MECHANICAL PROPERTIES IN RELATION TO SPECIFIC GRAVITY IN 342 CHINESE WOODS

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ABSTRACT

Based on 342 Chinese timber species separated into five distinct categories, relationships of various wood mechanical properties (S) with specific gravity (G) were examined at: 1) species rank; 2) generic rank; 3) the category rank as well as in all the softwoods or hardwoods as a whole. The curvilinear equation ($S = \alpha G^{\beta}$) was compared with the linear one ($S = a + bG$) in terms of the goodness at predicting mechanical properties through specific gravity. The results indicate that the mechanical property-specific gravity relationship varies remarkably with the taxonomic rank, the wood category, and wood mechanical property. Further, the goodness of the two equations in terms of the coefficient of determination also varies appreciably with the rank, the wood category, and wood mechanical property. As a whole, however, the curvilinear equation appears to be better than the linear one at predicting most mechanical properties, particularly at species rank and in terms of the regression coefficients.

Keywords: Specific gravity, mechanical properties, wood categories, Chinese woods, regression equations, relationships.

INTRODUCTION

Wood mechanical properties (S) in relation to specific gravity (G) were examined by Newlin and Wilson (1919) based on American woods, and the equation $S = \alpha G^{\beta}$ was first established for describing the relationships between specific gravity and mechanical properties of clear, straight-grained, and defect-free wood. The Wood Handbook (Forest Products Laboratory 1987) gave the regression equations based on the average specific gravity and mechanical property values for the commercially important 43 softwoods and 66 hardwoods grown in the United States. Armstrong et al. (1984) verified the equation with worldwide data on modulus of rupture, modulus of elasticity in static bending, and maximum crushing strength in compression parallel to the grain. The results show that grouping timbers by genera or by gross anatomical categories for developing mechanical property-specific gravity regressions may be preferable to grouping species on a geographical basis. Furthermore, Walton and Armstrong (1986) found significant differences in the mechanical property-specific gravity relationship between most generic groupings and between most pore arrangement groupings. On the other hand, however, it was stated by Liska (1965) and Forest Products Laboratory (1987) that mechanical properties within a species are linearly related to specific gravity, and thus could be better predicted by the linear equation $S = a + bG$. As a matter of fact, this linear equation has been widely used over the years for describing mechanical properties in relation to specific gravity in a species.

When one reviews the relationships between wood mechanical properties and specific gravity, it is natural to ask: 1) Do the relationships of wood mechanical properties with specific gravity change appreciably at different taxonomic ranks (viz. at species, generic and higher ranks)? 2) Between the curvilinear and linear equations, which is better at describing the mechanical property-specific gravity relation-

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ship? Is the linear equation better at species rank, but poorer at generic and higher ranks? 3) How about the regression coefficients of the two equations? Do they also change with the rank? Are they significant statistically? 4) Is the curvilinear equation good at describing various mechanical properties in relation to specific gravity? How about the goodness of the equations at predicting different mechanical properties? The present study aims at answering these questions. Various mechanical properties of major Chinese woods in relation to specific gravity were analyzed in the present study. The data on physico-mechanical properties of major Chinese woods (Anon. 1982) were considered as a unique population able to serve the present study: 1) The population includes a large number of timber species. 2) These species comprise different kinds of softwoods and hardwoods. 3) These species cover tropical, subtropical, and temperate elements. 4) The determination of wood mechanical properties for all the species studied followed one testing standard. 5) Various wood mechanical properties were determined.

MATERIALS AND METHODS

In total, 342 species comprising 74 softwoods and 268 hardwoods were included in the present study. These species include major commercial Chinese woods (Anon. 1982). In consideration of the obvious differences in macroscopic wood structure among the 342 species of softwoods and hardwoods, the following five distinct wood categories were recognized:

1) First softwood category (FSC): the softwoods with gradual transition from earlywood to latewood (e.g., *Abies* and *Picea*);
2) Second softwood category (SSC): the softwoods with abrupt transition from earlywood to latewood (e.g., *Larix* and hard pines);
3) Ring-porous wood category (RPC) (e.g., *Castanopsis* and *Quercus*);
4) Diffuse-porous wood category (DPC) (e.g., *Eucalyptus* and *Populus*);
5) Semi-ring-porous wood category (SPC) (e.g., *Fagus* and *Juglans*).

Among the 342 species studied, 37 species belong to the first softwood category, 37 species to the second softwood category, 58 species to the ring-porous wood category, 136 species to the diffuse-porous wood category, and 74 species to the semi-ring-porous wood category according to Cheng et al. (1979) and Cheng et al. (1992). Descriptive statistics for various mechanical properties of the five distinct wood categories were given by Zhang (1994b).

For those species that were distributed in limited regions or that were commercially less important, only one test was conducted for each of those species based on the trees sampled from one locality. For some important and widely distributed species, however, more than one (up to 16) tests were performed for individual species, and each test was based on the trees sampled from one of a wide range of localities throughout the distribution areas. In total, 557 tests were completed for the 342 species. For each test, normally at least 5 trees were collected from a locality, and at least 30 small clear specimens were prepared and tested for each mechanical property according to the Chinese National Standard (NSB 1980). Mechanical properties tested include:

A. Modulus of rupture in static bending (MOR);
B. Modulus of elasticity in static bending (MOE);
C. Maximum crushing strength in compression parallel to the grain (Cmax);
D. Maximum compression strength perpendicular to the grain (MCS):
   1) MCSp—The loading on the partial surface of the specimen (based on the average of the radial and tangential tests);
   2) MCSe—The loading on the entire surface of the specimen (based on the average of the radial and tangential tests);
E. Maximum shearing strength parallel to the grain (MSS) (based on the average of the radial and tangential tests);

F. Maximum tensile strength parallel to the grain (MTS);
G. Toughness (T);
H. Hardness (H): 1) Hx (transverse); 2) Hrt (based on the average of the radial and tangential tests);

Mechanical property values were adjusted to the air-dry condition, which is considered to be 15% moisture content in China. Wood specific gravity was based on the oven-dry weight/air-dry volume.

The relationships of mechanical properties with specific gravity in this study were explored at the following taxonomic ranks: 1) species rank; 2) generic rank; 3) category rank. In addition, the mechanical property-specific gravity relationship was also examined when all the softwoods or hardwoods studied were considered as a whole. When the relationship was examined at generic or higher rank, the intraspecific variation was not taken into account (viz. based on the average of all tests for individual species). The relationship at species rank, however, was based on the "species-localities" averages or shipment averages (cf. Newlin and Wilson 1919; Liska 1965). In the present study, the relationship at generic rank as well as at species rank was based on two common and important taxa selected from each wood category (except SPC). At generic rank, *Abies* (10 species) and *Picea* (9 species) were selected from FSC, *Larix* (7 species) and *Pinus* (hard pines only, 20 species) from SSC, *Eucalyptus* (11 species) and *Populus* (20 species) from DPC, and *Castanopsis* (15 species) and *Quercus* (12 species) from RPC. At species rank, the "species-localities" averages in a few cases (see Table 3) were from more than one species due to the limited number of the tests for individual species. Regression analysis was performed in the present study. Regression equation was presented for each mechanical property at different ranks and tested by analysis of variance, and the coefficient of determination (R^2) was given for the curvilinear and linear equations as a major index of the ability to predict mechanical properties through specific gravity.

RESULTS

Mechanical property-specific gravity relationship at the category rank as well as in all the softwoods or hardwood as a whole

For most mechanical properties (except MOR, MOE, and MTS) of the first softwood category (FSC), the linear equation ($S = a + bG$) has a slightly higher coefficient of determination (R^2) than the curvilinear one ($S = \alpha G^{\beta}$), as shown in Table 1. It indicates that the linear equation is able to explain a higher percentage of the variation in most mechanical properties except static bending properties and tensile strength. For SSC, however, the reverse holds true: in terms of the coefficient of determination, the curvilinear equation is better than the linear one at predicting most mechanical properties. If all the softwoods studied were considered as a whole (SW), the curvilinear equation is better at predicting most mechanical properties studied. Only the static bending properties are predicted slightly better by the linear equation. As shown in Fig. 1, however, the two prediction equations for MOR ($MOR = 149G^{0.951}$ and $MOR = 3.7 + 148G$) are actually quite close to each other, and the same, to a lesser extent, applies to MOE (Fig. 2). For RPC, the linear equation appears to be more or less better than the curvilinear one at predicting all the mechanical properties (except MTS) in terms of the coefficient of determination (see Table 1). For DPC, however, the curvilinear equation is better at predicting all the mechanical properties (except the static bending properties). For SPC, no remarkable differences in the coefficient of determination can be recognized between the two equations. When all the hardwoods studied were considered as a whole (HW), the curvilinear equation is able to better predict most mechanical properties, as found in the soft-

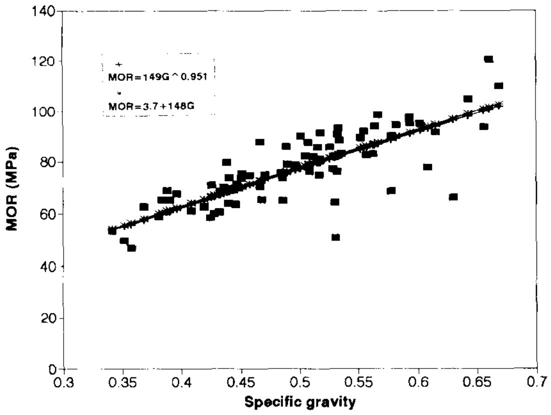

FIG. 1. MOR in relation to specific gravity in the softwoods as a whole (SW) and the comparison of the curvilinear and linear equations.

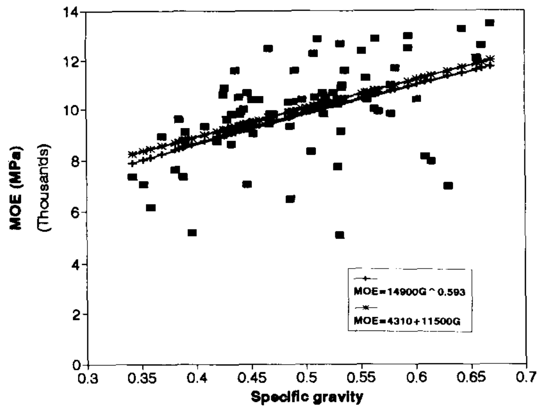

FIG. 2. MOE in relation to specific gravity in the softwoods as a whole (SW) and the comparison of the curvilinear and linear equations.

woods as a whole (SW). Further, the intercept (a) of the linear equation is often not significant statistically, while the two regression coefficients (α and β) of the curvilinear equation are both significant in almost all cases (Table 1). Moreover, the linear relationship using the intercept other than zero has no physical meaning (viz. it predicts a positive or negative property at zero specific gravity), while the curvilinear relationship can degenerate into a linear one when the exponent equals 1. As a whole, therefore, the curvilinear equation appears better than the linear one at predicting mechanical properties at the category or higher rank.

Table 1 also shows that Hrt, MOR, and Cmax in the softwoods as a whole (SW) are most closely related to specific gravity, while MOE and MTS are the least related to specific gravity (also see Figs. 1 and 2 for MOR and MOE as an example). It also holds true in the two softwood categories. But mechanical properties in SSC are generally more closely related to specific gravity than in FSC, and large differences in the relationships of T, MOE, and MTS with specific gravity can be recognized between the two softwood categories. As shown in Table 1, all the mechanical properties studied in SSC are significantly related to specific gravity, while MOE in FSC is not significantly related to specific gravity. In the hardwoods as a whole (HW), as in the softwoods as a whole (SW), H, MOR and Cmax are most closely related to specific gravity (see Fig. 3 for MOR as an example), while T and MTS are the least related to specific gravity. This largely applies to the individual hardwood categories. In general, the mechanical properties in RPC are remarkably less related to specific gravity than in DPC and SPC (Table 1), as demonstrated with MOE in Figs. 4 and 5. All the mechanical properties in RPC, however, are still significantly related to specific gravity, and about half of the variation in the mechanical properties can be explained by specific gravity. For DPC as well as SPC, over half (up to 95%) of the variation can be explained. Compared with the softwoods as a whole, it appears that all the mechanical properties in the hardwoods as a whole (HW) are appreciably more closely related to specific gravity (Table 1). For instance, MOE is poorly related to specific gravity in the softwoods as a whole, but closely related to specific gravity in the hardwoods as a whole (see Figs. 2 and 6). In general, specific gravity in the softwoods as a whole is able to account for about half of the variation in the mechanical properties, while over half, up to

TABLE 1. *The regression coefficients and the coefficient of determination (%) of the curvilinear equation (α, β and R^2—the first row of each mechanical property) and linear equation (a, b, and r^2—the second row) at the category rank (viz. RPC, DPC, SPC, FSC and SSC) as well as in all the softwoods (SW) or hardwoods as a whole (HW).*[1]

	RPC			DPC			SPC		
	α a	β b	R^2 r^2	α a	β b	R^2 r^2	α a	β b	R^2 r^2
MOR	130	0.687	53	150	1.095	80	149	1.037	92
	27.7	107	**58**	−7.9	157	**82**	−1.2	149	**93**
MOE	147	0.586	38	165	0.861	74	169	0.852	87
(×100)	43.1	111	**39**	14.7	153	**75**	16.7	154	87
Cmax	58.5	0.618	45	73.1	1.035	**92**	70.1	0.969	88
	13.8	48.1	**51**	−0.7	73.5	81	2.0	68.4	**89**
MCSp	13.1	1.133	51	16.3	1.633	**80**	16.6	1.674	**90**
	−2.8	17.3	**52**	−4.2	19.4	76	−5.4	21.9	82
MCSe	8.9	1.080	53	11.9	1.718	**78**	11.1	1.597	88
	−2.1	11.7	**55**	−2.9	13.6	74	−2.8	13.5	**89**
MSS	16.1	0.772	47	17.3	1.078	**74**	17.2	1.084	83
	2.2	14.7	**52**	−0.1	17.2	69	−1.0	18.5	**84**
MTS	145	0.570	**32**	158	0.841	**55**	164	0.893	72
	53.0	94.8	29	22.8	136	52	17.1	145	**80**
T	130	1.213	47	124	1.466	**51**	142	1.433	76
	−20.4	1.595	**48**	−31.9	1.612	45	−31.4	1.787	**79**
Hx	96	1.166	64	121	1.633	**85**	115	1.606	91
	−17.2	120	**71**	−42.5	161	84	−35.5	151	91
Hrt	90	1.429	68	115	2.027	**92**	116	2.025	**95**
	−27.0	120	**75**	−56.1	165	88	−48.7	161	93

[1] Underlined R^2 (r^2) and α (a) or/and β (b) indicate that the regression (tested by ANOVA) and the regression coefficient(s) are not significant at the 90% confidence level, respectively; the bold R^2 (or r^2) is relatively larger than the other one; all mechanical properties (except Tougness in N-M/m^2, ×1,000) in MPa (the same applies to Tables 2 and 3).

almost 90%, of the variation can be explained by specific gravity in the hardwoods as a whole.

As shown in Table 1, the regression coefficients α of the curvilinear equations for MOR in most wood categories (except RPC) are close to each other, and the same applies to another regression coefficient (β). It indicates that the prediction curves for most of the different soft-

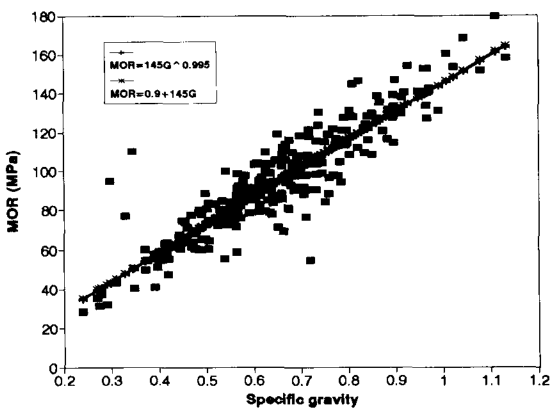

FIG. 3. MOR in relation to specific gravity in the hardwoods as a whole (HW) and the comparison of the curvilinear and linear equations.

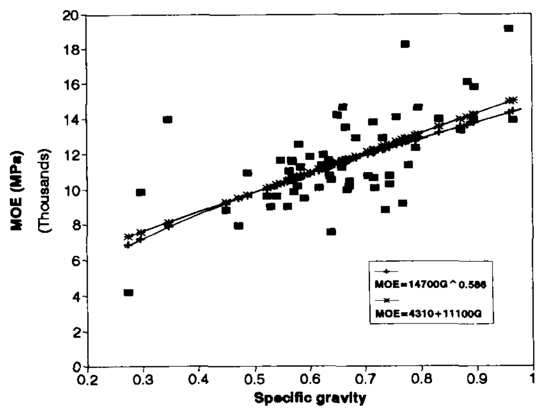

FIG. 4. MOE in relation to specific gravity in the ring-porous wood category (RPC) and the comparison of the curvilinear and linear equations.

TABLE 1. *Extended.*

HW			FSC			SSC			SW		
α a	β b	R^2 r^2	α a	β b	R^2 r^2	α a	β b	R^2 r^2	α a	β b	R^2 r^2
145	0.995	81	146	0.925	**53**	151	0.979	61	149	0.951	61
0.8	145	**82**	8.7	137	52	−0.3	115	**62**	3.7	148	**62**
162	0.802	73	126	0.389	**8**	161	0.692	28	149	0.593	21
20.6	146	73	69.6	56	5	29.4	141	**33**	43.1	115	**23**
68.8	0.932	78	78.3	1.001	52	63.4	0.717	**49**	68.3	0.826	**53**
2.7	67.2	**79**	1.3	76.1	**55**	11.0	55.6	46	7.4	62.7	52
15.8	1.571	**80**	25.7	2.072	51	10.8	1.137	**56**	13.2	1.317	**41**
−4.5	20.0	74	−8.8	31.0	**52**	−0.7	11.4	48	−2.4	15.7	31
11.0	1.562	**80**	14.7	1.905	43	9.1	1.432	**61**	9.7	1.451	**46**
−2.7	13.2	73	−4.3	17.1	**48**	−1.7	10.3	51	−1.9	11.1	41
17.2	1.037	**74**	21.9	1.517	42	15.3	1.068	**65**	17.0	1.209	**50**
−0.2	17.4	73	−3.2	22.1	**43**	0.5	13.5	39	−1.0	16.9	46
158	0.816	**60**	144	0.583	**21**	182	0.969	**45**	161	0.756	**36**
24.7	134	59	45.0	103	18	7.2	174	40	26.5	140	34
127	1.360	**58**	68	0.758	18	99	1.335	**67**	84	1.070	**45**
−28.3	1.636	56	4.7	0.743	**21**	−11.1	1.040	60	−2.8	0.893	42
115	1.552	85	123	1.687	54	69	1.047	**48**	79	1.180	**46**
−35.3	149	85	−26.5	132	**56**	−2.9	74	44	−6.5	85	43
110	1.921	**90**	106	1.991	60	79	1.676	**77**	85	1.740	**68**
−47.4	153	87	−25.4	106	**61**	−17.6	86	70	−18.3	89	65

wood and hardwood categories (except RPC) would be close to each other (see Fig. 7), namely, the predicted MOR values for the different wood categories of the same specific gravity may be comparable (viz. a comparable *weight-strength ratio*). But RPC is appreciably different from the other categories: when specific gravities are within the range of about 0.600,

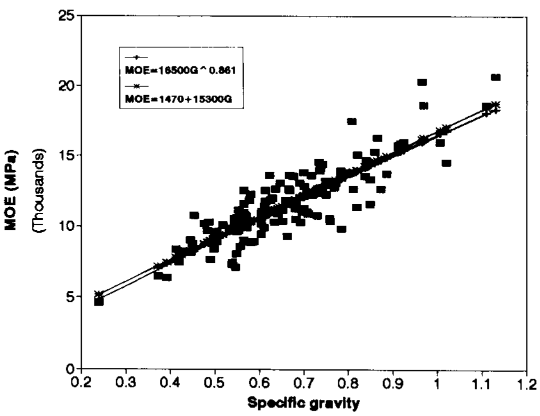

FIG. 5. MOE in relation to specific gravity in the diffuse-porous wood category (DPC) and the comparison of the curvilinear and linear equations.

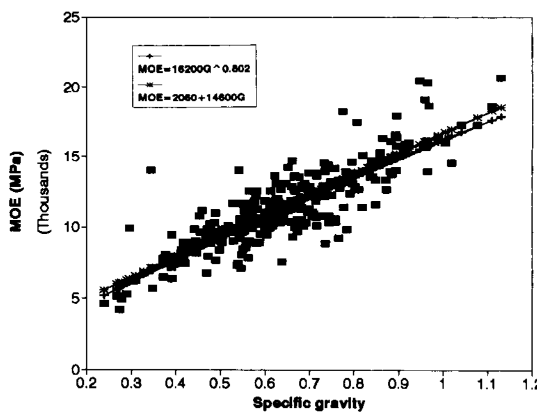

FIG. 6. MOE in relation to specific gravity in the hardwoods as a whole (HW) and the comparison of the curvilinear and linear equations.

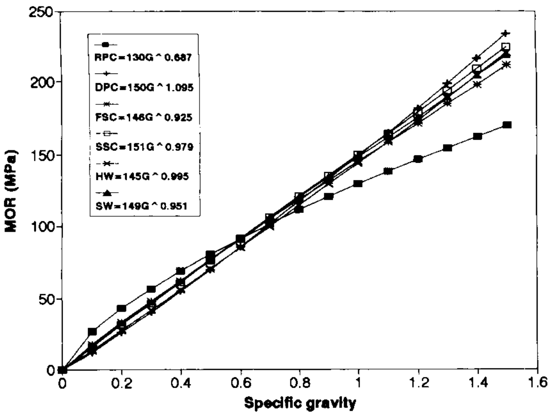

FIG. 7. The predicted MOR for the distinct wood categories.

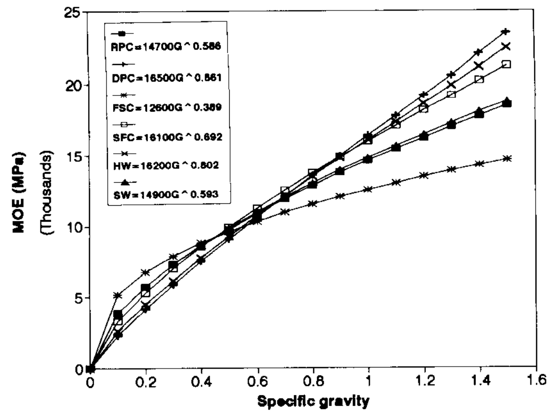

FIG. 8. The predicted MOE for the distinct wood categories.

the predicted MOR value for RPC is generally higher than those for the other categories of the same specific gravity; beyond that range it becomes lower (see Fig. 7). For MOE, the prediction curves for the individual wood categories are appreciably different. As shown in Table 1 and Fig. 8, the prediction equation for the first softwood category (MOE = $12{,}600G^{0.389}$) differs remarkably from SSC (MOE = $16{,}100G^{0.692}$) in both α and β. To a lesser extent, this holds true in two hardwood categories: RPC and DPC. Furthermore, as we noticed in MOR for RPC, the predicted MOE for a category is also related to the range of specific gravity in terms of the comparison with other categories of the same specific gravity. For instance, the predicted MOE for FSC is larger than those for the other categories within the range of 0.6000, but beyond that range MOE for this category does not increase as much as for other categories and thus becomes smaller than for other categories of the same specific gravity. Similar cases were also noticed in other mechanical properties (e.g., Cmax, MTS, MSS, MCSp, and MCSe) (figures not shown), and greater or lesser differences in the prediction curve between the individual wood categories exist. Moreover, the exponent (β) of the curvilinear equation for MOR in all the categories (except the RPC) is very close to 1 (ranging from 0.951 to 1.095), as shown in Table 1. It indicates that MOR at the category rank generally shows an almost linear relation with specific gravity (see Figs. 7 and 9). To a lesser extent, this also applies to MSS and Cmax (see Table 1 and Fig. 9); but H, MCS, and MOE have an appreciable curvilinear relation with specific gravity (see Fig. 9). As shown in Table 1, the exponents (β) of the curvilinear equations for MOE (0.389 to 0.861) and MTS (0.570 to 0.969) in all the wood categories are smaller than 1.000, while those for MCSp (1.133 to 2.072), MCSe (1.080 to 1.905), Hx (1.047 to 1.687), and Hrt (1.429 to 2.027) and T (except in FSC) are larger than 1.000. It implies that the latter mechanical properties may vary with specific gravity at a higher rate than MOE and MTS. In general, H and MCS vary with specific gravity at the highest rate among the various mechanical properties studied, next is T, followed by MSS, MOR, and Cmax, while MOE varies with specific gravity at the lowest rate, as demonstrated in Fig. 9. It should be noticed that both the changing rate and the linearity of a mechanical property with specific gravity in terms of the exponent (β) could be appreciably different between the wood categories, since the exponent (β) of the curvilinear equation for most mechanical properties is more or less different from category to category. Both MOR and Cmax in RPC, for instance, show an obvious curvilinear relation with specific gravity (β = 0.687, 0.618, respectively) although they have near linearity in other categories, and they vary with specific gravity at a slower rate (see Table 1 and Fig. 7 for MOR as an example). On the contrary, MCSe shows an appreciable curvilinear relation with specific gravity in most categories (β ranges from 1.432 to 1.905), but in RPC it tends to be linearly related to specific gravity ($\beta = 1.080$), and varies with specific gravity at a slower rate than in other categories. Table 1 also shows that compared with the two regression coefficients (α and β) of the curvilinear equation, those (a and b) of the linear equation show remarkably larger variation among the wood categories, and the intercept (a) appears to have a relatively wider range than the slope (b).

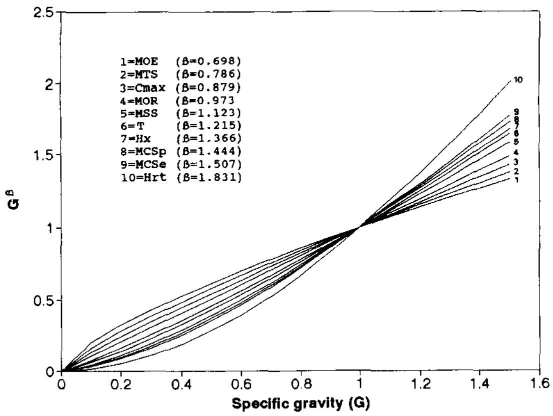

FIG. 9. The comparison of the prediction curves G^{β} (β based on the average of the softwoods and hardwoods) for various mechanical properties showing the changing rate and the linearity of individual mechanical properties with specific gravity.

Mechanical property-specific gravity relationship at generic rank

As in FSC, the linear equation in *Abies,* a genus belonging to FSC (a FSC genus), also has a slightly higher coefficient of determination than the curvilinear one (see Table 2); but it is not the case in *Picea,* another FSC genus where the curvilinear equation is able to explain a higher percentage of the variation in some mechanical properties (viz. MOE, MTS, T, and Hx). In *Larix,* a SSC genus, the curvilinear equation is better at predicting most mechanical properties, as found in SSC; but it does not hold true in *Pinus* (only including hard pines which belong to SSC), as shown in Table 2. The linear equation in the ring-porous genus *Castanopsis,* as in RPC, also has a more or less higher coefficient of determination for most mechanical properties; but it is not the case in the ring-porous genus *Quercus.* In *Eucalyptus,* a DPC genus, the curvilinear equation is able to explain more variation in some mechanical properties. In the diffuse-porous genus *Populus,* however, the linear equation appears to be able to explain more variation in most mechanical properties. If the two genera from each of the four categories studied were considered as a whole, it appears that the curvilinear equation vs. linear equation applied to the generic rank partly follows the case at the category rank. Furthermore, as we noticed at the category rank, the intercept (a) of the linear equation at generic rank is not significant in most cases as well (not shown), and this, to a lesser extent, applies to the regression coefficient b. However, it happens much less frequently to the two regression coefficients of the curvilinear equation, especially to α (see Table 2).

The relationships of mechanical properties with specific gravity at the generic rank, to some extent, vary with the genus under study (Table 2). In the diffuse-porous genus *Eucalyptus,* for instance, all the mechanical properties studied are remarkably more closely related to specific gravity than in the diffuse-porous genus *Populus.* But more often some properties in a genus are remarkably more closely related to specific gravity than in another genus of the same category, as shown in Table 2. If two genera from each category were considered as a whole, the mechanical properties in the SSC genera, unlike at the category rank, do not appear to be more closely related to specific gravity than in the FSC genera, and the mechanical properties in the two DPC genera are not remarkably more closely related to specific gravity than in the two RPC genera, either. But it appears to be true that most mechanical properties in the hardwood genera are slightly more closely related to specific gravity

TABLE 2. *The regression coefficients (α and β) and the coefficient of determination (R^2) of the curvilinear equation and the coefficient of determination (r^2) of the linear equation at generic rank.*

	FSC genus[1]				SSC genus[2]				DPC genus[3]				RPC genus[4]			
	α	β	R^2	r^2	α	β	R^2	r^2	α	β	R^2	r^2	α	β	R^2	r^2
MOR	131	0.762	36	**41**	163	1.107	64	**72**	151	1.413	72	**79**	138	0.830	75	**78**
	225	1.414	83	**85**	126	0.787	32	**34**	86	0.370	15	**18**	138	0.815	**53**	52
MOE	345	1.448	68	**73**	191	0.975	59	**66**	187	1.295	77	**83**	153	0.564	44	**47**
(×100)	306	1.388	**72**	71	126	0.432	5	**9**	149	0.677	**30**	28	160	0.370	7	7
Cmax	87	1.040	72	**75**	78	0.995	64	**69**	71	1.145	65	65	72	0.926	73	**78**
	102	1.278	69	**72**	64	0.788	54	**56**	86	0.370	15	**18**	69	1.129	69	**70**
MCSp	14.6	1.557	73	**75**	8.1	0.648	**39**	38	18.6	2.066	87	**90**	10.8	0.803	30	**35**
	11.0	1.125	35	35	6.5	0.442	12	12	8.0	0.927	23	**28**	17.8	2.375	**58**	51
MCSe	9.9	1.484	60	**62**	5.6	0.596	**14**	12	12.8	2.107	**65**	51	7.4	0.875	46	**54**
	12.2	1.857	29	**40**	4.1	0.290	2	1	4.6	0.628	9	**11**	11.8	2.045	**55**	54
MSS	17.7	1.400	27	**31**	11.7	0.706	**28**	19	15.4	0.811	**64**	62	13.8	0.791	46	**55**
	7.6	0.281	3	**5**	8.9	0.293	3	**7**	11.3	0.588	**25**	32	16.8	0.964	**42**	40
MTS	146	0.561	6	**7**	201	1.157	**61**	51	149	1.267	66	**72**	142	0.702	36	**42**
	373	1.715	**82**	78	149	0.683	**16**	15	99	0.202	3	**4**	136	−0.044	0	0
T	106	1.244	35	**37**	69	0.781	**61**	56	164	2.539	**71**	68	162	1.792	66	**73**
	193	2.053	**66**	65	78	1.008	41	**46**	205	1.740	24	**35**	132	0.847	18	**23**
Hx	249	2.454	80	**81**	43	0.287	**5**	2	104	1.361	**76**	72	85	1.100	60	**70**
	95	1.499	**48**	45	67	1.170	**46**	43	47	0.561	14	**19**	114	1.751	69	**70**
Hrt	176	2.644	79	**83**	48	1.038	**29**	26	109	2.000	**88**	87	100	1.877	**91**	89
	39	0.856	15	**16**	79	1.708	**73**	71	45	0.943	20	**26**	106	2.052	**87**	85

[1] The first-row and second-row results of each mechanical property were based on the FSC genera *Abies* and *Picea*, respectively.
[2] The first-row and second-row results were based on the SSC genera *Larix* and *Pinus* (hard pines only), respectively.
[3] The first-row and second-row results were based on the DPC genera *Eucalyptus* and *Populus*, respectively.
[4] The first-row and second-row results were based on the SSC genera *Castanopsis* and *Quercus*, respectively.

than in the softwood genera (Table 2), as we found at the category rank. Comparing Table 2 with Table 1, it appears that the relationships of most mechanical properties with specific gravity in the SSC genera and DPC genera are not as close as those in the respective categories, but it does not apply to other genera. As a whole, H, MOR, and Cmax at generic rank appear most closely related to specific gravity, while MSS at the softwood generic rank and MTS at the hardwood generic rank are the least related to specific gravity.

As shown in Table 2, the two regression coefficients (α and β) of the curvilinear equation for individual wood mechanical properties at generic rank show an appreciably wider range than at the category rank. For instance, the regression coefficients α and β for MOR at generic rank range from 86 to 225, and 0.370 to 1.414, respectively. This indicates that the predicted mechanical property values for the genera of the same specific gravity from different wood categories may be more different than at the category rank. Even for genera of the same category, they may still be appreciably different, as indicated by distinct regression coefficients (Table 2). The exponent (β) of the curvilinear equation for Cmax in most genera studied is still close to 1.000, but this does not apply to MOR and MSS. As shown in Table 2, the exponent (β) for MSS is smaller than 1.000 in most genera, and for MOR it could be smaller than 1.000 in some genera (e.g., *Abies, Castanopsis, Populus,* and *Quercus*), but it could be larger than 1.000 in other genera (e.g., *Eucalyptus* and *Picea*). This case also applies to other mechanical properties studied. Therefore, the relationships of most mechanical properties with specific gravity at generic rank vary in terms of the linearity, depending on the taxon under study.

Mechanical property-specific gravity relationship at species rank

For the species from FSC (FSC species), the linear equation is not better at all even in terms of the coefficient of determination (Table 3). On the contrary, the curvilinear equation is significantly better at predicting most mechanical properties, which is obviously different from the case at the category and generic ranks. The same applies to the SSC species where almost all the mechanical properties are better predicted by the curvilinear equation. At the RPC species rank, unlike at higher ranks, the curvilinear equation also appears to be better at predicting most mechanical properties, and this, to a lesser extent, applies to the DPC species rank. Therefore, at species rank the curvilinear equation is generally better than the linear one at predicting mechanical properties in terms of the coefficient of determination. Furthermore, we also noticed that the intercept (a) of the linear equation at species rank was not significant in most cases as well, and this, to a lesser extent, applies to the regression coefficient b (not shown). It, however, happens appreciably less frequently to the two regression coefficients (α and β) of the curvilinear equation.

As shown in Table 3, the relationships of mechanical properties with specific gravity at species rank also vary with the taxon under study, as noticed at the generic rank. For instance, most mechanical properties in one SSC species (*Cunninghamia lanceolata*) are obviously more closely related to specific gravity than in another SSC species (*Pinus massoniana*). A similar case also exists in the FSC species. As a whole, the mechanical properties at the SSC species rank do not appear to be more related to specific gravity than at the FSC species rank. However, the relationships of mechanical properties with specific gravity at the DPC species rank are appreciably closer than at the RPC species rank, and they are more or less comparable with those at the generic or higher ranks. But the relationships at the RPC species rank are remarkably lower than those at higher ranks. A similar case exists at the softwood species rank where some mechanical properties are poorly related to specific gravity. But it still holds true that the mechanical properties at the hardwood species rank are generally more closely related to specific gravity than at the softwood species rank.

TABLE 3. *Regression coefficients (α and β) and the coefficient of determination (R^2) of the curvilinear equation and the coefficient of determination (r^2) of the linear equation at species rank.*

	FSC species[1]				SSC species[2]				DPC species[3]				RPC species[4]			
	α	β	R^2	r^2	α	β	R^2	r^2	α	β	R^2	r^2	α	β	R^2	r^2
MOR	141	1.027	**38**	33	274	1.467	**49**	47	137	1.098	72	**75**	176	1.318	**65**	64
	223	1.387	**96**	95	106	0.397	**6**	3	155	1.085	**74**	71	131	0.842	**22**	20
MOE	303	1.493	49	**52**	199	0.808	23	**24**	174	1.104	58	**65**	178	0.955	33	**34**
(×100)	331	1.470	**83**	81	179	0.730	**21**	14	210	1.103	**49**	44	160	0.891	13	**18**
Cmax	101	1.390	20	22	90	0.947	**51**	48	70	1.022	73	73	69	0.943	21	**27**
	110	1.338	**93**	92	69	0.838	**18**	11	74	1.009	**55**	54	62	0.472	**6**	4
MCSp	4.3	0.085	0	0	11.5	1.244	**41**	38	15.5	1.659	84	**86**	10.7	0.860	11	11
	8.8	0.816	**31**	24	6.9	0.575	7	5	10.2	1.063	**43**	42	14.6	1.316	**10**	6
MCSe	6.3	1.089	21	**24**	15.6	2.009	**34**	31	9.8	1.367	78	**80**	9.9	1.312	24	24
	6.3	0.863	**43**	39	9.3	1.516	**29**	21	10.3	1.123	**50**	48	9.2	0.495	3	2
MSS	19.4	1.618	**13**	11	7.5	0.335	2	2	16.6	1.062	**74**	72	10.9	0.398	**5**	4
	7.4	0.218	3	3	12.0	0.621	**23**	18	16.8	1.580	**72**	71	18.3	1.569	54	54
MTS	156	0.716	**20**	17	200	1.017	**50**	49	158	1.192	53	**59**	101	0.257	1	1
	451	1.949	78	78	156	0.784	**16**	8	153	0.720	**34**	29	152	0.262	3	3
T	174	1.988	**51**	48	99	1.385	**28**	25	185	2.163	**42**	36	189	2.223	**38**	37
	191	2.047	**84**	60	84	1.009	**11**	3	284	2.018	**38**	36	59	−2.657	**14**	8
Hx	66	1.302	57	**61**	69	0.963	**35**	32	91	1.024	**71**	67	97	1.489	50	**51**
	90	1.442	**65**	43	52	0.734	**14**	10	61	0.872	**37**	35	105	1.630	**50**	44
Hrt	81	1.948	39	**43**	53	1.214	**52**	50	94	1.701	74	**76**	109	2.064	**75**	74
	43	1.004	**42**	34	45	0.810	**39**	32	92	1.778	**73**	70	106	2.100	**62**	55

[1] The first-row and second-row results of each mechanical property were based on the FSC *Pinus armandi* (a soft pine) and *Picea* species (*P. asperata* and *P. purpurea*), respectively.
[2] The first-row and second-row results were based on the SSC species *Cunninghamia lanceolata* and *Pinus massoniana* (a hard pine), respectively.
[3] The first-row and second-row results were based on the DPC *Eucalyptus* species (*E. globus* and *E. robusta*) and *Populus* species (*P. davidiana* and *P. tomentosa*), respectively.
[4] The first-row and second-row results were based on the SSC *Castanopsis* species (*C. fargesii* and *C. sclerophylla*) and *Quercus* species (*Q. acutissima* and *Q. variabilis*), respectively.

As a whole, H, MOR, and Cmax appear most closely related to specific gravity at the species rank, while MSS at the softwood species rank and MTS at the hardwood species rank are the least related to specific gravity, as we noticed at the generic rank.

Comparing Table 3 with Tables 1 and 2, the two regression coefficients (α and β) of the curvilinear equation for individual mechanical properties at the species rank also show an appreciably wider range than at the category rank, and they are usually (more or less) different from those at the generic rank as well. As shown in Table 3, the differences in the two coefficients of the regression equations for some mechanical properties between some species are quite large. It implies that the predicted *weight-strength ratios* for some species may be quite different. However, the regression coefficients of different species from the same category generally appear closer than those of the species from different categories although the differences in the two regression coefficients of different species from the same category still could be large. Furthermore, the relationships of mechanical properties with specific gravity in terms of the linearity also vary with individual mechanical properties as well as the species under study. For instance, MOR, Cmax, and MOE are almost linearly related to specific gravity only at the DPC species rank, but the linear relationship does not exist in other mechanical properties (e.g., T and Hrt). Moreover, the exponent (β) of the curvilinear equation is appreciably more frequently not significant than the regression coefficient α, as we noticed at the generic rank.

DISCUSSION

The curvilinear equation established by Newlin and Wilson (1919) was based on the results of tests on mixed softwoods and hardwoods. Liska (1965) followed the same treatment, but he found that the curvilinear equation does not differ appreciably in the goodness from the linear one. However, the present study indicates that the differences in the mechanical property-specific gravity relationship among the five wood categories are quite remarkable, and the goodness of the curvilinear and linear equations at describing the relationships in the individual categories is also appreciably different. Therefore, grouping timbers by the wood categories for developing mechanical property-specific gravity regressions appears to be preferable. A similar statement was also made by Armstrong et al. (1984), and they even suggest grouping timbers by genera. This is largely supported by the present study.

The present study clearly indicates that the curvilinear equation is better than the linear one at predicting mechanical properties at species rank in terms of both the coefficient of determination and the regression coefficients. Liska (1965) and Forest Products Laboratory (1987) believed that specific gravity and mechanical properties within a species show a linear relationship rather than a curvilinear one; and a significant linear relationship was reported in many studies (Kellogg and Ifju 1962; Liska 1965; Ifju 1969; Pearson and Gilmore 1971; Manwiller 1972; Bendtsen and Ethington 1972; Schniewind and Gammon 1983; Pearson 1988; Shepard and Shottafer 1992; Zhang and Zhong 1992). But a poor linear relationship between specific gravity and some mechanical properties was also noticed by some authors (McAlister 1976; Leclercq 1980; Schniewind and Gammon 1983; Hunt et al. 1989). In general, very few studies have compared the linear equation with the curvilinear one in terms of the goodness at predicting mechanical properties through specific gravity. Liska (1965) reported that a straight-line relationship between specific gravity and four mechanical properties in Douglas-fir was justified; but a few studies (Biblis 1969a, b; Biblis and Fitzgerald 1970) also found that a curvilinear equation was better than the linear one at describing the relationships of mechanical properties with specific gravity. It should be remembered that the relationships at species rank presented in this study, unlike most studies reported before, were established on the basis of the shipment averages rather than the results of individual specimens. We thus wonder whether there are appreciable differences in the mechanical property-specific gravity relationship at species rank based on the two different data sources, which will be explored in a subsequent study (Zhang 1994a). In addition, more species should be investigated in order to get a general conclusion on the mechanical property-specific gravity relationship at species rank because the present study indicates that the relationships at species rank, to some extent, vary with the species under study.

It appears difficult to understand a closer mechanical property-specific gravity relationship in the hardwoods as a whole (HW) than in the softwoods (SW) if the more complex structure of hardwoods is considered. However, a remarkably wider range of specific gravities in the hardwoods (roughly ranging from 0.2 to 1.2, see Fig. 3) than in the softwoods (roughly from 0.3 to 0.7, see Fig. 1) may be one contributing factor. In addition, the large variation in the amount of resin among the softwoods studied might be another factor because it, like extractives, adds weight (or specific gravity), but does not modify mechanical strength appreciably (Zhang and Zhong 1992). A closer mechanical property-specific gravity relationship in the diffuse-porous wood category than in the ring-porous wood category appears reasonable in the sense of the more uniform structure in the diffuse-porous woods. However, the appreciable differences in the relationship between the two softwood categories remain to be explored. An appreciably poorer relationship at species rank probably results from the fact that in the present study the mechanical property-specific gravity relationship in individual species was based on the shipment averages, and each test was based on the trees from one of a wide range of the localities throughout the distribution areas. If the study had been based on the results of individual specimens from the same locality, a closer relationship at species rank would have been expected.

CONCLUSIONS

In light of this study on the 342 Chinese woods, it is rational to conclude:

1. The relationships of mechanical properties with specific gravity vary remarkably with the taxonomic rank, the wood category, and wood mechanical property.
   a) In general, most mechanical properties at species rank are appreciably less related to specific gravity than at higher ranks. However, the relationships of mechanical properties with specific gravity at generic rank are partly comparable with those at higher ranks.
   b) Most mechanical properties in the second softwood category appear to be more closely related to specific gravity than in the first softwood category, but this does not hold true at lower ranks. In the ring-porous wood category, they are generally less related to specific gravity than in the diffuse-porous wood category, and this holds true at species rank, but not at generic rank. If the softwoods studied were considered as a whole, mechanical properties in the hardwoods as a whole are generally more closely related to specific gravity, and this applies more or less to the lower ranks as well.
   c) Among various mechanical properties studied, H, MOR, and Cmax at all ranks studied appear most closely related to specific gravity; but MOE and MTS in the softwoods as a whole and T and MTS in the hardwoods as a whole are the least related to specific gravity. This holds true at the category rank, but not at lower ranks where MSS (softwoods) and MTS (hardwoods) appear least related to specific gravity.
2. The goodness of the curvilinear equation and linear equation in terms of the coefficient of determination also varies appreciably with the taxonomic rank, the wood category, and wood mechanical properties. As a whole, however, the curvilinear equa-

tion appears better at predicting most mechanical properties, particularly at species rank.

3. Prediction curves (or the predicted *weight-strength ratios*) for the distinct wood categories are usually (except for MOR) different more or less, and this applies to the lower ranks. Further, the predicted *weight-strength ratio* for a wood category in terms of the comparison with other categories is related to the range of specific gravity (with a turning point at about 0.6000). Moreover, the prediction equation for MOR, MSS, and Cmax at the category or higher rank tends to be linear, but this does not apply to other mechanical properties and lower ranks. In general, H and MCS at the category or higher rank vary with specific gravity at the highest rate among the mechanical properties studied, next is T, followed by MSS, MOR, and Cmax, while MOE varies with specific gravity at the lowest rate. This, however, does not appear to be true at lower ranks. Between the two regression coefficients (α and β), the exponent (β) appears to be more frequently not significant at species and generic ranks, but both of them are remarkably less frequently not significant as compared with those of the linear equation.

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