviously higher than that on the radial and tangential surfaces. However, a comparison of the decreased extent of HB/HB_0 between radial and tangential surfaces showed that it was higher on the radial surface for the three softwood species, and the opposite trend was found for the three hardwood species. This may be because rays were the main factor controlling transverse anisotropy in hardwood, and earlywood–latewood interaction was more important for softwood.

3. Elastic recovery anisotropy was probably owing to failure when load was applied. It was difficult to establish a direct influence of EMC on elastic recovery. Other factors such as anatomical structure (fiber morphology or arrangement of fiber) or fracture behavior during hardness measurement might also affect our measurements of elastic recovery.

The above results provide comprehensive data sets of the relationships between wood density and anisotropic hardness for many wood species used for wood commercial application, such as for flooring or furniture, and especially for civil engineering for joint application in the transverse direction. Because wood is always exposed to varying climatic conditions, defining the relationships between hardness and EMC for softwood and hardwood is important for the effective use of wood.

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