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Estimating Janka Hardness from Specific Gravity for Tropical and Temperate Species

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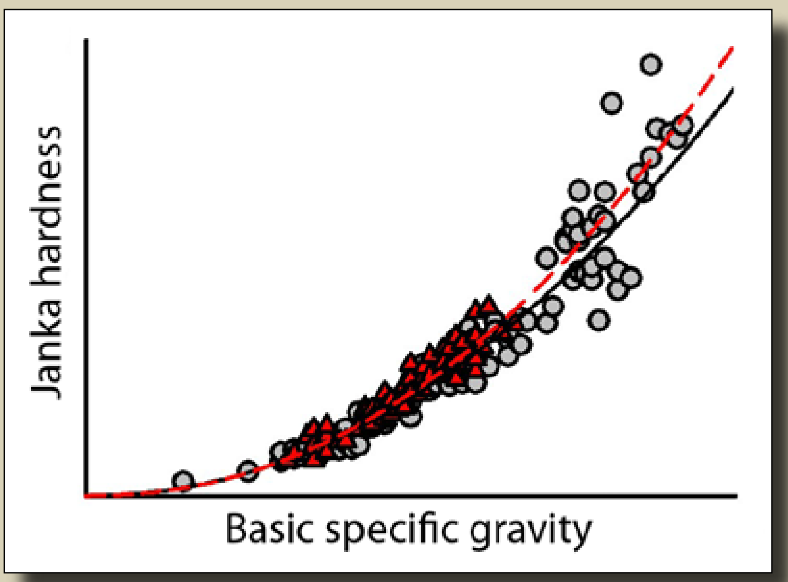

Abstract

Using mean values for basic (green) specific gravity and Janka side hardness for individual species obtained from the world literature, regression equations were developed to predict side hardness from specific gravity. Statistical and graphical methods showed that the hardness–specific gravity relationship is the same for tropical and temperate hardwoods, but that the relationship for softwoods is different from that for hardwoods. As expected, the relationship for green wood is different from that for wood at 12% moisture content.

Keywords: Janka hardness, specific gravity, temperate hardwoods, tropical hardwoods, softwoods

Acknowledgments

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Contents

Executive Summary

Background

There is increasing interest in using species from foreign origins, especially tropical hardwoods, for flooring. The *Wood Handbook* (FPL 1999) contains side hardness values obtained by the Janka test procedure for most domestic species and for almost 80 species commonly imported into the United States from countries other than Canada. However, there are beginning to be more requests for hardness values for foreign species for which we do not have Janka hardness results. The *Wood Handbook* also has equations that can be used to estimate Janka hardness from specific gravity. These equations were derived from data on domestic species and do not contain species with specific gravity values as high as those of many tropical hardwoods.

Objective

The objective of this study was to develop equations relating Janka hardness to specific gravity for both temperate and tropical hardwoods and temperate softwoods.

Materials and Methods

Basic specific gravity, also called green specific gravity (G_g), is the ovendry weight of a sample divided by the weight of water displaced by the sample's green volume. Because it is calculated from the maximum volume and minimum weight, the specific gravity is less variable than specific gravity values calculated using the weight of displaced water at other moisture contents (MCs). Data on the mean side hardness and mean G_g for 237 hardwood and 47 softwood species was taken from the *Wood Handbook* and other world literature (Appendix 1). Power models of the form Hardness = $a(G_g)^b$ were fit to these data.

Results

The side hardness–specific gravity relationships determined in this study are as follows. (Equation numbers are the same as those given in the text; the suffix "b" indicates the coefficient is for pounds force (lbf) rather than newtons (N).)

Green hardness, temperate softwoods
$H(\text{lbf}) = 1{,}560(G_g)^{1.50}$ $r^2 = 0.70$ (1b)
Green hardness, temperate hardwoods
$H(\text{lbf}) = 3{,}500(G_g)^{2.17}$ $r^2 = 0.91$ (2b)
Green hardness, tropical hardwoods
$H(\text{lbf}) = 3{,}000(G_g)^{1.91}$ $r^2 = 0.90$ (3b)
Green hardness, all hardwoods
$H(\text{lbf}) = 3{,}060(G_g)^{1.96}$ $r^2 = 0.90$ (4b)
12% hardness, temperate softwoods
$H(\text{lbf}) = 2{,}560(G_g)^{1.65}$ $r^2 = 0.73$ (5b)
12% hardness, temperate hardwoods
$H(\text{lbf}) = 4{,}470(G_g)^{2.14}$ $r^2 = 0.91$ (6b)
12% hardness, tropical hardwoods
$H(\text{lbf}) = 4{,}040(G_g)^{2.06}$ $r^2 = 0.94$ (7b)
12% hardness, all hardwoods
$H(\text{lbf}) = 4{,}090(G_g)^{2.05}$ $r^2 = 0.93$ (8b)

Discussion

The equations for hardness at 12% MC given above differ from those historically used in the *Wood Handbook*. The *Wood Handbook* equations relating hardness to specific gravity for dry wood have traditionally been based on hardness and specific gravity determined at 12% MC (G_{12}.) The equations for dry lumber given above are based on hardness at 12% MC and specific gravity when green. These equations may be converted to the G_{12} form using adjustment procedures given in ASTM D 2395-02 (2006). Using these adjustments, Equations (5b) and (8b) become

12% hardness, temperate softwoods
$H(\text{lbf}) = 2{,}560(G_{12}/(1+0.162G_{12}))$

12% hardness, all hardwoods
$H(\text{lbf}) = 4{,}090(G_{12}/(1+0.162G_{12}))$

where H is given in pounds force and G_{12} is specific gravity based on ovendry weight and volume at 12% MC.

Conclusions

1. The variability (range and standard deviation) of specific gravity for temperate softwoods is less than that of temperate hardwoods and much less than that of tropical hardwoods.
2. The hardness of dry wood is greater than that of green wood. For temperate softwoods, this increase is about 43%; for temperate hardwoods, it is about 31%; and for tropical hardwoods, it is about 26%.
3. For both green and dry wood, the relationship between hardness and specific gravity of temperate softwoods is different from that of hardwoods.
4. For both green and dry wood, the relationship between hardness and specific gravity of temperate hardwoods does not differ from that of tropical hardwoods. Thus the recommended estimation equations are Equations (1b) and (4b) for green wood and Equations (5b) and (8b) for wood at 12% MC.

Estimating Janka Hardness from Specific Gravity for Tropical and Temperate Species

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Introduction

In the United States, Janka hardness (ASTM D 143-94 (ASTM 2006)) was initially used as a minimally destructive test for estimating the strength and stiffness properties of wood (Green et al. 2006). Currently side hardness, determined using the Janka test, is a primary method used to assess the suitability of wood species for use as residential and commercial flooring. The *Wood Handbook* (FPL 1999) contains side hardness measurements for most domestic U.S. and Canadian hardwood (angiosperm) and softwood (gymnosperm) species likely to be used in flooring, and equations are presented that relate the average hardness of a species to its average specific gravity. Exotic species, especially tropical hardwoods, are a growing segment of the hardwood flooring market. The 1999 *Wood Handbook* also contains hardness values for almost 80 species that are commonly imported into the United States from countries other than Canada. However, there are imported species being considered for flooring for which we have no hardness data. Many of these species have G_g values greater than those used in deriving the *Wood Handbook* equations.

The objective of this study was to develop equations relating side hardness, as determined by the Janka test, to basic specific gravity, G_g. The data on which these equations are based are limited to average values of both G_g and hardness as determined from individual species.

Background

Although specific gravity is the single best predictor of clearwood mechanical properties (Panshin and de Zeeuw 1980), many other factors influence its predictive value. Wood moisture content (MC) is important, with hardness increasing as wood is dried below its fiber saturation point (Panshin and de Zeeuw 1980). Wood anatomy and structure are also very important. For native species of the United States, Newlin and Wilson (1919) reported relationships between specific gravity (*G*, based on volume at test) and hardness (*H*, in pounds) as power functions for green and dry (12%) MCs; they arrived at these functions by plotting their data as logarithms and visually determining the slopes and intercepts of the resulting straight lines. The coefficients for these equations (shown in Table 1) were updated by Markwardt in 1930 and were reported in the 1935 and 1940 editions of the *Wood Handbook* (FPL 1935, 1940). Their

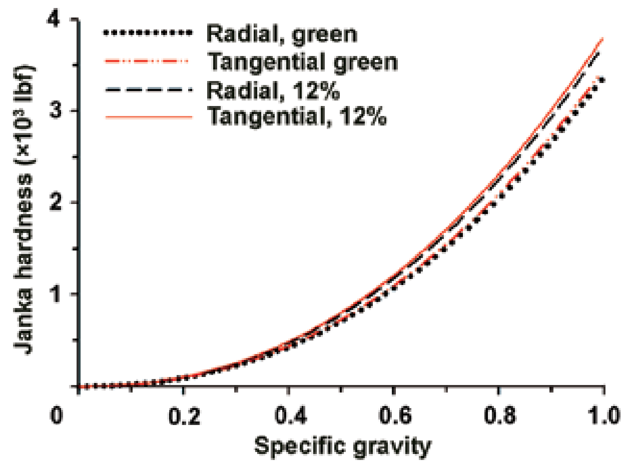

Figure 1— Side hardness relationships given in the 1935 edition of the *Wood Handbook.*

equations did not distinguish between softwoods and hardwoods but did indicate that they believed that ring orientation might be an important factor. Plots of these relationships showed little difference between radial and tangential values at a given MC level (Figure 1), so subsequent editions combined the tangential and radial data (Table 1).

Later editions of the *Wood Handbook* contained hardness data for some 60 (FPL 1974) and 80 (FPL 1987) tropical woods, but did not change the equations relating hardness and specific gravity, which are based only on the species native to the United States. By the early 1960s the clearwood data on wood properties had increased about 50% over that available in 1919. Liska (1965) conducted a preliminary evaluation of some properties using this expanded data set and concluded that if a power function is chosen, the power coefficient for green wood would likely not be the same as that for dry wood. Furthermore, he speculated that the relationship might be improved by separating hardwoods and softwoods. This was confirmed by Armstrong et al. (1984) and Walton and Armstrong (1986) who improved on the method for determining predictive equations for mechanical properties by using least squares regression on a much larger, worldwide, set of data. For the properties they studied, they found statistically significant differences between hardwoods and softwoods, and among some groups of hardwoods.

Table 1—Relationships between side hardness *H* and specific gravity *G* using $H = aG^b$ reported in the *Wood Handbook*[a]

Edition	Species grouping	MC	Orientation	*H* in lbf		*H* in N	
				a	*b*	*a*	*b*
1935, 1940[b]	All	Green	Radial	3,380	2.25	15,020	2.25
	All	Green	Tangential	3,460	2.25	15,380	2.25
	All	12%	Radial	3,720	2.25	16,530	2.25
	All	12%	Tangential	3,820	2.25	16,980	2.25
1955, 1974	All	Green	Average[c]	3,420	2.25	15,200	2.25
	All	12%	Average[c]	3,770	2.25	16,760	2.25
1987	All	Green	Average[c]	3,420	2.25	15,200	2.25
	All	12%	Average[c]	3,770	2.25	16,760	2.25
1999	Softwoods	Green	Average[c]	1,400	1.41	6,220	1.41
	Hardwoods	Green	Average[c]	3,720	2.31	16,530	2.31
	Softwoods	12%	Average[c]	1,930	1.50	8,580	1.50
	Hardwoods	12%	Average[c]	3,440	2.09	15,290	2.09

[a] Based on ovendry weight and volume at indicated MC.
[b] Originally reported in Newlin and Wilson (1919.)
[c] Determined from average of radial and tangential values.

In 1983, Green took Liska's advice and recomputed power function relationships between most mechanical properties and specific gravity as a function of both species type and MC using the data for domestic species given in the 1955 edition of the *Wood Handbook* (FPL 1955). These new relationships appeared in the 1987 edition of the *Wood Handbook* (FPL 1987), but new hardness relationships were not computed; thus the hardness relationships from the 1955 edition were maintained in the 1987 edition. For the 1999 edition of the *Wood Handbook* (FPL 1999), power function relationships for all mechanical properties, including hardness, were again computed and reported for the domestic U.S. species listed in that edition (Table 1).

Of the 164 woods from which Markwardt (1930) derived his equations, only a few are subtropical (*Avicennia nitida, Bursera simaruba, Coccolobis laurifolia, Conocarpus erecta, Dipholis salicifolia, Eucalyptus globulus, Eugenia confusa, Exothea paniculata, Ficus aurea, Krugiodendron ferreum, Metopium toxiferum, Rhizophora mangle, Sabal palmetto, Sideroxylon foetidissimum, Simarouba glauca*); all these are from Florida except the *Eucalyptus*, which is native to Australia. Subsequent equations were based on fewer species, and the subtropical woods had been removed. Thus, the equations have a strong temperate bias. Tropical species typically do not have the dramatic differences found between earlywood and latewood in temperate species; collectively they are more complex anatomically than temperate woods and thus may be poorly described by equations based on temperate species. With the growing interest in tropical species for flooring applications, their inclusion in property–specific gravity relationships is essential.

Materials and Methods

Specific Gravity and Hardness Definitions

Basic specific gravity G_g is the ovendry weight of a sample of wood divided by the weight of water displaced by the sample's green (undried) volume. Because it is based on the maximum volume and minimum weight, this measurement of specific gravity has traditionally been felt to be less variable than specific gravity at lower MCs. For the clearwood data bank summarized in the various editions of the *Wood Handbook*, there were generally also more trees selected for determination of green properties than for the determination of dry properties. The ratio of "green trees" to "dry trees" was about 5:1 for many species. Thus G_g provides a more reliable estimate of wood properties than does specific gravity based on volume at 12% MC (G_{12} in this report.)

Side hardness, as determined by the Janka test, is the load required to embed an 11.28-mm (0.444-in.) ball to one-half its diameter. Specific gravity measurement and hardness tests are described in American Society for Testing and Materials (ASTM) Standards D 2395-02 and D 143-94, respectively (ASTM 2006). It is quite possible that testers of Janka hardness may not have strictly adhered to the ASTM standards, particularly for the tests on tropical species. This may not pose a serious problem, however, since Green et al. (2006) have shown that some departures from the standards, such as specimen thickness, can still give equivalent results, and that values for radial and tangential surfaces are not different.

Data Sources

Basic specific gravity G_g and Janka hardness data used in this analysis came from four compilations: Kukachka (1970), Lavers (1983), Longwood (1962) and the *Wood Handbook* published by the Forest Products Laboratory (FPL 1999.) Many of the data published in the *Wood Handbook* for species native to the United States are identical to those published by Markwardt and Wilson (1935); however, many of their species were not included in the *Wood Handbook*, and many of their species have had additional data incorporated into the published values. Other references were reviewed[1] but analyses of their data showed most of them were summarized in the above-mentioned four sources. Where independent data were available from more than one source, the data from only one source were included. The Centre Technique Forestier Tropical tested some 400 tropical species (Sallenave 1955), but their hardness test measures the depth of the impression of a 3-cm steel cylinder under a 100-kg load (Chalais-Meudon hardness). Because there is no conversion from the Chalais-Meudon test to Janka hardness, these data were not used.

For derivation of specific gravity–hardness equations, only species that had both green and dry hardness values were used. These species are listed in Appendix 1, which also gives G_g, green and dry hardness values, the ratios of dry to green hardness, and the source of the data. To the extent that information was available, Appendix 1 contains the number of trees sampled for each species and the source of the data. Kukachka (1970) and Lavers (1983) listed the number of trees sampled in their compilations, but Longwood (1962) and the Forest Products Laboratory (FPL 1999) did not. To get this information, we referred to the original sources of the data. For the temperate species, the Forest Products Laboratory (FPL 1999) used the data of Markwardt and Wilson (1935), although sometimes additional information was added to get the published values.

Data not used in deriving the equations were used for model validation. These species and data are given in Appendix 2.

Data reported in pounds force (lbf) were converted to newtons (N) by dividing tabulated values by 0.225 lbf/N. In some cases, dry hardness was reported at an MC other than 12%. In these cases, hardness was converted using equation 4-3 of the 1999 *Wood Handbook*, given as

$$P = P_{12}(P_{12}/P_g)^{((12-M)(M_p-12))}$$

where P is the property (hardness) at the reported MC at test; P_{12} is the property (hardness) at 12% MC; P_g is the property (hardness) in the green condition; M is the reported percentage MC at test; and M_p is the percentage MC at the intersection of a horizontal line representing the strength of green wood and an inclined line representing the logarithm of the strength–MC relationship for dry wood, assumed to be 25% in this report, as recommended in the 1999 *Wood Handbook* for most species.

[1] Cheng 1985; Chudnoff 1973, 1984; Dickinson et al. 1949; FAO 1970; Flynn Jr. and Holder 2001; Heck 1937; Hess et al. 1950; Kukachka et al. 1968; Kynoch and Norton 1938; Lee and Chu 1965; Rijsdijk and Laming 1994; Teixeira et al. 1988; Vilela 1969; Wangaard and Muschler 1952; Wangaard et al. 1954; Wangaard et al. 1955

Separation of Data into Groupings

The data were divided into three major groups for comparison: temperate softwoods, temperate hardwoods, and tropical hardwoods. Tropical softwoods were not considered for equation derivation because only seven species (*Agathis vitiensis, Araucaria angustifolia, Cupressus lusitanica, Fitzroya cupressoides, Pinus caribaea, Pinus oocarpa, and Podocarpus guatemalensis*) had G_g and hardness data. They were, however, used for validation of the equations.

The division between temperate and tropical species was based on a correspondence analysis relating hardwood anatomical physiognomy with climate and latitude; this analysis will be the topic of a future publication. The correspondence analysis showed a dramatic change in wood anatomical physiognomy at 28° north latitude. Species north of this demarcation line show temperate anatomy, and species south of it, including southern hemisphere species, show tropical anatomy. Therefore, species were considered to be temperate if their natural range extended substantially north of 28° north latitude; otherwise they were considered to be tropical. This demarcation corresponds roughly to a mean annual temperature of 24°C and a cold month mean temperature of 15°C. Even the woody angiosperm flora of Argentine Tierra del Fuego, 53° to 55° south latitude, mean annual temperature 5.3°C, cold month mean temperature 1.1°C, although sparse (only 17 genera with wood anatomical data), has an anatomical physiognomy that is tropical in many respects. For example, anatomical features that are common in temperate floras, such as ring-porosity and marginal parenchyma, are absent from the Tierra del Fuego flora. On the other hand, some anatomical features that are common in temperate floras, such as pores arranged in tangential lines and rays commonly wider than ten-seriate, are also common in the Tierra del Fuego flora. The southernmost species considered in this report are *Nothofagus procera*, which is found as far south as 40° south latitude in Chile, and *Acacia mollissima*, found as far south as 43° south latitude in Tasmania.

Selection of Model Form

When Newlin and Wilson (1919) developed relationships between clearwood properties and specific gravity (G) they chose a power model of the form

$$\text{property} = aG^b$$

in part because they apparently felt that the function should go through the origin. Liska (1965) notes that while this assumption is logical, few species produce normal woody tissue with a specific gravity approaching zero. For individual

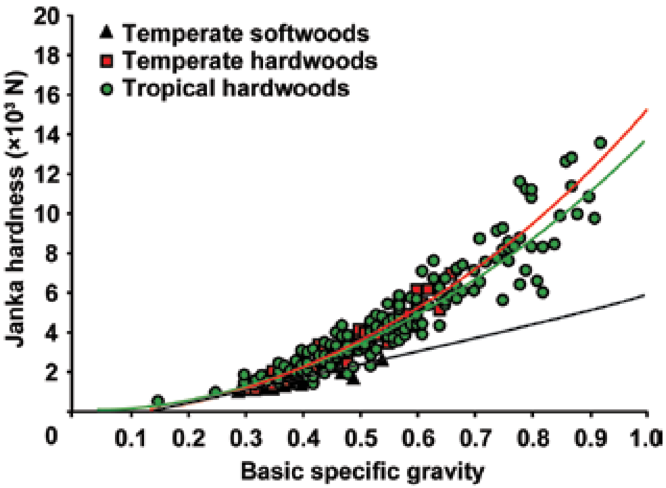

Figure 2—Side hardness–specific gravity relationships for green wood.

species, a linear regression may often provide the best fit to the data. However, when considering many combined species, it is more likely that we will have a wider range of specific gravity values and that some species may have comparatively low values. Thus the premise of a zero intercept seems inescapable. With the widespread use of computers to simulate the properties of solid-sawn and composite wood product properties, a property–specific gravity relationship that passes through the origin also provides added protection against unintended conclusions. Previous analysis of several model forms for the 1987 edition of the *Wood Handbook* had established that there was little difference in the goodness-of-fit criterion based on either the square root of the mean square error or on the variance for relationships between mechanical properties and specific gravity. Analysis of linear versus power model forms relating side hardness to specific gravity for the 1999 edition confirmed this observation. Thus the traditional power model was selected for use in this study.

Data Analysis

For each grouping, we calculated mean, range, standard deviation, and variance of the G_g, green hardness, and dry hardness. Range usually increases with sample size, and it is affected by extreme values. Therefore, we looked at two other measures of dispersion: standard deviation and variance. Variance is not biased by sample size, but its units are squares and are not as readily interpretable as those of standard deviation. Standard deviation is biased by sample size, but the bias is small for large samples. The correction for bias, derived by Gurland and Tripathi (1971), is only 0.53% for the temperate softwoods (47 species), 0.36% for the temperate hardwoods (71 species), and 0.17% for the tropical hardwoods (166 species.)

Hardness, in the green and dry conditions, was plotted against G_g for each group, power functions were fitted through the plotted points, and the defining equations were derived using linear regression. This is different from the procedure used to derive the equations given in the 1999 *Wood Handbook*, in which the dry values were plotted against G, which is based on volume at the indicated MC (green or 12%). General linear model (GLM) F-tests were used to determine equality of coefficients and exponents using SAS (1999.) Adequacy of the equations was evaluated through examination of residuals and by comparing predicted hardness to measured hardness for species not included in the equation derivations. These species, listed in Appendix 2, include the tropical softwoods and the woods that contained green or dry hardness values, but not both.

Results

Development of Predictive Equations

Table 2 presents the summary statistics for the 284 species given in Appendix 1 that were used to derive the equations. Of these, 47 were temperate softwoods, 71 were temperate hardwoods, and 166 were tropical hardwoods. As expected, G_g and hardness ranges increased with sample sizes for the three groups. However, intrinsic variability, as measured by standard deviations, also increased. Not surprisingly, the mean G_g of the temperate softwoods (0.39) was lower than that of both the temperate hardwoods (0.50) and the tropical hardwoods (0.56). The G_g standard deviation of the softwoods (0.054) showed them to be less variable than the temperate hardwoods (0.085) and much less variable than the tropical hardwoods (0.153). For the hardwoods, these results are consistent with those of Wiemann and Williamson (2002), who found that woody hardwood mean G_g decreased steadily with north latitude, and G_g range and standard deviation decreased dramatically upon transition from tropical to temperate habitats.

Figure 2 compares green side hardness as a function of G_g for the three species subgroups, and Figure 3 is the same comparison in the dry condition. For both green and dry wood, GLM F-tests showed that the regression equation for the softwoods was different from those for the hardwoods, but the two hardwood groups were not different (0.05 significance level.) Figures 2 and 3 also show that the hardness values are more scattered at greater G_g values (which include only tropical species.) The relationships between G_g and hardness in newtons, H(N), and pounds force, H(lbf), are given by the following equations:

Green hardness, temperate softwoods
$H(\text{N}) = 6{,}930(G_g)^{1.50}$ $\quad r^2 = 0.70$ (1a)
Green hardness, temperate hardwoods
$H(\text{N}) = 15{,}560(G_g)^{2.17}$ $\quad r^2 = 0.91$ (2a)
Green hardness, tropical hardwoods
$H(\text{N}) = 13{,}340(G_g)^{1.91}$ $\quad r^2 = 0.90$ (3a)
Green hardness, all hardwoods
$H(\text{N}) = 13{,}610(G_g)^{1.96}$ $\quad r^2 = 0.90$ (4a)
12% hardness, temperate softwoods
$H(\text{N}) = 11{,}400(G_g)^{1.65}$ $\quad r^2 = 0.73$ (5a)

Table 2—Summary of G_g and hardness statistics for species listed in Appendix 1

Property	Characteristic	Species grouping			
		Temperate softwoods	Temperate hardwoods	Tropical hardwoods	All species
	Number of species	47	71	166	284
G_g	Mean	0.39	0.50	0.56	0.52
	Standard deviation	0.054	0.085	0.153	0.141
	Minimum	0.29	0.31	0.15	0.15
	Maximum	0.54	0.66	0.92	0.92
	Range	0.25	0.35	0.77	0.77
H_g	Mean	1,720	3,550	4,790	3,970
	Standard deviation	420	1,300	2,710	2,450
	Minimum	1,020	1,110	530	530
	Maximum	2,620	6,960	13,570	13,570
	Range	1,600	5,850	13,040	13,040
H_{12}	Mean	2,470	4,620	6,020	5,080
	Standard deviation	650	1,660	3,690	3,230
	Minimum	1,420	1,550	620	620
	Maximum	3,860	8,270	18,950	18,950
	Range	2,440	6,720	18,330	18,330
Mean H_{12}/H_g ratio		1.43	1.31	1.26	1.28

12% hardness, temperate hardwoods
H(N) = 19,880$(Gg)^{2.14}$ $r^2 = 0.91$ (6a)
12% hardness, tropical hardwoods
H(N) = 17,960$(G_g)^{2.06}$ $r^2 = 0.94$ (7a)
12% hardness, all hardwoods
H(N) = 18,180$(G_g)^{2.05}$ $r^2 = 0.93$ (8a)
Green hardness, temperate softwoods
H(lbf) = 1,560$(G_g)^{1.50}$ $r^2 = 0.70$ (1b)
Green hardness, temperate hardwoods
H(lbf) = 3,500$(G_g)^{2.17}$ $r^2 = 0.91$ (2b)
Green hardness, tropical hardwoods
H(lbf) = 3,000$(G_g)^{1.91}$ $r^2 = 0.90$ (3b)
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12% hardness, tropical hardwoods
H(lbf) = 4,040$(G_g)^{2.06}$ $r^2 = 0.94$ (7b)
12% hardness, all hardwoods
H(lbf) = 4,090$(G_g)^{2.05}$ $r^2 = 0.93$ (8b)

For both green and dry hardness, the coefficients of these equations are similar to those given in the 1999 edition of the *Wood Handbook* (Figures 4 and 5). Note that to compare hardness relationships at 12% MC (Figure 5), it was necessary to adjust the specific gravity values in the *Wood Handbook* formula to G_g values. This was done by substituting the specific gravity at 12% MC, G_{12}, in the following formula:

$$G_{12} = G_g/(1 - 0.162G_g)$$

which was derived from equation X1.2 of ASTM D 2395-02 (ASTM 2006).

To determine if the equations for the softwoods were different from those for hardwoods because of their limited range in specific gravity, or rather to some fundamental difference between hardwoods and softwoods, we plotted green (Figure 6) and dry (Figure 7) hardness as a function of G_g for only those woods whose G_g values fell within the range 0.31 to 0.54, which is the range shared by the three groups. The relationships between G_g and hardness for woods with G_g in the range of 0.31 to 0.54 are given by the following equations:

Green hardness, temperate softwoods
H(N) = 6790$(G_g)^{1.48}$ $r^2 = 0.68$ (9)
Green hardness, temperate hardwoods
H(N) = 17030$(G_g)^{2.26}$ $r^2 = 0.85$ (10)

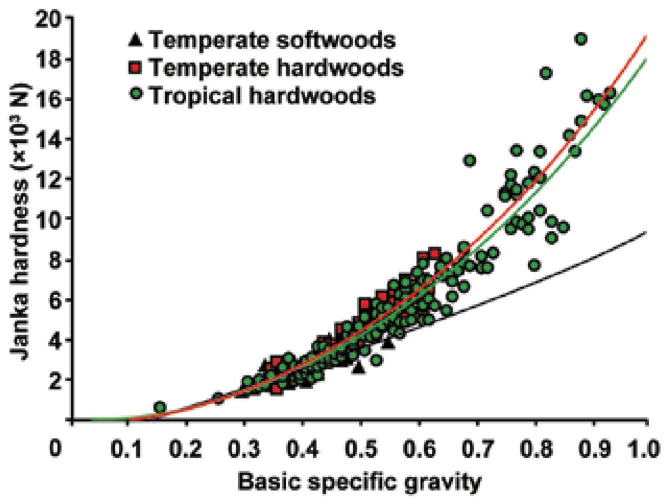

Figure 3—Side hardness–specific gravity relationships for wood at 12% MC.

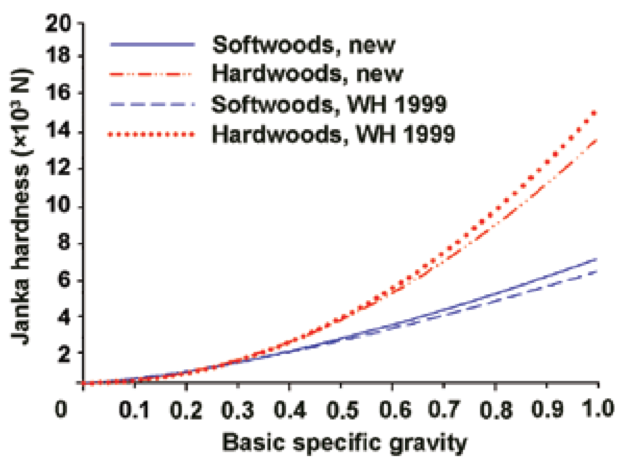

Figure 4—Comparison of our regression equations for green hardness (new) with those given in the 1999 edition of the *Wood Handbook* (FPL 1999).

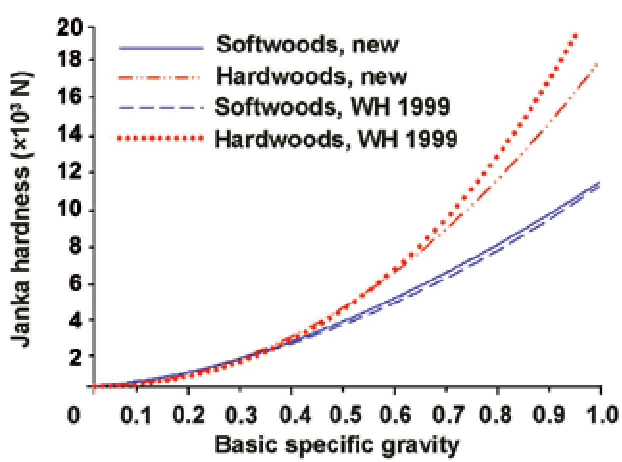

Figure 5—Comparison of our regression equations for hardness at 12% MC (new) with those given in the 1999 edition of the *Wood Handbook* after adjustment to G_g (FPL 1999).

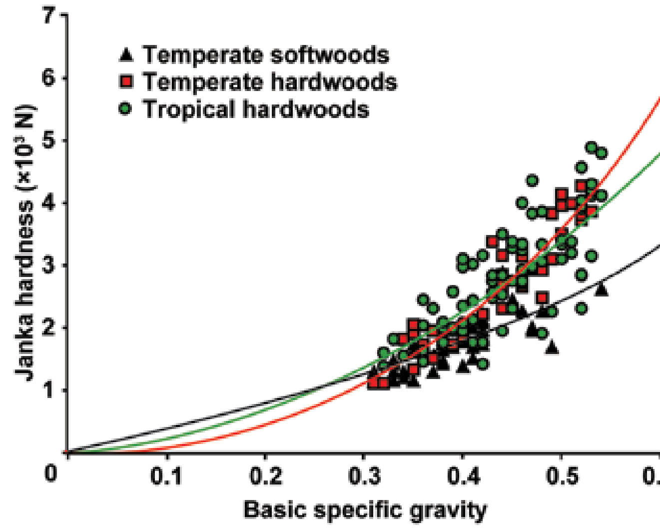

Figure 6—Side hardness–specific gravity relationships for green wood with G_g values between 0.31 and 0.54.

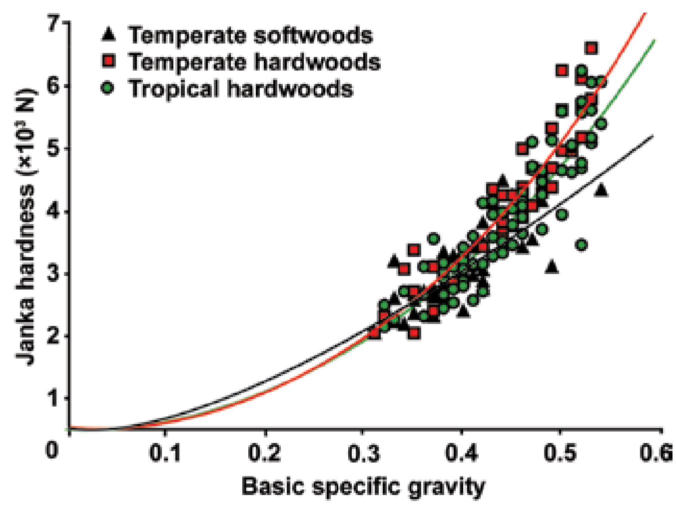

Figure 7—Side hardness–specific gravity relationships for wood at 12% MC and G_g values between 0.31 and 0.54.

Green hardness, tropical hardwoods

$H(\text{N}) = 12420(G_g)^{1.86}$ $\quad r^2 = 0.64$ (11)

12% hardness, temperate softwoods

$H(\text{N}) = 11240(G_g)^{1.63}$ $\quad r^2 = 0.70$ (12)

12% hardness, temperate hardwoods

$H(\text{N}) = 21660(G_g)^{2.24}$ $\quad r^2 = 0.86$ (13)

12% hardness, tropical hardwoods

$H(\text{N}) = 18720(G_g)^{2.13}$ $\quad r^2 = 0.82$ (14)

The plots and F-tests (0.05 level) for the reduced dataset show the same basic pattern as the plots using all the data—the softwoods are different from the two hardwood groups, which are not statistically significantly different from each other.

The above analyses were performed using the data as reported except for the correction of obvious mistakes such as misplaced decimals or reversal of numbers. The data expressed in newtons from the *Wood Handbook* (FPL 1999, table 4-3a) were recomputed from the data expressed in pounds (table 4-3b) in order to check the values of table 4-3a. The G_g values of *Picea sitchensis* and *Picea glauca* are listed, respectively, as 0.33 and 0.37 in table 4-3a, but as 0.37 and 0.33, respectively, in table 4-3b. The original data in Markwardt and Wilson (1935) gives $G_g = 0.37$ for both species, but the hardness data are the same as those in table 4-3b (350 lbf green, 510 lbf dry for *Picea sitchensis*; 320 lbf green, 480 lbf dry for *Picea glauca*.) Therefore, the G_g data for *Picea glauca* were deemed erroneous, the species does not appear in our Appendix 1, and it was not used in our analyses.

Notable by their absence are hardness values for the true hickories: *Carya* spp. subgenus *Eucarya*. Mechanical properties for seven species of *Carya* were tested by Markwardt and Wilson (1935), but they did not report values for hardness because the test specimens split during testing. Bendtsen and Ethington (1975) reported hardness values for four species of *Eucarya*, but their test trees came only from one site near Madison, Wisconsin, and are therefore not representative of the species as a whole.

As is true for most mechanical properties of wood, and is shown by Equations (1) to (8), hardness increases with a decrease in MC below the fiber saturation point, although the increase in hardness assumes that the test specimens do not suffer any degrade upon drying. In practice, this assumption is quite likely violated unless great care is taken in test specimen preparation. The mean increase in hardness upon drying from green to 12% MC is greater for softwoods (43%) than for either temperate (31%) or tropical (26%) hardwoods (Table 2). Wangaard and Muschler (1952) reported that side hardness of U.S. woods increased by 33% upon drying, whereas tropical American hardness increased by only 17%. Drawing inferences from the dry/green ratios requires caution. For nine species (*Afrormosia elata*, *Castanea sativa*, *Guarea excelsa*, *Shorea acuminatissima*, *Shorea faguetiana*, *Spondias mombin*, *Tabebuia donnell-smithii*, *Tabebuia insignis*, *Vochysia hondurensis*), the dry hardness was less than the green hardness, and for seven tropical species (*Cordia goeldiana*, *Dalbergia latifolia*, *Diospyros pilosanthera*, *Gonystylus bancanus*, *Gonystylus macrophyllus*, *Qualea albiflora*, *Syncarpia glomulifera*) it was more than double the green hardness. All except *Castanea sativa* are tropical, so these anomalous ratios are probably due to insufficient sample size or poor quality control. For example, data for *Shorea acuminatissima*, *Tabebuia insignis*, *Diospyros pilosanthera*, and *Qualea albiflora* are represented by only one tree each (Appendix 1).

Adequacy of the Fit

Predicted green hardness values were calculated using Equation (1a) for softwoods and Equation (4a) for hardwoods, and predicted dry hardness values were calculated using Equation (5a) for softwoods and Equation (8a) for hardwoods. Residuals were calculated as the measured hardness minus the predicted hardness. The residuals for green hardness are plotted against the predicted green hardness in Figure 8, and the residuals for dry hardness are plotted against the predicted dry hardness in Figure 9. In both cases, the variance increases with increasing predicted hardness and the residuals have a larger range for dry hardness (–3,513 N to 5,447 N) than for green hardness (–3,194 N to 3,247 N.) It is surprising that three species had dry hardness residuals greater than 4,000 N, because one would expect anomalous measured values of high specific gravity woods to be lower than expected due to splitting, as was the case with the *Carya* of Markwardt and Wilson (1935.) As a percentage of measured hardness, the dry residuals were no larger than the green residuals. For all species, the absolute mean percentage differences between measured and predicted hardness were 13% for green and 11% for dry. Measured hardness differed from predicted hardness by at least 25% for 34 species in the green condition, but only 20 species in the dry condition. Because dry hardness is, on average, about 28% greater than green hardness (Appendix 1), a given error will have less effect on the dry measured/predicted ratio than on the green ratio, and this may explain, at least in part, the lower ratios for dry hardness.

The measured hardness of the lowest specific gravity wood, *Ricinodendron rautanenii*, $G_g = 0.15$, is 220 N more than its predicted value for both green and dry hardness, which is 71% and 55% greater, respectively, than its predicted values of 310 N (green) and 400 N (dry.) Measured hardness also exceeds predicted hardness by more than 50% for the dry hardness of *Syncarpia glomulifera*, $G_g = 0.68$.

Measured green hardness is plotted against predicted green hardness in Figure 10, and measured dry hardness is plotted against predicted dry hardness in Figure 11. Lines have been drawn that represent equal measured and predicted values (1:1 line). The points are well distributed about these lines, indicating equally good fit for high and low hardness values of both softwoods and hardwoods in the green and dry conditions.

Prediction equations were validated using the data presented in Appendix 2. Predicted hardness for the tropical softwoods was calculated using both the temperate softwood equations (Equations (1a) and (5a)) and the hardwood equations (Equations (4a) and (8a)) and comparing the results. The hardwood equations gave a slightly better fit for low specific gravity species, but consistently overestimated hardness for the greater G_g (>0.45) species; therefore we conclude from our limited data that the softwood equations give a better fit for the tropical softwoods. Measured hardness is plotted against predicted hardness (both green and dry) in Figure 12, which also has a line that represents equal measured and predicted values. The points are well distributed about this line, indicating equally good fit for high and low

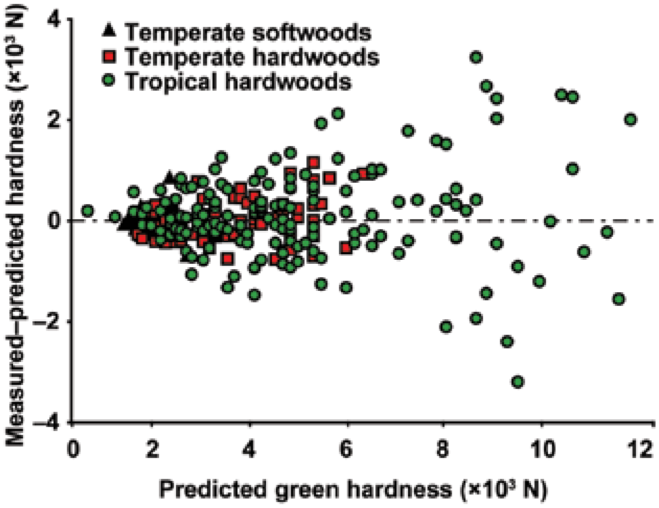

Figure 8—Residuals as a function of predicted hardness for green wood.

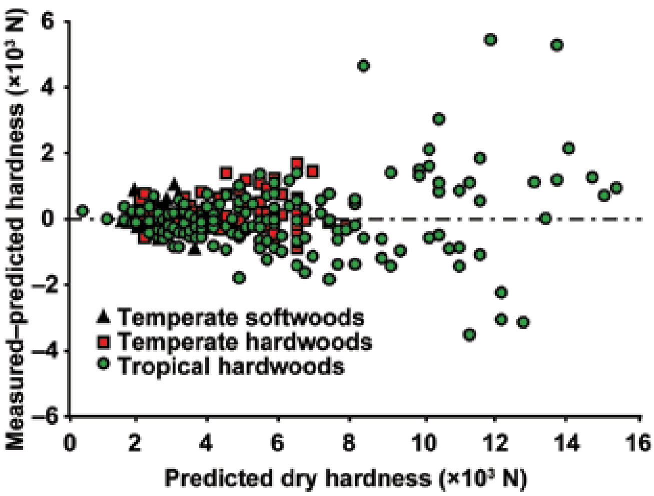

Figure 9—Residuals as a function of predicted hardness for wood at 12% MC.

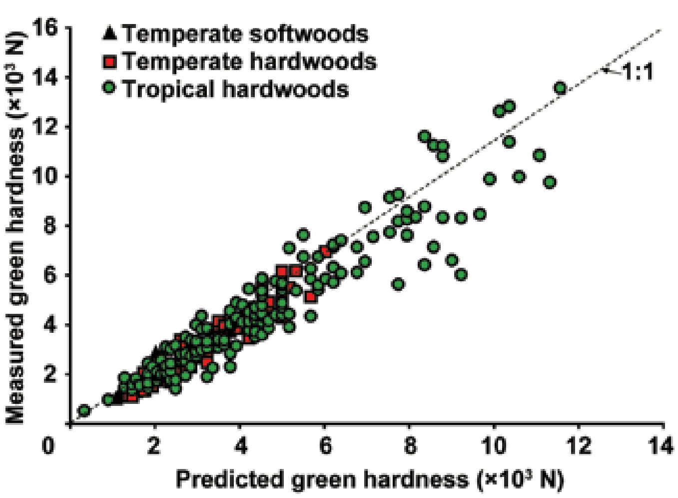

Figure 10—Measured and predicted hardness for green wood. Diagonal line represents equal measured and predicted hardness.

hardness values of both softwoods and hardwoods in the green and dry conditions.

To determine if hardness could be accurately extrapolated for extreme specific gravities, we looked at the predicted and measured hardness values of three woods that were not included in the data from which the equations were derived or validated. Two of these, balsa (*Ochroma pyramidale*) and quipo (*Cavanillesia platanifolia*), have very low specific gravities, and the other, lignum vitae (*Guaiacum officinale* and *Guaiacum sanctum*) has a very high specific gravity. Wiepking and Doyle (1944) tested balsa and quipo, and Greene (1959) tested lignum vitae. For all three species, G_g was calculated from the reported specific gravity values at indicated MCs using equation (3-5) from the *Wood Handbook* (FPL 1999). Janka hardness was reported graphically on a 12% MC basis for balsa and quipo. Hardness modulus was reported for lignum vitae, and was converted to Janka hardness using the formula derived by Lewis (1968), in which hardness modulus divided by 5.4 is equal to Janka hardness. Reported dry hardness values for the lightest balsa ($G_g = 0.07$) and quipo ($G_g = 0.08$) were 160 N and 220 N, respectively, and 17,260 N for the lignum vitae ($G_g = 0.99$). The values predicted using Equation (8) for these three woods were, respectively, 90 N, 110 N, and 17,910 N. The differences between measured and predicted values were +70 N for balsa (78% more than its predicted value), +110 N for quipo (100% more than its predicted value), and –650 N for lignum vitae (4% less than its predicted value.) It is evident, therefore, that the equations grossly underestimate the true hardness of very low specific gravity woods (as was seen for *Ricinodendron rautanenii*) but are adequate for high specific gravity woods.

Discussion

Modeling Property–Specific Gravity Relationships

Because wood is a biological material, its mechanical properties are subject to considerable variation. Tests to evaluate mechanical properties therefore depend upon how the forest trees were sampled to obtain test specimens. The clearwood data bank that is the basis for the hardness data in the *Wood Handbook* has been collected over a period of about 100 years. Over this time period, sampling procedures evolved considerably. ASTM D 5536-94 (ASTM 2006) describes in detail three methods that have been used historically to evaluate clearwood properties in the United States. Of these three methods, only the "random sampling" is assured to produce true probabilistic samples. Many of the *Wood Handbook* data were collected by the older methods. Therefore it is of interest to determine if hardness–specific gravity relationships determined by random sampling would differ substantially from those obtained in this paper.

Bendtsen (1966, 1968, 1972, 1973, 1974) and Bendtsen and Wahlgren (1970) determined clearwood properties for

12 softwoods that were sampled using the random sampling procedure of ASTM D 5536 (Table 3). For green specimens, their data are shown in Figure 13, along with the new model developed in this paper (Equation (5)) and the model from the 1999 edition of the *Wood Handbook*. Because the database for both models is virtually the same, it might be expected that both models should fit the data. Inspection of Figure 13 confirms this expectation. The results for dry wood from the random studies are shown in Figure 14. In this case, the specific gravities obtained in the random study are based on ovendry weight and volume at 12% MC. Here the *Wood Handbook* model fits the data points, but the model as presented in Equation (5) does not. This is because Equation (5) is based on the ovendry weight and green volume. If the specific gravity value in Equation (5) is corrected to a 12% volume basis, then it also provides a reasonable fit to the data (Figure 14.)

Unfortunately, we do not have data for a high-density hardwood species that was sampled by the random procedure as this might have given us better insight into the effect of sampling procedure on property–specific gravity relationships. However, we can conclude that there is no evidence to suggest that a random procedure is required.

Predictive Equations Based on Specific Gravity at 12% MC

The flooring industry in the United States commonly uses specific gravity and side hardness at 12% MC in evaluating species for flooring applications. Our equations for hardness at 12% MC are based on basic (green) specific gravity. Furthermore, they are based on hardness in newtons, and the flooring industry uses hardness measured in pounds force. A number of alternatives are readily available for modeling the effect of MC on specific gravity. The equations of ASTM D 2395-02 are based on the publication of MacLean (1958), and assume linear shrinkage from a green MC of 30%. A slightly different procedure is given in the appendix of Simpson (1993). Simpson used an average shrinkage relationship for wood based on information presented in Stamm (1964), and an assumed green MC of 30%. We derived an equation (not shown here) using the separate relationships for hardwoods and softwoods given in Stamm (1964), and an assumed green MC of 28% (a value closer to experimental observations (Green 1989, Stamm 1964). Differences among the procedures used to convert G_g to G_{12} would be trivial and only of academic interest. Furthermore, species with high extractive contents would still likely shrink less. Given the variability that exists in wood shrinkage and that we are trying to use one relationship that applies to a large number of species, such refinements are not justified.[2] Therefore, we have adopted the relationships given in ASTM D 2395-02, equation X1.2. This yields the following adjustment formula for correction from G_g to specific gravity at 12% MC (G_{12}):

$$G_{12} = G_g/(1 - 0.162G_g)$$

Thus, for softwoods at 12% MC, the hardness–specific gravity relationships given in Equations (5a) and (5b) become

12% hardness, temperate softwoods
$H(\text{N}) = 11{,}400(G_{12}/(1 + 0.162G_{12}))$ (15a)
12% hardness, temperate softwoods
$H(\text{lbf}) = 2{,}560(G_{12}/(1 + 0.162G_{12}))$ (15b)

For hardwoods, the relationships given in Equations (8a) and (8b) become

12% hardness, hardwoods
$H(\text{N}) = 18{,}180(G_{12}/(1 + 0.162G_{12}))$ (16a)

[2]In addition to the references given in chapter 13 of Stamm (1964), additional information of specific gravity–shrinkage relationships for species with high extractive contents may be found in Nearn (1955).

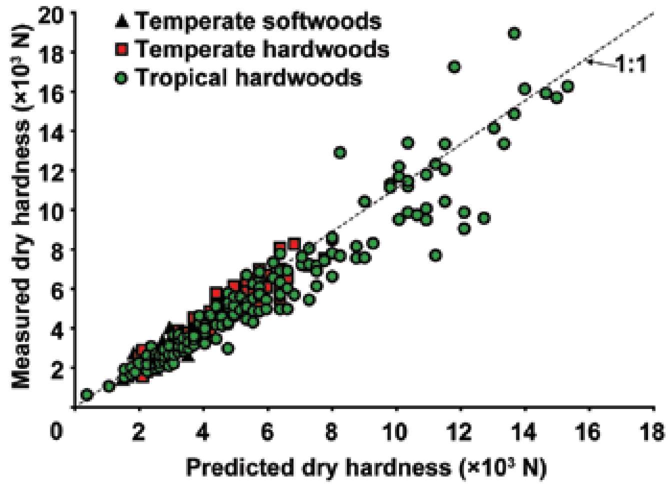

Figure 11—Measured and predicted hardness for wood at 12% MC. Diagonal line represents equal measured and predicted hardness.

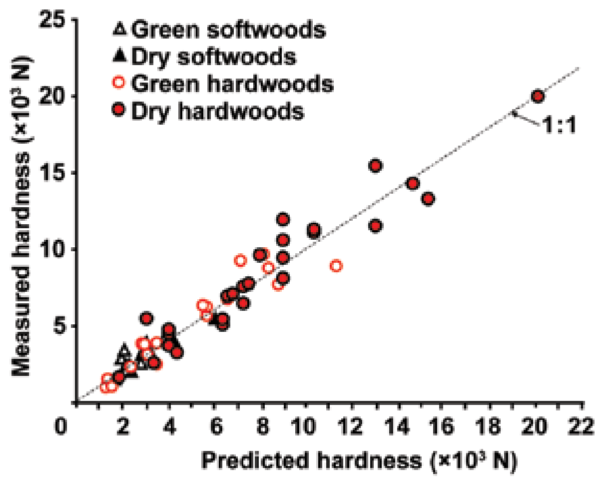

Figure 12—Measured and predicted hardness for species not used in deriving equations.

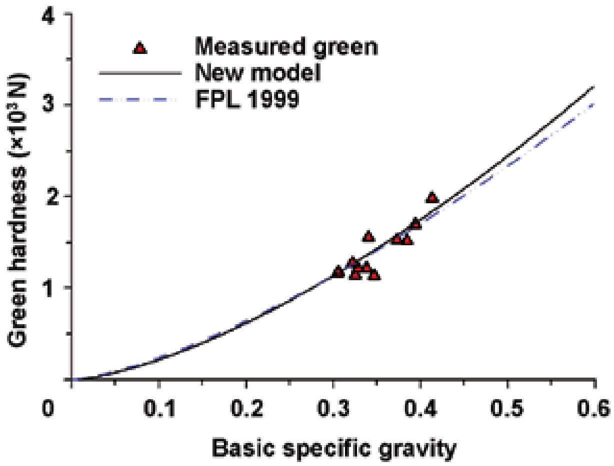

Figure 13—Hardness–specific gravity relationships for green wood determined for 12 softwood species sampled according to the random sampling procedure of ASTM D 5536-94 (ASTM 2006), compared with the plot of Equation (1a) (new model) and the green softwood relationship from Table 1 (FPL 1999.)

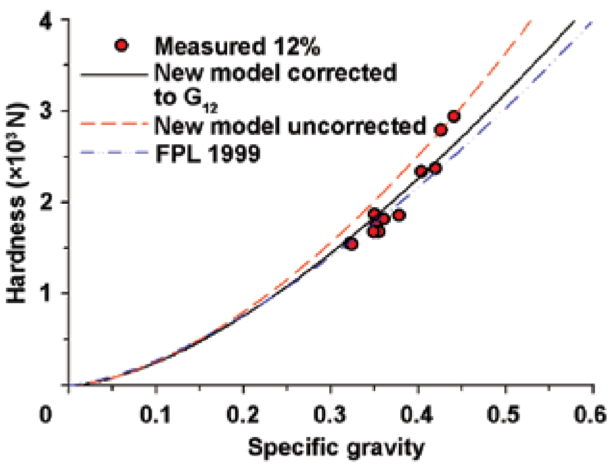

Figure 14—Hardness–specific gravity relationships for wood at 12% MC determined for 12 softwood species sampled according to the random sampling procedure of ASTM D 5536-94 (ASTM 2006), compared with the plot of Equation (5a) with specific gravity values corrected to 12% moisture content basis (new model corrected to G_{12}), with reported basic specific gravity values (new model uncorrected) and the dry softwood relationship from Table 1 (FPL 1999.)

12% hardness, hardwoods

$$H(\text{lbf}) = 4{,}090(G_{12}/(1 + 0.162G_{12})) \quad (16b)$$

Effect of MC on Hardness

Green et al. (2006) recommended that the equation $P = P_{12}(P_{12}/P_g)^{((12-M)/(M_p-12))}$ (FPL 1999) be used to adjust side hardness for change in MC. A few months after Green et al. (2006) was published, we found a study that provided additional insight into the use of this formula with tropical species (Sekiya 1936). Sekiya conducted side hardness tests on three wood species using a procedure that generally follows the procedures of the Meyer hardness (H_M) test. With the Meyer test, the depth of indentation of a round ball is determined for a fixed load (whereas with the Janka test, the load required to obtain a fixed indentation is determined). However, the general conclusions should be directly applicable to the Janka procedure. The following observations are extracted from Sekiya's report.

Table 3—Side hardness *H* determined using the random sampling procedure of ASTM D 5536-94[a]

Species	Green		12% MC	
	G	*H* (N)	*G*	*H* (N)
Redwood	0.34	1,560	0.35	1,870
Spruce pine	0.413	1,990	0.441	2,940
Engelmann spruce	0.325	1,150	0.352	1,750
Western white pine	0.347	1,140	0.378	1,860
Sugar pine	0.338	1,220	0.355	1,680
Western redcedar	0.306	1,170	0.322	1,550
Port-Orford-cedar	0.394	1,700	0.426	2,790
Subalpine fir	0.305	1,170	0.324	1,540
Black spruce	0.384	1,520	0.420	2,370
Red spruce	0.373	1,530	0.404	2,340
White spruce	0.328	1,220	0.361	1,820
Balsam fir	0.322	1,270	0.349	1,680

[a] Specific gravity *G* is based on volume at test, except for redwood at 12% MC, which is based on green volume.

Sekiya determined the effect of MC on Meyer hardness for three species: *Phellodendron amurense* (kihada), *Panax ricinifolium* (harigiri), and *Cercidiphyllum japonicum* (katsura). Test specimens were 3 by 3 by 2 cm, and a 20-mm ball was pressed into the end surface of each specimen under a load of 300 kg. His results are reproduced in Appendix 3.

Sekiya mentioned previous research by Wilson (1920) that found a linear relationship between the logarithm of a given property and MC for various strength properties of wood and investigated the use of this relationship for H_M. Figure 15, which is our plot of the data of Appendix 3, is similar to figures given by Sekiya. Figure 15 follows Wilson's exponential relationship quite well, even to very low MCs. The regression lines for kihada and harigiri are reasonably parallel, but that for katsura has a lesser slope. It seems possible that some splitting may have occurred with katsura at MCs of 1% and 3%. If these two data points are not included, then the regression slope would be very close to that of the other two species. With the standard Janka test procedure, it might be even more difficult to avoid splitting at MCs below about 6% to 8%, especially with higher density species. Nevertheless, these data support the use of Wilson's exponential relationship for adjusting hardness for change in MC.

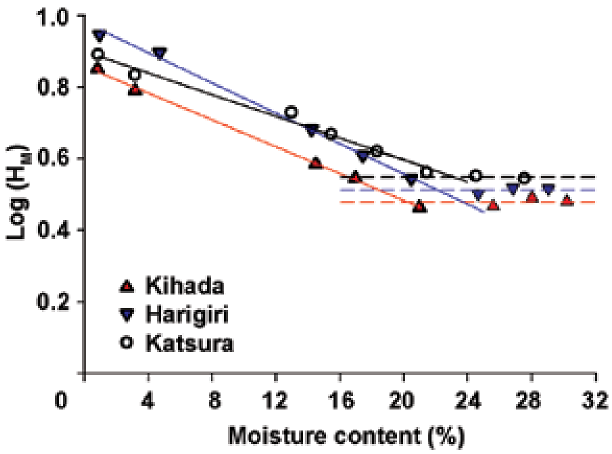

Figure 15—Effect of moisture content on Meyer hardness (H_M, in mm) plotted as logarithms from data in Sekiya (1936). Sloped solid lines are linear fits to the dry hardness values; horizontal dashed lines are mean values of green hardness values.

Conclusions

From the results of our study, we conclude the following:

- The standard deviation of G_g for temperate softwoods is less than that for temperate hardwoods and much less than that for tropical hardwoods.
- The hardness of dry lumber is generally greater than that of green wood. For temperate softwoods, this increase is about 46%; for temperate hardwoods, it is about 31%; for tropical hardwoods, it is about 23%.
- The relationship between hardness and G_g is not the same for softwoods and hardwoods, whether green or dry.
- For green hardness (H_g) and dry hardness (H_{12}) of softwoods, the relationship of hardness to G_g is probably the same for temperate and tropical species. The recommended estimation equations are therefore $H_g = 6{,}930G_g^{1.50}$ and $H_{12} = 11{,}400G_g^{1.65}$.
- For green and dry hardness of hardwoods, the relationship of hardness to G_g is the same for temperate and tropical species. The recommended estimation equations are $H_g = 13{,}610G_g^{1.96}$ and $H_{12} = 18{,}180G_g^{2.05}$.

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Appendix 1—Specific Gravity, Side Hardness, Number of Trees Sampled, and Sources of Data for Species Used to Derive Equations (1) to (8)[a]

		Side hardness (N)				Sample size	
Species	SG	Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

		Side hardness (N)				Sample size	
Species	SG	Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

Species	SG	Side hardness (N)				Sample size	
		Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

Species	SG	Side hardness (N)				Sample size	
		Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

Species	SG	Side hardness (N)				Sample size	
		Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

Species	SG	Side hardness (N)				Sample size	
		Green	Dry	Dry/green ratio	Source	No. of trees[b]	Reference

Appendix 2—Specific Gravity, Side Hardness, and Sources of Data for Species Not Used in the Derivations of the Equations

		Measured hardness (N)		
Species	**SG**	**Green**	**Dry**	**Source**
Tropical softwoods				
Agathis vitiensis	0.45	3470	3960	Lavers
Araucaria angustifolia	0.46	2490	3470	FPL
Cupressus lusitanica	0.39	1510	2040	FPL
Fitzroya cupressoides	0.38		2490	Kukachka
Pinus caribaea	0.68	4360	5510	FPL
Pinus oocarpa	0.55	2580	4040	FPL
Podocarpus guatemalensis	0.43	2890	3160	Lavers
Temperate hardwoods				
Cornus florida	0.64	6270		Kukachka
Diospyros virginiana	0.64	5690		Kukachka
Tropical hardwoods				
Andira inermis	0.65		7780	FPL
Aspidosperma polyneuron	0.69	6760		Kukachka
Aucoumea klaineana	0.33		1690	FPL
Brachystegia spiciformis	0.71		8130	Kukachka
Brosimum alicastrum	0.72	9290		Kukachka
Brosimum costaricanum	0.64		7600	Kukachka
Bursera simaruba	0.30	1020		Kukachka
Calycophyllum spruceanum	0.76		11330	Kukachka
Carapa nicaraguensis	0.42		5510	Kukachka
Cariniana brasiliensis	0.46	3820		Kukachka
Cariniana spp.	0.48		4530	FPL
Catostemma fragrans	0.50	2530		Longwood
Cedrelinga catenaeformis	0.45	3870		FPL
Ceiba samauma	0.50		3290	Kukachka
Chloroxylon swietenia	0.85		11560	Kukachka
Cordia trichotoma	0.50	3910		Kukachka
Diospyros crassiflora	0.90		14310	Kukachka
Diospyros mespiliformis	0.71		9470	Kukachka
Diospyros philippensis	0.80	7730		Kukachka
Distemonanthus benthamianus	0.60		5470	Kukachka
Enterolobium cyclocarpum	0.31	1560		Kukachka
Eperua falcata	0.78	8800		Longwood
Guaiacum spp.	1.05		20000	FPL
Guibourtia arnoldiana	0.65		7780	FPL
Guibourtia spp.	0.71		11960	FPL
Hopea odorata	0.64		6490	Kukachka
Mora gonggrijpii	0.92		13310	Kukachka
Mora oleifera	0.60		5110	Kukachka
Paratecoma peroba	0.63	6360		Kukachka
Paratecoma peroba	0.62		7110	FPL
Peltogyne confertiflora	0.77	9690		Kukachka
Quercus copeyensis	0.71		10620	Kukachka
Quercus costaricensis	0.61		6980	Kukachka
Quercus oleiodes	0.91	8930		Kukachka

Species	SG	Measured hardness (N) Green	Dry	Source
Quercus seemannii	0.67		9640	Kukachka
Quercus spp.	0.76		11110	FPL
Shorea almon	0.44		2620	Kukachka
Shorea philippinensis	0.41	2360		Kukachka
Shorea polita	0.47	3160		Kukachka
Simarouba glauca	0.33	1070		Kukachka
Tabebuia guayacan	0.85		15470	Kukachka
Terminalia ivorensis	0.48		3730	Kukachka
Turraeanthus africanus	0.48		4800	FPL

Appendix 3—Meyer hardness (H_M) as a function of MC (Sekiya 1936)

Species	Number tested	*G*	MC (%)	H_M (mm)
Kihada	30	0.358	0.8	7.09
	30	0.333	3.2	6.16
	30	0.382	14.5	3.84
	30	0.387	17.0	3.51
	30	0.371	20.9	2.90
	12	0.408	25.6	2.92
	15	0.423	28.0	3.09
	10	0.425	30.1	3.01
Harigiri	30	0.452	1.0	8.85
	30	0.494	4.7	7.90
	30	0.501	14.2	4.80
	30	0.487	17.4	4.06
	30	0.497	20.5	3.50
	12	0.479	24.6	3.17
	13	0.409	26.8	3.29
	13	0.451	29.0	3.28
Katsura	30	0.414	0.9	7.77
	30	0.382	3.2	6.53
	30	0.434	13.0	5.37
	30	0.431	15.4	4.65
	30	0.442	18.3	4.16
	12	0.430	21.4	3.64
	12	0.410	24.5	3.57
	12	0.436	27.5	3.50