J Wood Sci (1999) 45:127–133

ORIGINAL ARTICLE

Song-Yung Wang · Hou-Lin Wang

Effects of moisture content and specific gravity on static bending properties and hardness of six wood species*

Received: May 26, 1998 / Accepted: September 18, 1998

Abstract This study was designed to investigate the effects of moisture content (MC) and specific gravity (SG) on the bending strength and hardness of six wood species including Japanese cedar (*Cryptomeria japonica* D. Don), China fir (*Cunninghamia lanceolata*), western hemlock (*Tsuga heterophylla*), red meranti (*Shorea* spp.), Selangan batu (*Shorea* spp.), and red oak (*Quercus* spp.). The experimental results are summarized as follows: Effects of MC and SG on the strength (MOR), stiffness (MOE), and hardness (H_B) could be represented by a multiregression formulas. A negative correlation existed between these properties and MC, whereas a postive correlation showed between them and the SG. The changing rate of these properties induced by 1% MC changes varied with the wood species: 2.6% change in MOR was observed in Japanese cedar, China fir, western hemlock, red meranti, and Selangan batu; and 3.9% was found in red oak. For MOE, a 0.58% change was observed in Japanese cedar, China fir, and red meranti; western hemlock and Selangan batu exhibited 1.2% and red oak 2.5%. For hardness, a 1.1% change was observed in Japanese cedar, western hemlock, and red oak; red meranti and China fir exhibited 3.3%; and Selangan batu 1.8%.

Key words Moisture content · Specific gravity · Strength · Stiffness · Hardness

Introduction

It is well known that wood is a hygroscopic, elastic material; hence its mechanical properties are highly affected by the change of its moisture content (MC). In general, most mechanical properties of wood vary inversely with the MC of the wood below the fiber saturation point (FSP). It was reported that the average changing rates for the static bending modulus of elasticity (MOE), modulus of rupture (MOR), compression parallel-to-grain, and hardness of certain clear wood can be approximated, respectively, as 2%, 4%, 6%, and 2.5% for 1% MC change below FSP at a constant temperature of 70°F (21.1°C). Furthermore, a logarithm formula representing the strength–MC relation for wood with MC below the FSP was also developed by Forest Products Laboratory (FPL)[1] in which variables such as the strength of wood at an MC of 12% and green condition, as well as a specific value of MC, at which the wood strength begin to change when drying from the green condition was considered. That formula provided more accurate prediction of the strength–MC relations of wood, but the specific values of MC were reported for only 13 wood species. Therefore, in this study the effect of MC (below FSP) on the static bending properties and hardness of six wood species was closely examined statistically. Mean values for more accurate prediction of the strength changing rate as affected by the moisture fluctuation are presented. Furthermore, the interrelation among the mechanical properties, moisture content, and specific gravity was statistically analyzed.

Materials and methods

Materials

Wood specimens cut from six wood species, including China fir (*Cunninghamia lanceolata*), Japanese cedar (*Cryptomeria japonica* D. Don), western hemlock (*Tsuga heterophylla*), red meranti (*Shorea* spp.), red oak (*Quercus* spp.), and Selangan batu (*Shorea* spp.) were prepared for this study. The specific gravity of these six wood species based on their oven-dried (OD) condition (ϱ_o) ranged from 0.33 to 0.90.

S.-Y. Wang (✉) · H.-L. Wang
Department of Forestry, College of Agriculture, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei, Taiwan, ROC
Tel. +886-2363-1736; Fax +886-2-23631736
e-mail: sywang@ccms.ntu.edu.tw

---

* A part of this report was presented at the 48th annual meeting of the Japan Wood Research Society in Shizuoka, Japan, April 3–5, 1998

Table 1. Temperature and relative humidity conditions for designated equilibrium moisture content

Condition no.	Dry bulb temperature (°C)	Difference between dry and wet bulb temperature (°C)	Relative humidity (%)	Extimated moisture content (%)
1	20.00	0.23	98.00	25.00
2	20.00	1.22	89.00	20.00
3	20.00	2.60	77.20	15.00
4	20.00	5.43	54.79	10.00
5	20.00	9.80	24.30	5.00
6	20.00	14.07	0	0

The dimensions of specimens for static bending were 37 cm (long, in longitudinal direction) × 3 cm (width) × 1.5 cm (thick) and 4 cm (long, in longitudital direction) × 3 cm (width) × 1.5 cm (thick) for the hardness test.

Methods

Adjustment of MC of tested specimens

The MC of specimens was one of the major variables in this study. The designated six MC levels ranged from 0% to 25% at intervals of 5%. The constant temperature and relative humidity (RH) conditions for obtaining the equilibrium moisture content (EMC) are given in Table 1. Conditions 1 to 4 (MC levels: 25%, 20%, 15%, and 10%) were controlled using conditioning chambers with a constant temperature of 20°C; and their RHs were set at the levels of 98%, 89%, 77.2%, and 54.79%, respectively. However, conditions 5 and 6 (i.e., MC 5% and 0%) were obtained using the concentration of sulfuric acid solution in a desiccator under a constant temperature of 20°C.[2] The concentrations of sulfuric acid solution were 56.63% and 100% for conditions 5 and 6, respectively. All specimens were conditioned about 2 months until they reached their EMC.

Static bending tests

The static bending test was conducted in accordance with the central concentration loading method.[3] A Shimadzu model UH-10A testing machine was used. The span/depth ratio was 14 for all specimens. The average crosshead was 150 kgf/cm²/min of bending strength. The proportional limit and ultimate load and deflection were recorded, and the MOE and MOR were calculated.

Hardness tests

The hardness test was conducted in accordance with the Brinell hardness method.[4] The Brinell hardness of tangential sections of specimens (H_B) was calculated from the following formula

$$H_B = P/10\ \left(\mathrm{kgf/mm^2}\right) \tag{1}$$

where P represents the corresponded loading with $1/\pi$ mm of the press depth of the steel ball (10 mm in diameter). The OD-based specific gravity (ϱ_o) and MC were obtained using the specimens cut from both ends (dimension 4 × 3 × 1.5 cm) of the bending specimens.

Table 2. OD-based specific gravity of six wood species

Wood species	ϱ_o	Coefficient of variation (%)
China fir	0.33 ± 0.012	3.6
Japanese cedar	0.38 ± 0.027	7.1
Western hemlock	0.45 ± 0.033	7.3
Red oak	0.66 ± 0.029	4.4
Red meranti	0.48 ± 0.045	9.4
Selangan batu	0.90 ± 0.048	5.3

There were 30 samples of each wood species.
ϱ_o, specific gravity (results are the means ± SD).

Results and discussions

Oven-dried-based specific gravity

The oven-dried (OD)-based specific gravity for each wood species (ϱ_o) obtained under the designated six conditions are given in Table 2. It was found that the ϱ_o value for China fir was lowest, and largest value was found for Selangan batu. The lowest variation coefficient (CV) occurred in China fir specimens, and a higher variation was seen in red meranti.

Relations between humidity conditioning and moisture contents

The protocol used by Forest Products Laboratory – US. Department of Agriculture (FPL-USDA) for conditioning the MC of spruce wood was adapted for controlling temperature and RH in this study. However, the MC of specimens tested was not in full agreement with the values as described in the FPL observation and certainly varied with the wood species. Because the constant temperature was controlled at 20°C in this study, the RH was considered to be the sole affecting factor. Their relations could be represented by the following exponential formulas; and five other wood species showed a similar trend:

China fir: $\mathrm{MC} = 3.26e^{0.020\mathrm{RH}}\quad r = 0.98^{**}$ (2)
Japanese cedar: $\mathrm{MC} = 4.62e^{0.018\mathrm{RH}}\quad r = 0.96^{**}$ (3)

Western hemlock: $MC = 2.41e^{0.026RH}$ $r = 0.97^{**}$ (4)
Red oak: $MC = 2.58e^{0.023RH}$ $r = 0.94^{**}$ (5)
Red meranti: $MC = 2.39e^{0.025RH}$ $r = 0.96^{**}$ (6)
Selangan batu: $MC = 2.95e^{0.022RH}$ $r = 0.95^{**}$ (7)

where the double asterisk (**) indicates great significance resulted from the *F*-value test at the 0.01 confidence level, which means that the EMC of wood could be predicted by the RH in a constant-temperature environment.[5–7] When the RH was set at 0 in these exponential formulas, the EMC values were not equal to 0. This may be attributed to the fact that the conditions of 0% and 24.3% RH were maintained using sulfuric-acid solution, and it may be not enough to provide a completely equilibrated condition for the duration of 2 months. However, when RH was set at 100%, EMC reached the FSP values of that wood species. The FSPs of six wood species calculated from the above formulas were 25.1% for China fir, 28.5% for Japanese cedar, 33.8% for western hemlock, 24.5% for red oak, 30.0% for red meranti, and 27.4% for Selangan batu. It was found that in coniferous wood the FSP values increased with an increase in their ϱ_0 values. In decreasing order, it was Western hemlock > Japanese cedar > China fir. This is in agreement with a previous report[8], in which an FSP value of 31.1%–34.0% for Japanese cedar, and 26.2%–29.2% for China fir were observed using the shrinkage measurement methods; Western hemlock was not investigated in that study.

Wang and Cho[9] conducted the desorption and adsorption experiment at constant temperatures of 20°, 30°, and 40°C, under various RH conditions. From the hygroisotherm of 20°C, EMC values observed at the 100% RH condition were considered to be the FSP. With this approach, values of 29.70% and 29.65% were obtained from desorption conditions and 28.96% and 29.93% during adsorption for Japanese cedar and southern red oak, respectively. The results for Japanese cedar in that study were close to those of this study, but the value for southern red oak was slightly higher than that found in this study.

Effects of moisture content and specific gravity on MOR

It is well known that the static strength of wood is affected by many factors, including moisture content, specific gravity, grain angle, and the width of the annual ring and knots. In this study, moisture content was considered to be the principal variable for investigating the effect of MC levels on static bending strength. It was found that MOR values decreased linearly with the increase of MC and could be expressed by the following linear regression formulas:

China fir:
$MOR = 972.88 - 18.31MC$, $r = 0.76^{**}$ (8)
Japanese cedar:
$MOR = 897.67 - 15.27MC$, $r = 0.64^{**}$ (9)
Western hemlock:
$MOR = 1195.68 - 22.70MC$, $r = 0.91^{**}$ (10)
Red oak:
$MOR = 1409.19 - 31.46MC$, $r = 0.85^{**}$ (11)
Red meranti:
$MOR = 1605.52 - 16.37MC$, $r = 0.64^{**}$ (12)
Selangan batu:
$MOR = 2333.39 - 51.00MC$ $r = 0.79^{**}$ (13)

Although the above-listed correlation coefficients (*r*) are not very high, highly significant differences (0.01 confidence level, **) existed as shown in an *F*-value test. Further examination of the experimental data indicated that the variation of specific gravity within an individual wood species was large; hence specific gravity was not considered a dependent variable, whereas the relation between specific strength MOR/ϱ_0 and MC was considered to be. They can be expressed as follows:

China fir:
$MOR/\varrho_0 = 268577 - 1526.93MC$, $r = 0.45^{**}$ (14)
Japanese cedar:
$MOR/\varrho_0 = 160891 - 874.08MC$, $r = 0.17^{**}$ (15)
Western hemlock:
$MOR/\varrho_0 = 223352 - 1823.37MC$, $r = 0.63^{**}$ (16)
Red oak:
$MOR/\varrho_0 = 185622 - 3239.80MC$, $r = 0.88^{**}$ (17)
Red meranti:
$MOR/\varrho_0 = 243395 - 1356.99MC$, $r = 0.31^{**}$ (18)
Selangan batu:
$MOR/\varrho_0 = 223901 - 2325.50MC$, $r = 0.50^{**}$ (19)

Although the *F*-value test indicated that the correlation coefficients (*r*) were greatly significant at the 0.01 level, the resultant *r* values were poor in comparison with those when the specific gravity was not considered (i.e., MOR vs. MC). Therefore it seems that the specific MOR cannot be used satisfactorily for experimental data analysis. However, much more impressive results were obtained when the multivariable analysis[10] was conducted. When MC and ϱ_0 are considered independent variables, MOR can be expressed by multiregressions formulas as shown in Table 3.

Obviously, the correlation coefficients (*r*), ranging from 0.75 to 0.94, were much more significant than those in the single-variable linear regression formulas. Hence the multivariable regression offers a better explanation of material properties analysis when variation may exist. However, in the multivariable analysis the intercorrelation among dependent variables must not exist, otherwise the analyzed result would be significantly affected. Therefore, the OD-based specific gravity (ϱ_0) was used instead of the air-dried values (ϱ) to exclude the MC effect on specific gravity.

From the above results, a negative correlation between MOR and MC and a positive correlation between MOR and ϱ_0 were observed. Although a positive correlation between MOR and ϱ_0 has been reported by many researchers, their results varied with wood species.[11–16]

Below FSP, the relation between MOR and MC is generally assumed to have an approximately 4% increase or decrease of MOR induced by every 1% decrease or increase of moisture content in most wood species. The applicability and accuracy of this strength changing rate will be closely

Table 3. Coefficients of the multiregression formulas for the relations among MC, ϱ_o, and strength properties of six wood species

Wood species and kinds of strength	$y = a + bx_1 + cx_2$			
	a	b	c	r
China fir				
MOR	−460.29	−18.07**	394.46**	0.93
MOE	−44700.1	−538.2**	392005.4**	0.80
H_B	−0.30	−0.013**	3.31*	0.58
Japanese cedar				
MOR	213.03	−16.49**	1814.09**	0.80
MOE	−55359.02	−412.85	310036**	0.82
H_B	1.21	−0.011*	25.44**	0.55
Western hemlock				
MOR	276.09	−21.22**	1976.13**	0.94
MOE	60837.79	−914.42**	2.255	0.71
H_B	−7.73	−0.029*	52.07*	0.86
Red oak				
MOR	922.76	−31.18**	736.23	0.84
MOE	10683.05	−2066.73**	92025.04	0.88
H_B	19.02	−0.078**	21.57	0.71
Red meranti				
MOR	38.74	−16.21**	2220.38**	0.75
MOE	8868.94	−647.41	28854.12**	0.51
H_B	6.83	−0.0096**	6.81	0.43
Selangan batu				
MOR	−4058.01	−48.72**	7172.78**	0.93
MOE	−497784.9	−1909.96**	783792**	0.85
H_B	22.54	−0.028**	8.41	0.42

y, represents MOR, MOE, and H_B, respectively; x_1 and x_2 shows MC and ϱ_o, respectively; a, b, c, coefficient for multiregression formulas.
*, **, significant (0.05 level) and very significant (0.01 level) by F-tests.

examined using the results of the six wood species studied and discussed as follows.

Assume MOR is a function of MC [i.e., MOR = f(MC)]. The MOR changing rate induced by the 1% increase (or decrease) of MC compared to the 12% (air-dried condition) at a condition of MC may be expressed as following formulas:

$$\left(\frac{\mathrm{dMOR}}{\mathrm{dMC}}\right) \times \frac{1}{\mathrm{MOR}_{12}} = \frac{\mathrm{MOR}}{\mathrm{MOR}_{12}} = \frac{f(\mathrm{MC})}{\mathrm{MOR}_{12}} = \frac{f(\mathrm{MC})}{f(12)} \tag{20}$$

Because six wood species were used in this study the regression formulas for MOR and MC were assumed as follows:

$$\mathrm{MOR}_1 = f_1(\mathrm{MC}), \quad \mathrm{MOR}_2 = f_2(\mathrm{MC}) \ldots \mathrm{MOR}_6 = f_6(\mathrm{MC}) \tag{21}$$

The MOR changing rate induced by a 1% increase (or decrease) in moisture content for six wood species may be expressed as follows:

$$\text{MOR changing rate} = \frac{f_1'(\mathrm{MC})}{f_1(12)}, \frac{f_2'(\mathrm{MC})}{f_2(12)} \cdots \frac{f_6'(\mathrm{MC})}{f_6(12)} \tag{22}$$

If significant differences were not observed among these six wood species as analyzed by Duncans' multiple new range method,[17] the variation among them could be neglected. Hence this MOR changing rate should be applicable to all wood species; otherwise significant variations among wood species cannot be ignored.

Six MC conditions (0%, 5%, 10%, 15%, 20%, 25%) were chosen for the study. These six MC variables were substituted into the regression formula for each wood species, and 36 groups of data were obtained for Duncans' multiple new-range analysis according to the analyzed result for each wood species. If results showed large differences among the changing rates of $f'(0)/f(12)$, $f'(5)/f(12)$, $f'(10)/f(12)$, $f'(15)/f(12)$, $f'(20)/f(12)$, and $f'(25)/f(12)$, Duncans' multiple new-range analysis is statistically meanless because of the low F values. That means that the analyzed result would be worthless. Therefore, the function of MOR = f(MC) would be considered efficient. Several functions were used for analysis, and their applicability and suitability were compared each other as follows.[18–20]

$$(1)\mathrm{MOR} = f(\mathrm{MC}) = a - b \cdot \mathrm{MC}(\mathrm{MC} < \mathrm{FSP}) \tag{23}$$

This is a popularly used linear regression formula, where a and b are material constants and positive, However, because the MOR changing rate with reference to that at 12% MC is

$$\frac{f'(\mathrm{MC})}{f(12)} = \frac{b}{a \pm 12b}$$

it follows that the six wood species studied provided data as follows

$$\frac{f_i'(\mathrm{MC}_j)}{f_i(12)} = \frac{b_i}{a_i - 12b_i}, \quad i = 1, 2, \ldots 6, j = 1, 2, \ldots 6. \tag{24}$$

where i = 1 to i = 6 designate the six wood species; and j = 1 to j = 6 designate the six MC conditions (i.e., j = 1; MC = 0%; . . . j = 6; MC = 25%) and a_i and b_i are material constants for the six wood species studied. The value of $b_i/(a_i - 12b_i)$ is a constant and is wood-species dependent, but it is independent of MC. Hence Duncans' multiple new-range analysis could not be conducted.

$$\begin{gathered}(2)\mathrm{MOR} = f\left(\overline{\mathrm{MC}}\right) = a - b\overline{\mathrm{MC}} - c\overline{\mathrm{MC}}^2 \text{ or} \\ c\overline{\mathrm{MC}}^2 + b\overline{\mathrm{MC}} + (\mathrm{MOR} - a) = 0\end{gathered} \tag{25}$$

physically 0 < MC < FSP (i.e., $\overline{\mathrm{MC}}$ is alway positive and real) and MOR − a < 0 (i.e., MOR ≤ a, MOR and a, positive and real); hence at $\overline{\mathrm{MC}} = 0$, $\mathrm{MOR}|^{=a}_{\overline{\mathrm{MC}}=0}$ is the maximum value,
where a, b, and c are material constants, and must be real. Mathematically, there are three possible solutions for this quartic function:

(A) If $b^2 - 4(\mathrm{MOR} - a)c > 0$, the MC (roots) are real and unequal, which is physically meaningless because the value of MOR is always less than the value when $\overline{\mathrm{MC}}$ is greater than 0%. It is impossible to have a single value of MOR at two different levels of moisture content. Thus, this approach must be ignored.

(B) If $b^2 - 4(\mathrm{MOR} - a)c < 0$, the MC (roots) are imaginary and unequal which is also physically meaningless because $\overline{\mathrm{MC}}$ is alway real. Hence this solution must be excluded.

(C) If $b^2 - 4(\mathrm{MOR} - a)c = 0$, the MC (roots) are real and equal, which is physically meaningful because only a single value of MC exists for the MOR at that MC condition. Furthermore, $b^2 = 4(\mathrm{MOR} - a)c$ leads to c, which must be negative and real because $\mathrm{MOR} - a < 0$ for all MC conditions that are less than 0%. It follows that $\overline{\mathrm{MC}}$ must be equal to $-b/2c$. Thus b must be positive for a positive value of $\overline{\mathrm{MC}}$, and a is a specified value of MOR. This solution is acceptable both mathematically and physically.

Using the argument described above, it follows that the MOR changing rate with reference to that at 12% MC condition for the six wood species had a general form as

$$\frac{f_i'\left(\overline{\mathrm{MC}}_j\right)}{f_i(12)} = \frac{-b_i - 2c_i\overline{\mathrm{MC}}_j}{a_i - 12b_i - 144c_i}$$

where, $i = 1$ to $i = 6$ designates the six wood species, and $j = 1$ to $j = 6$ designates the six MC conditions. Thus the Duncans' multiple new-range analysis could be performed. The results are shown in Table 4.

$$(3)\mathrm{MOR} = ae^{-b\overline{\mathrm{MC}}}, \quad 0 \le \overline{\mathrm{MC}} \le \mathrm{FSP} \tag{26}$$

where a and b are material constants and positive, and a is the value of MOR at the oven-dried condition. It follows that the MOR changing rate with reference to that at 12% MC for the six wood species studied are

$$\frac{f_i\left(\overline{\mathrm{MC}}\right)}{f_i(12)} = \frac{-a_i b_i e^{-b_i\overline{\mathrm{MC}}_j}}{a_i e^{-12b_i}} = b_i e^{-b_i\left(\overline{\mathrm{MC}}_j - 12\right)} \tag{27}$$

The characteristics of this equation are different with that discussed in (2) because it yields only negative values (i.e., $-b_i < 0$, b_i is possible).

The MOR changing rate induced by 1% MC fluctuation for six wood species was analyzed using the Duncans' multiple new-range method as shown in Table 4. It is evident from Table 4 that the MOR changing rate was homogeneous for five wood species (red meranti, China fir, Japanese cedar, Selangan batu, and western hemlock) and had an average value of 2.6%; a larger value of 3.9% was seen for red oak. It also was found that the MOR changing rate for the six wood species studied were lower than 4%, which is commonly accepted by the wood science and technology community.

Oda et al.[21] investigated the relations between MC and $\sigma_{//}/\sigma\,g_{//}$ ($\sigma_{//}$ and $\sigma\,g_{//}$ represented the compression strength parallel-to-grain in air-dried and water-saturated conditions, respectively). Their results indicated that the relations could be represented by a semilogarithmic equation, as shown as

$$\sigma_{//}/\sigma g_{//} = a - b\log\mathrm{MC}, \ (0 < \mathrm{MC})$$

where a and b were constants (positive), and they varied with wood species. However, at the MC range of 11%–19%, the relations between, $\sigma_{15}/\sigma\,g_{//}$ (σ_{15} represented the compression strength parallel-to-grain in 15% MC), and MC could be described by a linear regression. The average value of σ changing rate for nine conifereous wood species was 6.3%, which was consistent with the value of 6% used in general. However, the study of Oda et al.[21] showed that the distribution ranged from 4.8% (asunaro) to 7.8% (akamatsu), suggesting that the variation in wood species did exist.

Effects of moisture content and specific gravity on MOE

Results from static bending tests indicated that the relations among MC, ϱ_0, and MOE could be represented by the multiregression formula shown in Table 3. It was found that a negative correlation existed between MOE and MC, but there was a positive correlation between MOE and ϱ_0. However, there were no significant effects of MC on MOE in Japanese cedar or red meranti. Similarly, there were no significant effects of ϱ_0 on MOE in Western hemlock or red oak.

The MOE changing rate induced by 1% MC fluctuation for six wood species was analyzed using the same method as described above, and results of Duncans' multiple new-range test are showed in Table 4. It is evident from Table 4 that the MOE changing rate was homogeneous for Japanese cedar, red meranti, and China fir, with an average value of 0.58%; a similar trend was shown in western hemlock and Selangan batu, with an average value of 1.2%. A larger value of 2.5% was shown in red oak. It also was found that the MOE changing rate for five wood species studied were lower than 2%, a figure commonly used by the wood science and technology community, except for red oak. This suggests that variation in wood species existed, and the 2% value may not be suitable for all wood species. The results from our study are in agreement with the findings reported by Gerhard[22] and Ross and Pellerin,[23] in which they indicated that below FSP a negative correlation existed between MOE and MC.

Table 4. Duncans' multiple new-range test for strength change rate induced by 1% MC change

Wood Species	Rate of change (%)		
	MOR[a]	MOE[b]	H_B[c]
Red meranti	1.92	0.57	3.02
China fir	2.55	0.62	3.49
Japanese cedar	2.70	0.56	1.10
Selangan batu	2.89	1.21	1.83
Western hemlock	2.93	1.20	1.10
Red oak	3.85	2.50	1.11

There were six samples for each determination.
There were no significant differences between the following wood species. MOR: red maranti, China fir, Japanese cedar, Selangan batu, and western hemlock; on between Selangan batu, western hemlock, and red oak. MOE: Japanese cedar, red meranti, and China fir; or between western hemlock and Selangan batu. H_B: Japanese cedar, western hemlock, and red oak; on between red meranti and China fir.

Effects of moisture content and specific gravity on hardness

Results of hardness tests indicated that the relations among MC, ϱ_o, and Brinell hardness (H_B) could be represented by multiregression formulas, as shown in Table 3.

It was found that a negative correlation existed between H_B and MC, ranging from significant differences (0.05 level,*) to highly significant differences (0.01 level, **). A positive correlation also existed between H_B and ϱ_o, but the differences were not significant for the three hardwoods (red oak, red meranti, and Selangan batu).

The H_B changing rate induced by 1% MC fluctuation for six wood species was analyzed using the same method as described above. The results of Duncans' multiple new-range test were shown in Table 4. It is evident from Table 4 that the H_B changing rates for Japanese cedar, western hemlock, and red oak can be classified as a homogeneous group, represented by an average value of 1.1%. Similar trends were showed for red meranti and China fir with an average value of 3.3%. Selangan batu had a value of 1.8%. A value of 2.5% is generally used for the H_B changing rate for the longitudinal surface of wood (average of radial and tangential faces) induced by 1% MC fluctuation. However, this study suggests that the H_B changing rate varied with the wood species.

Correlation among the three strength properties

If the MC of the six wood species is neglected, correlations among three strength properties could be represented by the following positive linear regression formulas:

$$\mathrm{MOR} = 5.04 + 0.0094\mathrm{MOE} \quad r = 0.88^{**} \tag{28}$$

$$\mathrm{MOR} = 442.62 + 361.78H_B \quad r = 0.73^{**} \tag{29}$$

$$\mathrm{MOE} = 60611 + 28486H_B \quad r = 0.61^{**} \tag{30}$$

The correlation coefficients were highly significant at the 0.01 confidence level, as indicated by the F value test, when each wood species was considered individually. They also showed positive correlations between MOR and MOE, MOR and H_B, and MOE and H_B for six wood species. Concerning the relation between MOR and MOE, their correlation coefficients ranged from 0.63 (Japanese cedar and red meranti) to 0.87 (red oak). They also were shown to be highly significant (0.01 level) by the F value test. These results are in agreement with results reporetd by many wood researchers.[24–28] However, as to the relation between MOR and H_B, their correlation coefficients ranged from 0.31 (red meranti) to 0.86 (western hemlock); and the correlation coefficients for MOE and H_B ranged from 0.26 (red meranti) to 0.66 (red oak).

Conclusions

Based on the above observations, the following conclusions can be drawn.

1. Under a constant temperature, the MC of wood increases exponentially with an increase of RH. That is, the MC of woods could be predicted by the RH in that environment.
2. Effects of MC and ϱ_o on strength (MOR, MOE, H_B) can be represented by multiregression formulas. A negative correlation existed between strength and MC, and a positive correlation existed between strength and ϱ_o.
3. Strength can be assumed as an exponential function of MC, and the strength changing rate induced by 1% MC fluctuation could be obtained by Duncans' multiple new-range analysis. Such rates varied with wood species: 2.6% MOR changing rate was observed in Japanese cedar, China fir, western henlock, red meranti, and Selangan batu; it was 3.9% in red oak. MOE changing rate of 0.58% was observed in Japanese cedar, China fir, and red oak; it was 1.2% in western hemlock and Selangan batu and 2.5% in red oak. An H_B changing rate of 1.1% was found in Japanese cedar, western hemlock, and red oak; 3.3% in red meranti and China fir; and 1.8% in Selangan batu.
4. Intercorrelations among MOR, MOE, and H_B could be represented by positive linear regression formulas.

Acknowledgments The investigation reported in this paper was supported financially by the National Science Council of the Republic of China (NSC87-2313-B-002-119). The authors thank Dr. R.C. Tang, Professor of the School of Forestry, Auburn University Alabama, USA for his advice.

References

1. Wood Handbook 72 (1987) Wood as an engineering material. Forest Products Laboratory, Forest Service, USDA, P4-36-39
2. Forestry and Forest Products Research Institute (1982) Wood Industry Handbook revised 3rd edn, Maruzan Published KK, P1056
3. Chinese National Standard CNS454 (1981) Method of test for static bending of wood. National Standard Bureau, Taipei, Taiwan, ROC
4. Chinese National Standard CNS460 (1981) Method test for hardness of wood. National Standard Bureau, Taipei, Taiwan, ROC
5. Avramidis S (1989) Evalvation of "three-variable" models for the prediction of the equilibrium moisture content in wood. Wood Sci Technol 23:251–258
6. Simpson WT (1971) Equilibrium moisture content prediction for wood. For Prod J 21(5):48–49
7. Simpson WT (1973) Predicting equilibrium moisture content of wood by mathematical models. USDA FPL, Madison, WI
8. Wang SY (1989) Studies on the fundamental properties of the economical tree species in Taiwan (IV). Q J Chin For 22(1):3–22
9. Wang SY, Cho CL (1993) Equilibrium moisture contents of six wood species and their influences. Mokuzai Gakkaishi 39:126–137
10. Hwang CE (1986), Multivarable analysis. Chinese Economic Enterprise Institute, Taipei, Taiwan, ROC
11. Lin CR, Shih NY, Wang SY (1992) Studies on the lumber grades and bending properties of Japanese cedar and China-fir plantation trees. Q J Exp For NTU6(1):71–101
12. Schneider MH, Sebastian LP (1991) Bending strength and stiffness of Caribbean pine from Trinidad and Tobago. Wood Fiber Sci 23:468–471
13. Wang SY, Tserng WH (1993) Variation in compression parallel-to grain and bending strength of China fir (*Cunninghamia lanceolata*) grown in Taiwan. Q J Exp For NTU 7(1):65–77
14. Wang YR, Chen BJ (1990) Study on the in-grade variance of dimension lumber strength distribution. For Prod Ind 9(2):97–109.

15. Wang SY, Chiu CM (1993) Wood properties of Japanese cedar originated by seed and vegetative reproduction in Taiwan. VI. Compression and bending properties. Mokuzai Gakkaishi 39:1128–1139.
16. Wang SY, Lin SH (1996) Effects of plantation spacings on the quality of visually graded lumber and mechanical properties of Taiwan-grown Japanese cedar. Mokuzai Gakkaishi 42:435–444
17. Duncan DB (1995) Multiple range and multiple F tests. Biometrics 11:1–42
18. Barett JD, Lau W (1991) Bending strength adjustments for moisture content for structural lumber. Wood Sci Technol 25:433–447
19. Green DW, Link CL, Debonis AL, Mclain TE (1986) Predicting the effect of moisture content on flexural properties of Southern pine dimension lumber. Wood Fiber Sci 18(1):134–156
20. Green DW, Erans JW, Barrett JD, Aplin EN (1987) Predicting the effect of moisture on the flexural properties of Douglas-fir dimension lumber. Wood Fiber Sci 20(1):107–131
21. Oda K, Tsutsumi J, Matsumura J (1994) Effects of moisture contents on mechanical properties of several softwood. II. Effects on compressive strength and annual ring structure. Mokuzai Gakkaishi 40(2):113–118
22. Gerhard CC (1975) Stress wave and MOE of sweetgum ranging from 150 to 15 percent MC. For Prod J 25(4):51–57
23. Ross RJ, Pellerin RF (1991) NDE of green material with stress waves; preliminary results using dimension lumber. For Prod J 41(6):57–59
24. Atherton GH (1980) Preliminary study of proportional limit as predictor of ultimate strength in bending. For Prod J 30(11):47–53
25. Faust TD, McAlister RH, Zarnoch SJ (1990) Strength and stiffness properties of sweetgum and yellow-popular structural lumber. For Prod J 40(10):58–64
26. Tanaka T (1988) Evaluation of strength by non-destructive test: application for sugi wood attacked by borer-insect. Wood Ind (Mokuzai Kogyo) 43(2):20–25
27. Wang SY, Ko CY (1998) The dynamic modulus of elasticity and bending properties of large beam of Japanese cedar for Taiwan-grown in different plantation spacing sites. J Wood Sci 44:62–68
28. Zhou H, Smith I (1991) Factors influencing bending properties of white spruce lumber. Wood Fiber Sci 23(4):483–500