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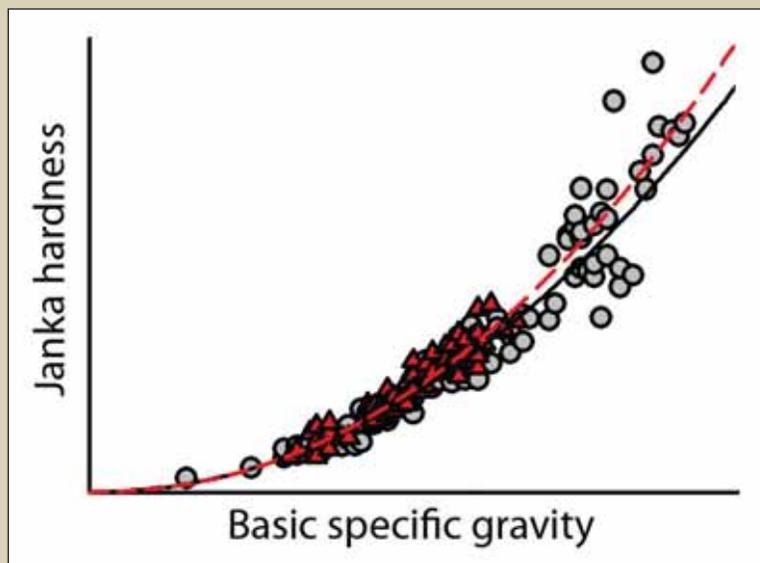
Research  
Paper  
FPL-RP-643



# Estimating Janka Hardness from Specific Gravity for Tropical and Temperate Species

Michael C. Wiemann

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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

Funding for this study was provided by the Forest Products Laboratory. The authors are grateful for the reviews of Matt Myers (Armstrong World Industries), James P. Armstrong (West Virginia University), and David E. Kretschmann (Forest Products Laboratory).

September 2007

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Wiemann, Michael C.; Green, David W. 2007. Estimating Janka hardness from specific gravity for tropical and temperate species. Research Paper FPL-RP-643. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 21 p.

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## Contents

	<i>Page</i>
Executive Summary .....	<i>i</i>
Introduction.....	1
Background.....	1
Materials and Methods.....	2
Specific Gravity and Hardness Definitions.....	2
Data Sources .....	3
Separation of Data into Groupings .....	3
Selection of Model Form .....	3
Data Analysis .....	4
Results.....	4
Development of Predictive Equations .....	4
Adequacy of the Fit.....	7
Discussion.....	8
Modeling Property–Specific Gravity Relationships .....	8
Predictive Equations Based on Specific Gravity at 12% MC .....	9
Effect of MC on Hardness .....	10
Conclusions.....	11
Literature Cited .....	11
Appendix 1—Specific Gravity, Side Hardness, Number of Trees Sampled, and Sources of Data for Species Used to Derive Equations (1) to (8) .....	14
Appendix 2—Specific Gravity, Side Hardness, and Sources of Data for Species Not Used in the Derivations of the Equations .....	20
Appendix 3—Meyer hardness ( $H_M$ ) as a function of MC (Sekiya 1936).....	21

# 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 oven-dry 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  $\text{Hardness} = a(G_g)^b$  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).)

$$\text{Green hardness, temperate softwoods} \\ H(\text{lbf}) = 1,560(G_g)^{1.50} \quad r^2 = 0.70 \quad (1b)$$

$$\text{Green hardness, temperate hardwoods} \\ H(\text{lbf}) = 3,500(G_g)^{2.17} \quad r^2 = 0.91 \quad (2b)$$

$$\text{Green hardness, tropical hardwoods} \\ H(\text{lbf}) = 3,000(G_g)^{1.91} \quad r^2 = 0.90 \quad (3b)$$

$$\text{Green hardness, all hardwoods} \\ H(\text{lbf}) = 3,060(G_g)^{1.96} \quad r^2 = 0.90 \quad (4b)$$

$$\text{12\% hardness, temperate softwoods} \\ H(\text{lbf}) = 2,560(G_g)^{1.65} \quad r^2 = 0.73 \quad (5b)$$

$$\text{12\% hardness, temperate hardwoods} \\ H(\text{lbf}) = 4,470(G_g)^{2.14} \quad r^2 = 0.91 \quad (6b)$$

$$\text{12\% hardness, tropical hardwoods} \\ H(\text{lbf}) = 4,040(G_g)^{2.06} \quad r^2 = 0.94 \quad (7b)$$

$$\text{12\% hardness, all hardwoods} \\ H(\text{lbf}) = 4,090(G_g)^{2.05} \quad r^2 = 0.93 \quad (8b)$$

## 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

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

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

where  $H$  is given in pounds force and  $G_{12}$  is specific gravity based on oven-dry 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

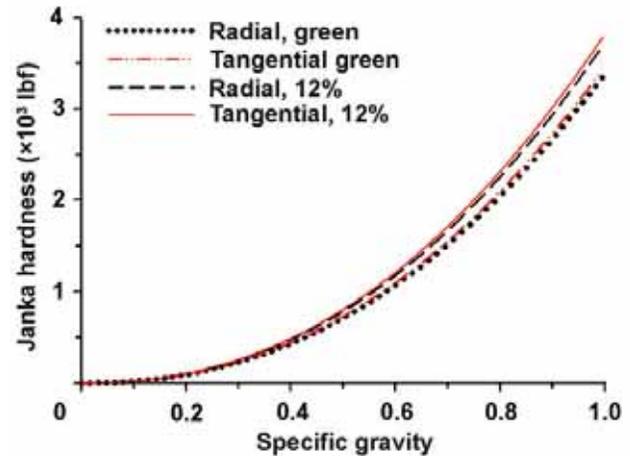


Figure 1— Side hardness relationships given in the 1935 edition of the *Wood Handbook*.

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*<sup>a</sup>**

Edition	Species grouping	MC	Orientation	$H$ in lbf		$H$ in N	
				$a$	$b$	$a$	$b$
1935, 1940 <sup>b</sup>	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 <sup>c</sup>	3,420	2.25	15,200	2.25
	All	12%	Average <sup>c</sup>	3,770	2.25	16,760	2.25
1987	All	Green	Average <sup>c</sup>	3,420	2.25	15,200	2.25
	All	12%	Average <sup>c</sup>	3,770	2.25	16,760	2.25
1999	Softwoods	Green	Average <sup>c</sup>	1,400	1.41	6,220	1.41
	Hardwoods	Green	Average <sup>c</sup>	3,720	2.31	16,530	2.31
	Softwoods	12%	Average <sup>c</sup>	1,930	1.50	8,580	1.50
	Hardwoods	12%	Average <sup>c</sup>	3,440	2.09	15,290	2.09

<sup>a</sup> Based on oven-dry weight and volume at indicated MC.

<sup>b</sup> Originally reported in Newlin and Wilson (1919.)

<sup>c</sup> 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 oven-dry 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<sup>1</sup> 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.

## 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

<sup>1</sup>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; Rijdsdijk and Laming 1994; Teixeira et al. 1988; Vilela 1969; Wangaard and Muschler 1952; Wangaard et al. 1954; Wangaard et al. 1955

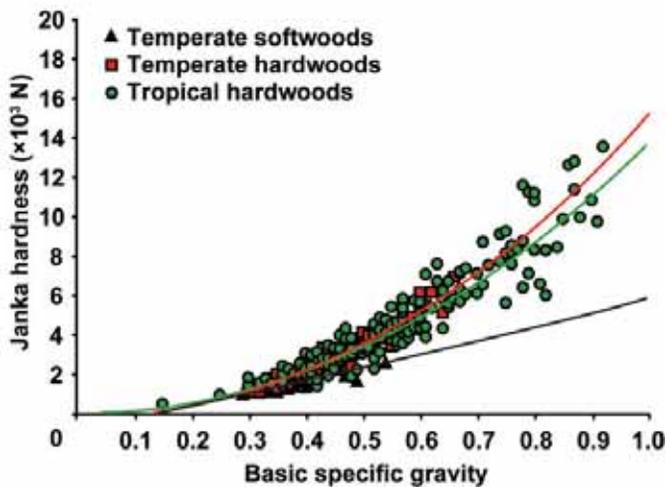


Figure 2—Side hardness–specific gravity relationships for green wood.

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:

$$\begin{aligned} \text{Green hardness, temperate softwoods} \\ H(N) = 6,930(G_g)^{1.50} \quad r^2 = 0.70 \end{aligned} \quad (1a)$$

$$\begin{aligned} \text{Green hardness, temperate hardwoods} \\ H(N) = 1,5560(G_g)^{2.17} \quad r^2 = 0.91 \end{aligned} \quad (2a)$$

$$\begin{aligned} \text{Green hardness, tropical hardwoods} \\ H(N) = 13,340(G_g)^{1.91} \quad r^2 = 0.90 \end{aligned} \quad (3a)$$

$$\begin{aligned} \text{Green hardness, all hardwoods} \\ H(N) = 13,610(G_g)^{1.96} \quad r^2 = 0.90 \end{aligned} \quad (4a)$$

$$\begin{aligned} \text{12% hardness, temperate softwoods} \\ H(N) = 11,400(G_g)^{1.65} \quad r^2 = 0.73 \end{aligned} \quad (5a)$$

**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  
 $H(N) = 19,880(G_g)^{2.14}$   $r^2 = 0.91$  (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  
 $H(\text{lbf}) = 1,560(G_g)^{1.50}$   $r^2 = 0.70$  (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  
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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)

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)

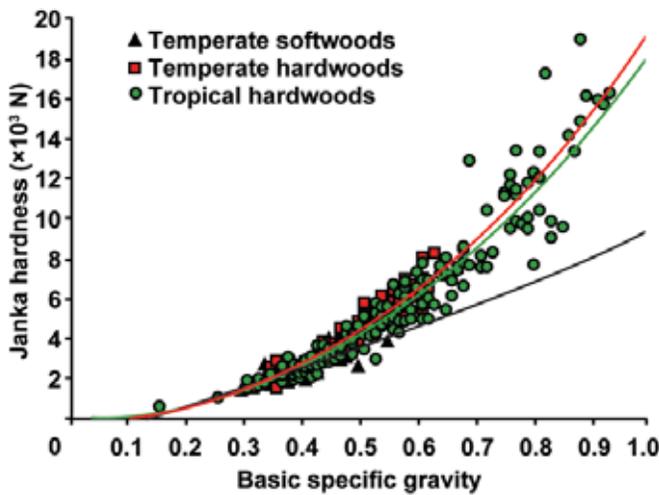


Figure 3—Side hardness–specific gravity relationships for wood at 12% MC.

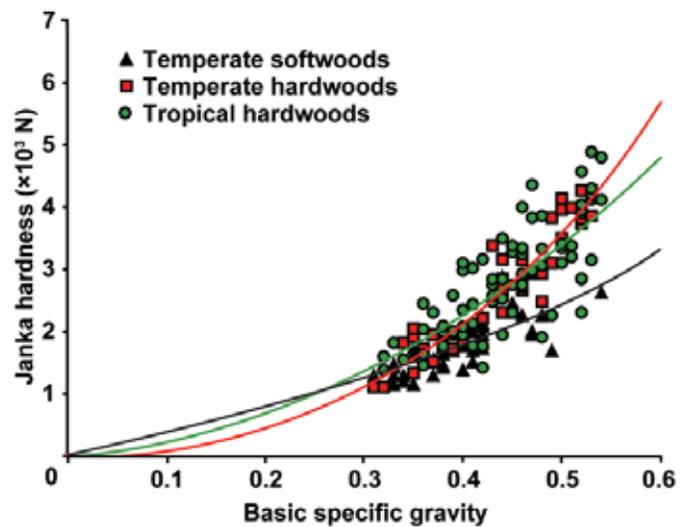


Figure 6—Side hardness–specific gravity relationships for green wood with  $G_g$  values between 0.31 and 0.54.

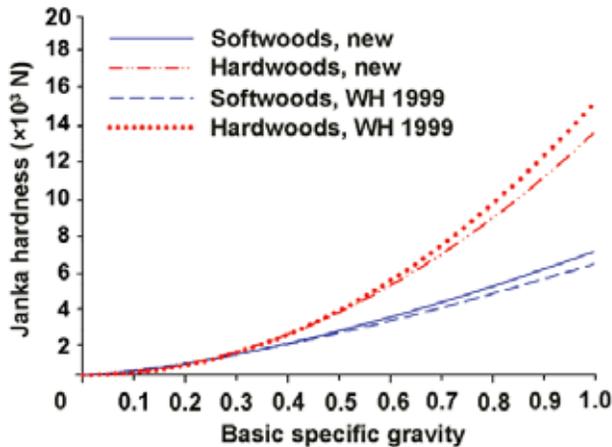


Figure 4—Comparison of our regression equations for green hardness (new) with those given in the 1999 edition of the *Wood Handbook* (FPL 1999).

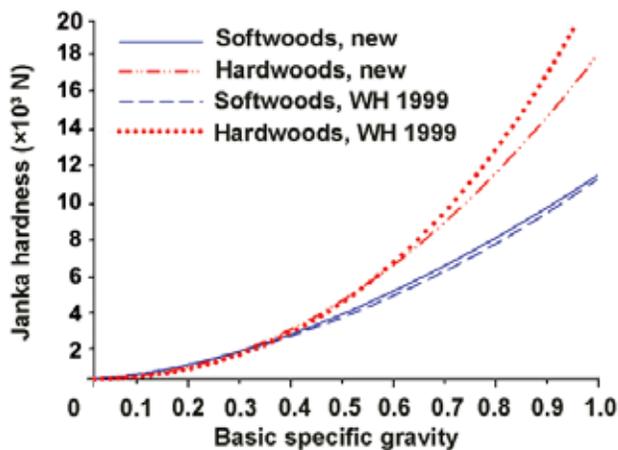


Figure 5—Comparison of our regression equations for hardness at 12% MC (new) with those given in the 1999 edition of the *Wood Handbook* after adjustment to  $G_g$  (FPL 1999).

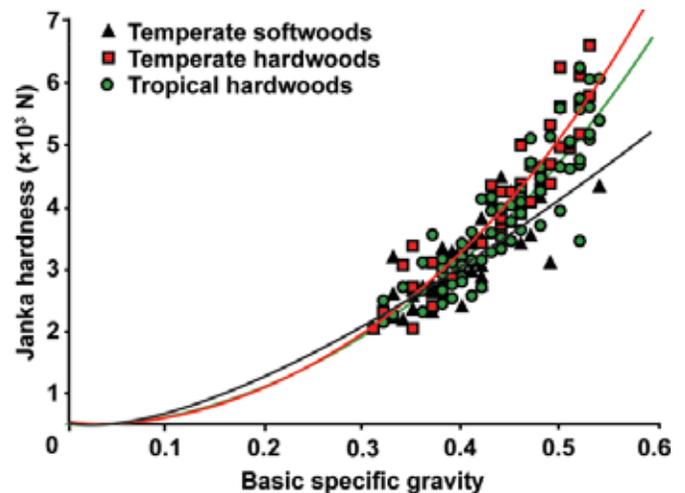


Figure 7—Side hardness–specific gravity relationships for wood at 12% MC and  $G_g$  values between 0.31 and 0.54.

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

$$12\% \text{ hardness, temperate softwoods} \\ H(N) = 11240(G_g)^{1.63} \quad r^2 = 0.70 \quad (12)$$

$$12\% \text{ hardness, temperate hardwoods} \\ H(N) = 21660(G_g)^{2.24} \quad r^2 = 0.86 \quad (13)$$

$$12\% \text{ hardness, tropical hardwoods} \\ H(N) = 18720(G_g)^{2.13} \quad r^2 = 0.82 \quad (14)$$

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 calcu-

lated 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

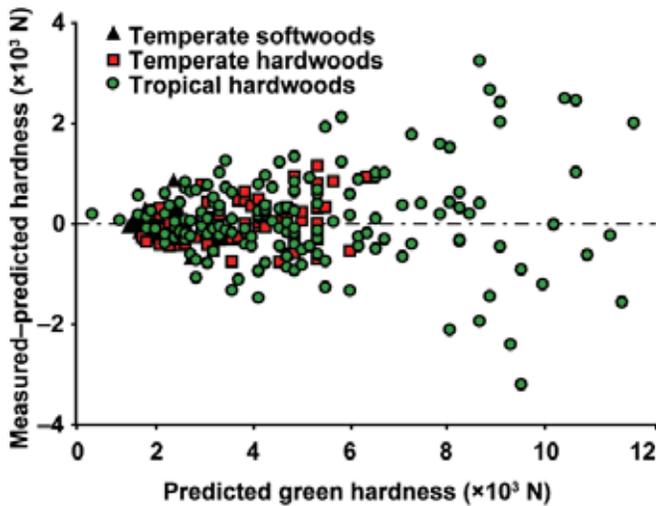


Figure 8—Residuals as a function of predicted hardness for green wood.

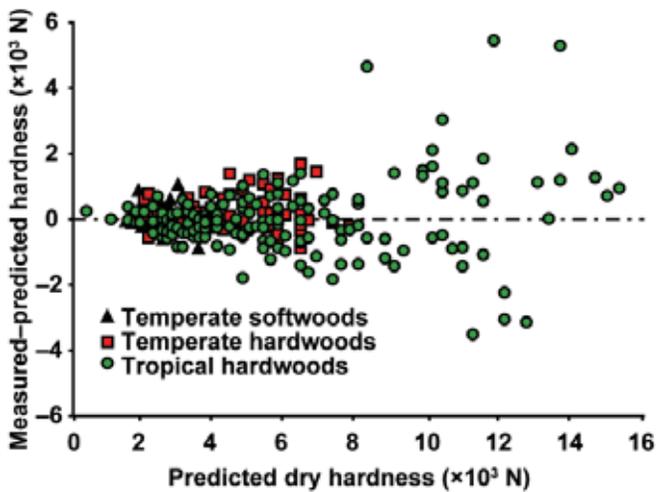


Figure 9—Residuals as a function of predicted hardness for wood at 12% MC.

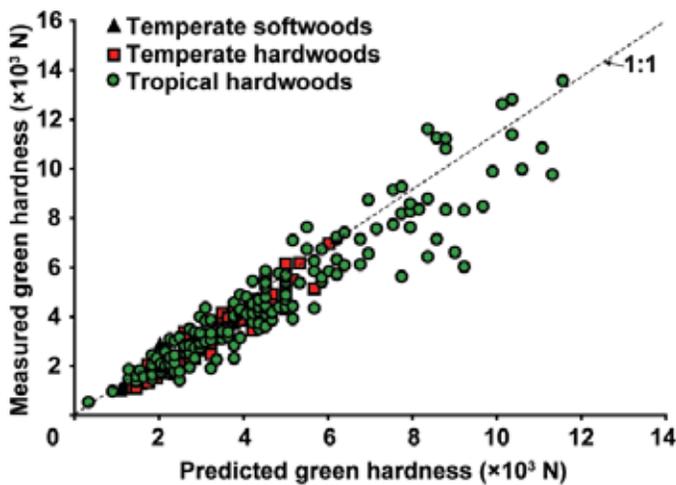


Figure 10—Measured and predicted hardness for green wood. Diagonal line represents equal measured and predicted hardness.

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 oven-dry 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 oven-dry 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.<sup>2</sup> Therefore, we have adopted the relationships

<sup>2</sup>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).

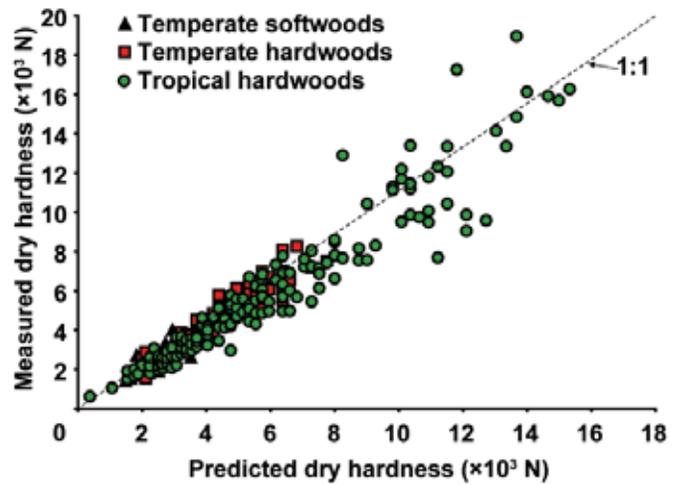


Figure 11—Measured and predicted hardness for wood at 12% MC. Diagonal line represents equal measured and predicted hardness.

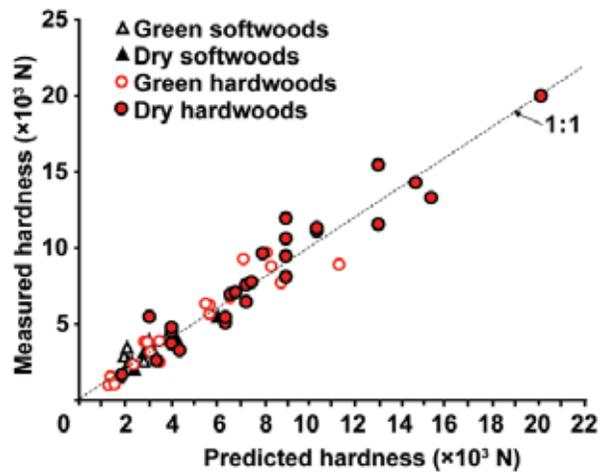


Figure 12—Measured and predicted hardness for species not used in deriving equations.

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

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

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

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

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

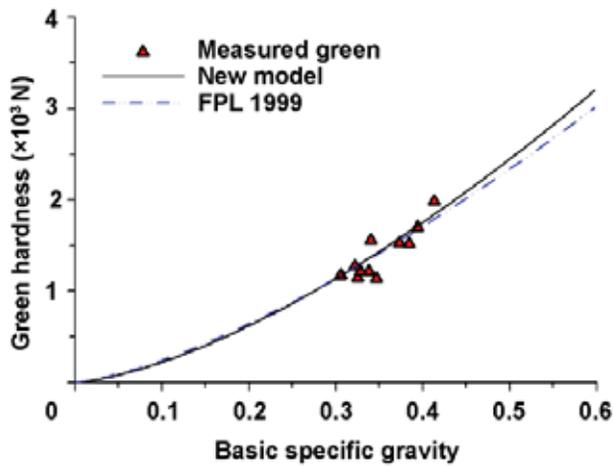


Figure 13—Hardness–specific gravity relationships for green wood determined for 12 softwood species sampled according to the random sampling procedure of ASTM D 5536-94 (ASTM 2006), compared with the plot of Equation (1a) (new model) and the green softwood relationship from Table 1 (FPL 1999.)

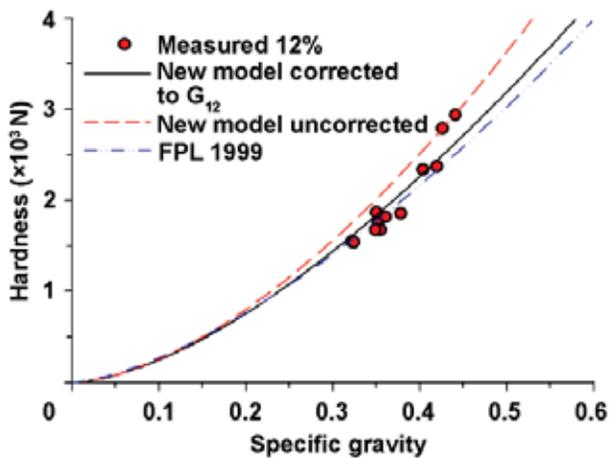


Figure 14—Hardness–specific gravity relationships for wood at 12% MC determined for 12 softwood species sampled according to the random sampling procedure of ASTM D 5536-94 (ASTM 2006), compared with the plot of Equation (5a) with specific gravity values corrected to 12% moisture content basis (new model 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

Table 3—Side hardness  $H$  determined using the random sampling procedure of ASTM D 5536-94<sup>a</sup>

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

<sup>a</sup> Specific gravity  $G$  is based on volume at test, except for redwood at 12% MC, which is based on green volume.

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.

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.

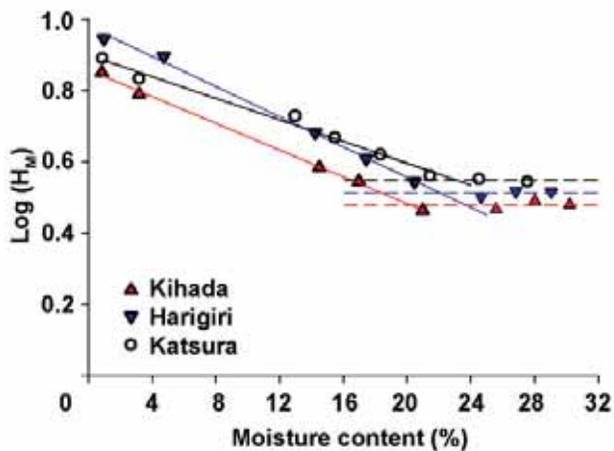


Figure 15—Effect of moisture content on Meyer hardness ( $H_M$ , in mm) plotted as logarithms from data in Sekiya (1936). Sloped solid lines are linear fits to the dry hardness values; horizontal dashed lines are mean values of green hardness values.

## 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)<sup>a</sup>

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<b>Temperate softwoods</b>							
<i>Abies alba</i>	0.38	1910	2850	1.49	Lavers	15	Lavers
<i>Abies amabilis</i>	0.40	1380	1910	1.38	FPL	6	MW
<i>Abies balsamea</i>	0.33	1290	1770	1.37	FPL	5	MW
<i>Abies concolor</i>	0.37	1510	2130	1.41	FPL	20+	MW+
<i>Abies grandis</i>	0.35	1600	2170	1.36	FPL	10	MW
<i>Abies lasiocarpa</i>	0.31	1150	1550	1.35	FPL	5+	MW+
<i>Abies magnifica</i>	0.36	1600	2220	1.39	FPL	5+	MW+
<i>Abies procera</i>	0.37	1290	1820	1.41	FPL	9	MW
<i>Chamaecyparis lawsoniana</i>	0.39	1690	2790	1.65	FPL	14+	MW+
<i>Chamaecyparis nootkatensis</i>	0.42	1950	2570	1.32	FPL	8	MW
<i>Chamaecyparis thyoides</i>	0.31	1290	1550	1.20	FPL	10	MW
<i>Juniperus virginiana</i>	0.44	2880	4000	1.39	FPL	5	MW
<i>Larix decidua</i>	0.45	2450	3770	1.54	Lavers	77	Lavers
<i>Larix kaempferi</i>	0.41	2140	2940	1.37	Lavers	59 & 20 joists	Lavers
<i>Larix laricina</i>	0.49	1690	2620	1.55	FPL	5	MW
<i>Larix occidentalis</i>	0.48	2260	3680	1.63	FPL	13+	MW+
<i>Libocedrus decurrens</i>	0.35	1730	2080	1.20	FPL	4	MW
<i>Picea abies</i>	0.33	1420	2110	1.49	Lavers	188	Lavers
<i>Picea engelmannii</i>	0.33	1150	1730	1.50	FPL	10+	MW+
<i>Picea mariana</i>	0.38	1640	2310	1.41	FPL	5	MW
<i>Picea omorika</i>	0.33	1470	2710	1.84	Lavers	5	Lavers
<i>Picea rubens</i>	0.37	1550	2170	1.40	FPL	11	MW
<i>Picea sitchensis</i>	0.37	1550	2260	1.46	FPL	25	MW
<i>Pinus banksiana</i>	0.40	1770	2530	1.43	FPL	5+	MW+
<i>Pinus contorta</i>	0.38	1460	2130	1.46	FPL	28	MW
<i>Pinus echinata</i>	0.47	1950	3060	1.57	FPL	36	MW
<i>Pinus glabra</i>	0.41	2000	2930	1.47	FPL		
<i>Pinus lambertiana</i>	0.34	1200	1690	1.41	FPL	9+	MW+
<i>Pinus monticola</i>	0.35	1150	1860	1.62	FPL	5+	MW+
<i>Pinus nigra</i>	0.40	1910	2890	1.51	Lavers	38 & 20 joists	Lavers
<i>Pinus palustris</i>	0.54	2620	3860	1.47	FPL	44+	MW+
<i>Pinus pinaster</i>	0.41	1690	2670	1.58	Lavers	7	Lavers
<i>Pinus ponderosa</i>	0.38	1420	2040	1.44	FPL	26+	MW+
<i>Pinus radiata</i>	0.42	2130	3330	1.56	FPL		
<i>Pinus resinosa</i>	0.41	1510	2480	1.64	FPL	5+	MW+
<i>Pinus strobus</i>	0.34	1290	1690	1.31	FPL	15+	MW+
<i>Pinus sylvestris</i>	0.42	2220	2980	1.34	Lavers	61	Lavers
<i>Pinus taeda</i>	0.47	2000	3060	1.53	FPL	56	MW
<i>Pinus virginiana</i>	0.45	2390	3280	1.37	FPL		
<i>Pseudotsuga menziesii</i>	0.46	2260	2930	1.30	FPL	80+	MW+
<i>Sequoia sempervirens</i>	0.38	1820	2130	1.17	FPL	16	MW
<i>Taxodium distichum</i>	0.42	1730	2260	1.31	FPL	10	MW
<i>Thuja occidentalis</i>	0.29	1020	1420	1.39	FPL	5	MW
<i>Thuja plicata</i>	0.31	1150	1550	1.35	FPL	15+	MW+
<i>Tsuga canadensis</i>	0.38	1770	2220	1.25	FPL	20	MW
<i>Tsuga heterophylla</i>	0.42	1820	2390	1.31	FPL	18+	MW+
<i>Tsuga mertensiana</i>	0.42	2080	3020	1.45	FPL	10+	MW+

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<b>Temperate hardwoods</b>							
<i>Acer macrophyllum</i>	0.44	2750	3770	1.37	FPL	5	MW
<i>Acer nigrum</i>	0.52	3730	5230	1.40	FPL	1	MW
<i>Acer pseudoplatanus</i>	0.49	3830	4850	1.27	Lavers	16	Lavers
<i>Acer rubrum</i>	0.49	3100	4210	1.36	FPL	14	MW
<i>Acer saccharinum</i>	0.44	2620	3100	1.18	FPL	5	MW
<i>Acer saccharum</i>	0.56	4300	6430	1.50	FPL	17	MW
<i>Aesculus hippocastanum</i>	0.44	2580	3340	1.29	Lavers	3 planks	Lavers
<i>Alnus glutinosa</i>	0.42	2220	2940	1.32	Lavers	8	Lavers
<i>Alnus rubra</i>	0.37	1950	2620	1.34	FPL	6	MW
<i>Betula alleghaniensis</i>	0.55	3460	5590	1.62	FPL	17	MW
<i>Betula lenta</i>	0.60	4300	6520	1.52	FPL	10	MW
<i>Betula papyrifera</i>	0.48	2480	4040	1.63	FPL	10	MW
<i>Carpinus betulus</i>	0.57	5470	6980	1.28	Lavers	12	Lavers
<i>Carya illinoensis</i>	0.60	5810	8070	1.39	FPL	5	MW
<i>Castanea dentata</i>	0.40	1860	2390	1.28	FPL	10	MW
<i>Castanea sativa</i>	0.44	3160	3070	0.97	Lavers	13	Lavers
<i>Celtis occidentalis</i>	0.49	3100	3900	1.26	FPL	6	MW
<i>Fagus grandifolia</i>	0.56	3770	5760	1.53	FPL	17	MW
<i>Fagus sylvatica</i>	0.55	4270	6410	1.50	Lavers	36	Lavers
<i>Fraxinus americana</i>	0.55	4260	5850	1.37	FPL	23	MW
<i>Fraxinus excelsior</i>	0.53	4270	6140	1.44	Lavers	67	Lavers
<i>Fraxinus latifolia</i>	0.50	3500	5140	1.47	FPL	3	MW
<i>Fraxinus nigra</i>	0.45	2310	3770	1.63	FPL	6	MW
<i>Fraxinus pennsylvanica</i>	0.53	3860	5320	1.38	FPL	10	MW
<i>Gleditsia triacanthos</i>	0.60	6160	7010	1.14	FPL	6	MW
<i>Juglans cinerea</i>	0.36	1730	2170	1.25	FPL	10	MW
<i>Juglans nigra</i>	0.51	3990	4480	1.12	FPL	5	MW
<i>Juglans regia</i>	0.47	2970	3600	1.21	Kukachka	10	Kukachka
<i>Liquidambar styraciflua</i>	0.46	2660	3770	1.42	FPL	5+	MW+
<i>Liriodendron tulipifera</i>	0.40	1950	2390	1.23	FPL	11+	MW+
<i>Magnolia acuminata</i>	0.44	2310	3100	1.34	FPL	5	MW
<i>Magnolia grandiflora</i>	0.46	3280	4520	1.38	FPL	2	MW
<i>Nyssa aquatica</i>	0.46	3150	3900	1.24	FPL	6	MW
<i>Nyssa sylvatica</i>	0.46	2840	3590	1.26	FPL	5	MW
<i>Platanus acerifolia</i>	0.52	4270	5650	1.32	Lavers	1	Lavers
<i>Platanus occidentalis</i>	0.46	2710	3410	1.26	FPL	10	MW
<i>Populus canadensis</i>	0.35	2050	2220	1.08	Lavers	18	Lavers
<i>Populus canescens</i>	0.39	1730	2360	1.36	Lavers	6	Lavers
<i>Populus deltoides</i>	0.37	1510	1910	1.26	FPL	5	MW
<i>Populus tremuloides</i>	0.35	1330	1550	1.17	FPL	11	MW
<i>Populus trichocarpa</i>	0.31	1110	1550	1.40	FPL	5	MW
<i>Prunus avium</i>	0.50	4140	5780	1.40	Lavers	8	Lavers
<i>Prunus serotina</i>	0.47	2930	4210	1.44	FPL	5	MW
<i>Quercus alba</i>	0.60	4700	6030	1.28	FPL	20	MW
<i>Quercus bicolor</i>	0.64	5140	7180	1.40	FPL	1	MW
<i>Quercus cerris</i>	0.62	6180	8270	1.34	Lavers	6	Lavers
<i>Quercus coccinea</i>	0.60	5320	6210	1.17	FPL	5	MW

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<i>Quercus falcata</i>	0.52	3810	4700	1.23	FPL	4	MW
<i>Quercus falcata</i> var. <i>pagodifolia</i>	0.61	5500	6560	1.19	FPL		
<i>Quercus laurifolia</i>	0.56	4430	5370	1.21	FPL	35	MW
<i>Quercus lyrata</i>	0.57	4260	5280	1.24	FPL		
<i>Quercus macrocarpa</i>	0.58	4920	6080	1.24	FPL	5	MW
<i>Quercus michauxii</i>	0.60	4920	5500	1.12	FPL	4	MW
<i>Quercus nigra</i>	0.56	4480	5280	1.18	FPL	5	MW
<i>Quercus palustris</i>	0.58	4750	6700	1.41	FPL	5	MW
<i>Quercus phellos</i>	0.56	4350	6470	1.49	FPL	2	MW
<i>Quercus prinus</i>	0.57	3950	5010	1.27	FPL	5	MW
<i>Quercus rubra</i>	0.56	4430	5720	1.29	FPL	33	MW
<i>Quercus stellata</i>	0.60	5010	6030	1.20	FPL	10	MW
<i>Quercus velutina</i>	0.56	4700	5370	1.14	FPL	8	MW
<i>Robinia pseudoacacia</i>	0.66	6960	7540	1.08	FPL	3	MW
<i>Salix alba</i>	0.34	1820	2580	1.42	Lavers	10	Lavers
<i>Salix fragilis</i>	0.35	1910	2890	1.51	Lavers	10	Lavers
<i>Tilia americana</i>	0.32	1110	1820	1.64	FPL	8+	MW+
<i>Tilia vulgaris</i>	0.44	2850	3160	1.11	Lavers	2	Lavers
<i>Ulmus americana</i>	0.46	2750	3680	1.34	FPL	12	MW
<i>Ulmus glabra</i>	0.50	3960	4490	1.13	Lavers	12	Lavers
<i>Ulmus hollandica</i>	0.43	3380	3870	1.14	Lavers	18	Lavers
<i>Ulmus procera</i>	0.43	3380	3650	1.08	Lavers	16	Lavers
<i>Ulmus rubra</i>	0.48	2930	3810	1.30	FPL	6	MW
<i>Ulmus thomasii</i>	0.57	4170	5850	1.40	FPL	5	MW
<b>Tropical hardwoods</b>							
<i>Acacia mollissima</i>	0.60	5690	7780	1.37	Lavers	114 sticks	Lavers
<i>Afrormosia elata</i>	0.61	7100	6920	0.97	FPL	6	FPL1974
<i>Azelia quanzensis</i>	0.76	7610	9870	1.30	Lavers	1	Lavers
<i>Albizia falcata</i>	0.32	1600	2000	1.25	Kukachka	5	Kukachka
<i>Albizia lebbek</i>	0.55	4520	5280	1.17	Kukachka	5	Kukachka
<i>Alstonia boonei</i>	0.36	1640	1820	1.11	Kukachka	1	Kukachka
<i>Anacardium excelsum</i>	0.41	1770	2080	1.18	Kukachka	6	Kukachka
<i>Anthocephalus chinensis</i>	0.38	2090	2680	1.28	Lavers	5	Lavers
<i>Astronium graveolens</i>	0.84	8470	9580	1.13	FPL	4	WM
<i>Autranella congolensis</i>	0.76	8270	13400	1.62	Lavers	6 pieces	Lavers
<i>Bagassa guianensis</i>	0.68	7410	7670	1.04	Longwood	1 log & planks	WM
<i>Berlinia acuminata</i>	0.57	4450	6050	1.36	Lavers	5	Lavers
<i>Berlinia grandiflora</i>	0.61	4430	6030	1.36	Kukachka	5	Kukachka
<i>Brachylaena hutchinsii</i>	0.77	8360	9740	1.17	Lavers	9	Lavers
<i>Brachystegia eurycoma</i>	0.60	5410	6340	1.17	Kukachka	5	Kukachka
<i>Byrsonima spicata</i>	0.57	5160	6810	1.32	Lavers	10	Lavers
<i>Calophyllum brasiliense</i>	0.52	3950	5100	1.29	FPL	3	WSG
<i>Calycophyllum candidissimum</i>	0.67	7230	8600	1.19	FPL		
<i>Canarium schweinfurthii</i>	0.45	2310	2970	1.29	Kukachka	4	Kukachka
<i>Carapa guianensis</i>	0.56	4700	5510	1.17	Longwood	2	WM
<i>Carapa procera</i>	0.53	3150	4610	1.46	Kukachka	2	Kukachka
<i>Cassipourea malosana</i>	0.59	4400	7340	1.67	Lavers	5	Lavers
<i>Cedrela angustifolia</i>	0.38	2000	2530	1.27	Kukachka	2	Kukachka

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<i>Cedrela mexicana</i>	0.34	1550	2220	1.43	Kukachka	1	Kukachka
<i>Cedrela oaxacensis</i>	0.41	2440	2660	1.09	Kukachka	3	Kukachka
<i>Ceiba pentandra</i>	0.25	980	1060	1.08	FPL	3	WKM
<i>Ceratopetalum apetalum</i>	0.50	3340	5120	1.53	Lavers	1	Lavers
<i>Chlorophora excelsa</i>	0.54	4800	5600	1.17	Lavers	2	Lavers
<i>Cordia alliodora</i>	0.44	3500	3500	1.00	Kukachka	13	Kukachka
<i>Cordia goeldiana</i>	0.52	4570	5280	1.16	Kukachka	2	Kukachka
<i>Cordia millenii</i>	0.36	2450	2620	1.07	Lavers	3	Lavers
<i>Cullenia excelsa</i>	0.51	3200	4540	1.42	Lavers	5	Lavers
<i>Cylicodiscus gabunensis</i>	0.79	11250	12320	1.10	Lavers	3	Lavers
<i>Cynometra alexandri</i>	0.74	7740	11300	1.46	Lavers	3	Lavers
<i>Dalbergia latifolia</i>	0.75	5640	11690	2.07	Kukachka	5	Kukachka
<i>Dalbergia nigra</i>	0.80	10820	12060	1.11	FPL		
<i>Dalbergia sissoo</i>	0.65	6740	6890	1.02	Kukachka	5	Kukachka
<i>Dicorynia guianensis</i>	0.60	4880	5720	1.17	FPL	2	WM
<i>Diospyros pilosanthera</i>	0.81	6610	17250	2.61	Kukachka	1	Kukachka
<i>Diplotropis purpurea</i>	0.78	8780	9490	1.08	FPL	4	WKM
<i>Dipterocarpus acutangulus</i>	0.60	4710	5650	1.20	Lavers	4	Lavers
<i>Dipterocarpus caudiferus</i>	0.51	3200	4580	1.43	Lavers	5	Lavers
<i>Dipterocarpus zeylanicus</i>	0.65	5600	6140	1.10	Lavers	8	Lavers
<i>Dipteryx odorata</i>	0.91	9760	15700	1.61	Longwood	1	WM
<i>Dracontomelon dao</i>	0.46	3330	3680	1.11	Kukachka	2	Kukachka
<i>Dryobalanops beccarii</i>	0.58	3870	5440	1.41	Lavers	5	Lavers
<i>Dryobalanops keithii</i>	0.60	4400	4970	1.13	Lavers	5	Lavers
<i>Dryobalanops lanceolata</i>	0.64	4350	5450	1.25	Kukachka	5	Kukachka
<i>Dyera costulata</i>	0.36	1460	1820	1.25	FPL	3	LC
<i>Entandrophragma angolensis</i>	0.50	3410	4170	1.22	Kukachka	3	Kukachka
<i>Entandrophragma cylindricum</i>	0.55	4520	6700	1.48	FPL	5	FPL1974
<i>Entandrophragma utile</i>	0.57	4790	5590	1.17	Kukachka	>1 green; >4 dry	Kukachka
<i>Eucalyptus diversicolor</i>	0.82	6030	9050	1.50	FPL	26 green, 21 dry	FPL1974
<i>Eucalyptus marginata</i>	0.67	5720	8470	1.48	FPL	28	FPL1974
<i>Eucalyptus microcorys</i>	0.82	8320	9870	1.19	Lavers	3	Lavers
<i>Eucalyptus paniculata</i>	0.90	10850	15920	1.47	Lavers	3	Lavers
<i>Eucalyptus pilularis</i>	0.60	5600	6940	1.24	Lavers	3	Lavers
<i>Eusideroxylon zwageri</i>	0.86	12630	13360	1.06	Lavers	5	Lavers
<i>Euxylophora paraense</i>	0.70	7140	8150	1.14	Kukachka	3	Kukachka
<i>Gonystylus bancanus</i>	0.52	2840	5760	2.03	FPL	9	FPL1974
<i>Gonystylus macrophyllus</i>	0.52	2850	5780	2.03	Lavers	9	Lavers
<i>Gossweilerodendron balsamiferum</i>	0.45	2750	3280	1.19	Kukachka	31 green; 36 dry	Kukachka
<i>Goupia glabra</i>	0.70	6120	7560	1.24	Longwood	2	WM
<i>Guarea cedrata</i>	0.48	3860	3990	1.03	Kukachka	2	Kukachka
<i>Guarea excelsa</i>	0.46	4000	3600	0.90	Lavers	3	Lavers
<i>Guarea thompsonii</i>	0.56	4210	4880	1.16	Kukachka	4	Kukachka
<i>Heritiera simplicifolia</i>	0.53	4180	5140	1.23	Lavers	2	Lavers
<i>Heritiera utilis</i>	0.56	4660	4880	1.05	Kukachka	7	Kukachka
<i>Hevea brasiliensis</i>	0.57	3600	4870	1.35	Lavers	10 logs	Lavers
<i>Hieronyma laxiflora</i>	0.65	5410	7170	1.33	Longwood	3	WSG
<i>Hopea sangal</i>	0.55	3780	4690	1.24	Lavers	5	Lavers

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<i>Humiria balsamifera</i>	0.66	5850	7430	1.27	Longwood	3	WSG
<i>Hura crepitans</i>	0.38	1950	2440	1.25	FPL	7	WM
<i>Hymenaea courbaril</i>	0.71	8740	10420	1.19	FPL	9	WM
<i>Hymenaea davisii</i>	0.67	7140	7810	1.09	Longwood	3	WM
<i>Hymenolobium excelsum</i>	0.63	7630	7630	1.00	FPL	3	WKM
<i>Khaya anthotheca</i>	0.46	3240	3810	1.18	Kukachka	4	Kukachka
<i>Khaya grandifoliola</i>	0.57	5190	6080	1.17	Kukachka	5	Kukachka
<i>Khaya ivorensis</i>	0.43	2840	3680	1.30	Kukachka	11	Kukachka
<i>Khaya nyasica</i>	0.47	3830	4240	1.11	Lavers	3 green, 2 dry	Lavers
<i>Koompassia malaccensis</i>	0.71	6560	7580	1.16	FPL		
<i>Koordersiodendron pinnatum</i>	0.72	7560	8310	1.10	Lavers	5	Lavers
<i>Licania buxiflora</i>	0.88	9980	16130	1.62	Longwood	3	WKM
<i>Licania macrophylla</i>	0.76	7630	11190	1.47	Longwood	6	WKM
<i>Lonchocarpus castilloi</i>	0.78	11610	11790	1.02	Lavers	1	Lavers
<i>Lophira alata</i>	0.87	12820	14860	1.16	FPL		
<i>Lovoa trichilioides</i>	0.48	3060	4170	1.36	Kukachka	2	Kukachka
<i>Maesopsis eminii</i>	0.41	3020	3110	1.03	Lavers	1	Lavers
<i>Manilkara bidentata</i>	0.85	9890	14150	1.43	FPL	7	WM
<i>Mansonina altissima</i>	0.57	5370	5720	1.07	Kukachka	1	Kukachka
<i>Mora excelsa</i>	0.78	6430	10060	1.56	Longwood	>4	WSG
<i>Nauclea diderrichii</i>	0.63	6740	7230	1.07	FPL		
<i>Newtonia buchananii</i>	0.47	4360	4630	1.06	Lavers	6	Lavers
<i>Nothofagus procera</i>	0.37	2310	3070	1.33	Lavers	12	Lavers
<i>Ocotea rodiaei</i>	0.80	8340	10420	1.25	FPL		
<i>Ocotea rubra</i>	0.52	2310	2970	1.29	Longwood	5	WM
<i>Ocotea usambarensis</i>	0.51	3380	4140	1.22	Lavers	11	Lavers
<i>Octomeles sumatrana</i>	0.32	1380	1650	1.20	Lavers	5	Lavers
<i>Olea guineensis</i>	0.75	8180	12190	1.49	Lavers	12	Lavers
<i>Oxystigma oxyphyllum</i>	0.53	4890	5590	1.14	Lavers	5	Lavers
<i>Parashorea plicata</i>	0.46	2930	3150	1.08	Kukachka	5	Kukachka
<i>Parashorea tomentella</i>	0.39	2580	2620	1.02	Lavers	5	Lavers
<i>Peltogyne densiflora</i>	0.75	9270	9510	1.03	Kukachka	3	Kukachka
<i>Peltogyne pubescens</i>	0.74	9140	11130	1.22	Longwood		
<i>Pentacme contorta</i>	0.43	2570	3100	1.21	Kukachka	19 green; 18 dry	Kukachka
<i>Phoebe porosa</i>	0.52	3900	4210	1.08	Kukachka	3	Kukachka
<i>Piptadeniastrum africanum</i>	0.57	5870	6850	1.17	Lavers	5	Lavers
<i>Pithecellobium saman</i>	0.48	3330	3780	1.14	Longwood	2	WKM
<i>Pometia pinnata</i>	0.57	4120	6520	1.58	Kukachka	5 green; 6 dry	Kukachka
<i>Pometia tomentosa</i>	0.56	3730	5500	1.47	Kukachka	7	Kukachka
<i>Prioria copaifera</i>	0.40	1950	2790	1.43	FPL	3	WM
<i>Protium decandrum</i>	0.53	4300	5140	1.20	Longwood		
<i>Protium schomburgkiana</i>	0.48	1910	3220	1.69	Longwood	1	KN
<i>Pseudosindora palustris</i>	0.56	4210	6250	1.48	FPL		
<i>Pterocarpus angolensis</i>	0.59	5760	6560	1.14	Kukachka	3	Kukachka
<i>Pterocarpus indicus</i>	0.53	4210	4700	1.12	Kukachka	15 green; 14 dry	Kukachka
<i>Pterygota bequaertii</i>	0.56	3510	4310	1.23	Lavers	5	Lavers
<i>Pterygota macrocarpa</i>	0.47	2980	4180	1.40	Lavers	5	Lavers
<i>Pycnanthus angolensis</i>	0.40	2080	2710	1.30	FPL		

Species	SG	Side hardness (N)			Source	Sample size	
		Green	Dry	Dry/green ratio		No. of trees <sup>b</sup>	Reference
<i>Qualea albiflora</i>	0.49	2260	4660	2.06	Longwood	1	WM
<i>Qualea rosea</i>	0.53	4120	4690	1.14	Longwood	3	WSG
<i>Ricinodendron rautanenii</i>	0.15	530	620	1.17	Lavers	5 planks	Lavers
<i>Scottellia coriacea</i>	0.56	4400	4850	1.10	Lavers	2	Lavers
<i>Shorea acuminatissima</i>	0.40	2980	2580	0.87	Lavers	1	Lavers
<i>Shorea dasyphylla</i>	0.43	2480	2790	1.13	Kukachka	2	Kukachka
<i>Shorea faguettiana</i>	0.45	3380	3290	0.97	Lavers	5	Lavers
<i>Shorea gibbosa</i>	0.42	3160	3650	1.16	Lavers	1	Lavers
<i>Shorea guiso</i>	0.67	6320	6630	1.05	Lavers	5	Lavers
<i>Shorea hopeifolia</i>	0.46	3340	3420	1.02	Lavers	1	Lavers
<i>Shorea leptoclados</i>	0.39	2000	2260	1.13	Kukachka	5	Kukachka
<i>Shorea macrophylla</i>	0.30	1470	1510	1.03	Lavers	5	Lavers
<i>Shorea negrosensis</i>	0.44	2530	3020	1.19	Kukachka	15	Kukachka
<i>Shorea parvifolia</i>	0.39	1950	2040	1.05	Kukachka	5	Kukachka
<i>Shorea pauciflora</i>	0.50	3100	3460	1.12	Kukachka	5	Kukachka
<i>Shorea polysperma</i>	0.46	2750	3410	1.24	Kukachka	19 green; 17 dry	Kukachka
<i>Shorea smithiana</i>	0.40	1950	2390	1.23	Kukachka	5	Kukachka
<i>Shorea squamata</i>	0.41	2130	2620	1.23	Kukachka	14 green, 12 dry	Kukachka
<i>Shorea superba</i>	0.62	5380	5690	1.06	Lavers	2	Lavers
<i>Shorea waltonii</i>	0.36	2040	2170	1.06	Kukachka	4	Kukachka
<i>Simarouba amara</i>	0.38	1730	1950	1.13	Longwood	2	WM
<i>Spondias mombin</i>	0.40	2350	2310	0.98	Kukachka	3	Kukachka
<i>Staudtia stipitata</i>	0.76	8580	11460	1.34	Lavers	1	Lavers
<i>Sterculia oblonga</i>	0.61	3910	4980	1.27	Lavers	5	Lavers
<i>Sterculia pruriens</i>	0.44	2840	3480	1.23	Longwood	1	KN
<i>Sterculia rhinopetala</i>	0.64	6270	8050	1.28	Lavers	5	Lavers
<i>Swartzia leiocalycina</i>	0.87	11390	18950	1.66	Lavers	4	Lavers
<i>Swietenia macrophylla</i>	0.45	3280	3550	1.08	FPL	> 4	WM
<i>Swietenia mahagoni</i>	0.57	4350	5900	1.36	Longwood	5	H
<i>Symphonia globulifera</i>	0.58	4170	4970	1.19	FPL	7	WSG
<i>Syncarpia glomulifera</i>	0.68	6090	12900	2.12	Lavers	5	Lavers
<i>Tabebuia chrysantha</i>	0.80	11220	13350	1.19	Kukachka	3	Kukachka
<i>Tabebuia donnell-smithii</i>	0.40	3100	2930	0.95	FPL	3	WM
<i>Tabebuia insignis</i>	0.55	5450	5080	0.93	Longwood	1	KN
<i>Tabebuia rosea</i>	0.52	4040	4290	1.06	Longwood	9	WM
<i>Tabebuia serratifolia</i>	0.92	13570	16270	1.20	Longwood	3	WKM
<i>Tectona grandis</i>	0.55	4140	4450	1.07	Lavers	60 planks	Lavers
<i>Terminalia amazonia</i>	0.64	5850	7250	1.24	Longwood	9	WM
<i>Terminalia superba</i>	0.38	1770	2170	1.23	FPL		
<i>Tieghemella heckelii</i>	0.54	4120	4920	1.19	Kukachka	4	Kukachka
<i>Triplochiton scleroxylon</i>	0.30	1860	1910	1.03	FPL	2	FPL1974
<i>Virola koschnyi</i>	0.44	1950	2840	1.46	Kukachka	8	Kukachka
<i>Virola michellii</i>	0.42	1770	2660	1.50	Kukachka	3	Kukachka
<i>Virola surinamensis</i>	0.42	1420	2220	1.56	Longwood	2	WKM
<i>Vochysia guianensis</i>	0.43	2750	3460	1.26	Longwood	1	WM
<i>Vochysia hondurensis</i>	0.33	1820	1770	0.97	Longwood	3	WM
<i>Vouacapoua americana</i>	0.79	7140	7700	1.08	Longwood	3	WKM

<sup>a</sup> The number of trees tested by Markwardt and Wilson (1935) are referenced as MW if the values are those published in the *Wood Handbook*; the number of trees tested by them is followed by a + (MW+) if the values published are different due to additional test data. For the tropical species, FPL (1999) and Longwood (1962) compiled data published in the following reports: FPL (1974) (FPL1974); Heck (1937) (H); Kynoch and Norton (1938) (KN); Lee and Chu (1965) (LC); Wangaard et al. (1954) (WKM); Wangaard and Muschler (1952) (WM); and Wangaard et al. (1955) (WSG).

<sup>b</sup> Although this column is labelled "No. of trees," sometimes the material tested was specified as logs, sticks, planks or pieces, and sometimes the number is not the same for the green material and dry material; in these cases, the listing in the column is annotated accordingly.

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

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

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

