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Structure-property relationship of wood in East-Liaoning oak *

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Summary. Relationships between various anatomical parameters and selected physico-mechanical properties of wood were examined statistically in East-Liaoning Oak. Path analysis revealed that the key anatomical factors influencing wood shrinkage vary with the type of shrinkage: both radial and tangential shrinkage are mainly controlled by fiber diameter, differential shrinkage mainly by microfibrillar angle and volumetric shrinkage by tissue proportions; specific gravity is determined directly by percentage of cell wall material, while the percentage, in turn, is closely related to tissue proportions, among which vessel proportion is the most important; tensile strength is closely related to microfibrillar angle and specific gravity is not always a good estimator of strength.

Introduction

It has been shown by many investigators that wood property is closely related to its structure (Ifju 1983), and the many and varied useful properties of wood arise from its cellular characters (Bamber 1981). There is an increasing awareness that understanding of the behavior of wood is to be obtained from the study of its structure and composition, and it is particularly important to understand the anatomical cause of variable structural performance of wood (Boyd 1982). Relationship between structure and property has been of interest to wood scientists for some time (Berry et al. 1983). During recent decades, many anatomical studies on wood properties have been carried out, and a few papers (Dinwoodie 1975; Hillis 1989; Ifju et al. 1978) reviewed the relationships. In general, however, anatomical characters studied are usually limited. In some cases, only few anatomical parameters were studied in relation to properties. A detailed analysis of wood structure has been considered necessary to explain wood properties in the best way (Leclecq 1980). In the present paper, various anatomical parameters were studied in detail in East-Liaoning Oak to evaluate statistically the relationships of various anatomical parameters and selected physico-mechanical properties, and an attempt was made to find out the key anatomical parame-

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ters influencing the physico-mechanical properties. Special discussion has been given to specific gravity as an estimator of wood properties.

Materials and methods

Five dominant trees of East-Liaoning Oak (*Quercus liaotungensis* Koidz.) were selected from Zhongtiao Forests, Sauxi. One 20 cm thick disc was removed at breast height from each tree. One radial segment from pith to bark, 1 cm wide tangentially, 20 cm high longitudinally, was selected from each 20 cm thick disc. From each of the five 20 cm high radius segments, then, four radial segments of different heights, 6 cm, 6 cm, 2 cm and 2 cm high, were removed. First two 6 cm high segments were used for testing tensile strength, the third one for anatomical studies and the last for specific gravity and shrinkage studies.

Small ring specimens for structure and property studies, each containing one growth ring of different age, were taken from the pith of each radius outward at intervals of three growth rings. Specimens for determination of specific gravity and shrinkage are 1.5 cm longitudinally, 1 cm tangentially, growth ring width radially; specimens for tensile strength are 6 cm longitudinally, 1 cm tangentially, growth ring width radially and specimens for anatomical studies is 2 cm longitudinally, 1 cm tangentially and a little larger than growth ring width radially.

Small ring specimens for anatomical studies were softened for sectioning. Temporary transverse sections and maceration slides were prepared for microscopic examination. Thirty measurements of radial and tangential diameter of vessels were made on transverse sections, and thirty fibers on maceration slides were measured to determine average length and diameter. Thirty fibers were randomly selected in each growth ring for the measurement of microfibrillar angle of the S_2 layer of wood fibers by polarized light microscopy (Leney 1981). Measurements of tissue proportions were made according to the Dot-grid integrating eyepiece technique (Quirk 1975).

The specific gravity of the small ring specimens was based on an oven-dry weight/green volume (Zhang, Zhong 1991). The determination of shrinkage coefficients (radial, tangential, differential and volumetric), combined with specific gravity determination, is based on the change from air-dry volume to oven-dry volume.

An Instron Testing Machine was used for testing the tensile strength of small ring specimens. Each small specimen was securely gripped with special jaws at a span of 4 cm. The force upon the specimens is measured to 0.1 kg. One block was sampled immediately at one end of each small tensile specimen for determination of moisture content after failure was developed.

The correlation coefficient provides a measure of association. But correlation coefficients between different anatomical parameters and physico-mechanical properties usually can not be used to properly evaluate the importance of different anatomical parameters in controlling wood properties since there are high correlations between certain anatomical parameters themselves (Giraud 1980), fiber length and microfibrillar angle, for instance. Partial regression coefficient is one of the most important indexes with which to judge the influence of cause factor X_i upon effect factor Y. However, partial regression coefficients, $B_1, B_2, \ldots, B_n$, are related to the unite of the factors. They, therefore, can not be used for the comparison of the influences of $X_1, X_2, \ldots, X_n$ upon Y, neither. Path coefficients are just ones where the influence of the unite is eliminated. Thus path analysis, as the first author (Zhang 1986) pointed out, is a useful tool to evaluate the relationships between structure and property.

Path coefficients, as a matter of fact, are standardized partial regression coefficients (P_{yi}):

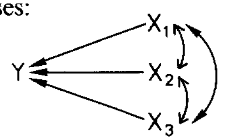
$$P_{yi} = B_i \frac{S_{xi}}{S_y}$$

Where: P_{yi} = the path coefficient for the path from X_i to Y; B_i = partial regression coefficient of X_i and Y; S_{xi}, S_y = standard deviations of X_i and Y;

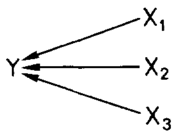
Path coefficients can be presented in matrix notations as:

$$\begin{pmatrix} r_{11} \cdots\cdots r_{1n} \\ \cdots\cdots\cdots\cdots \\ r_{n1} \cdots\cdots r_{nn} \end{pmatrix} \begin{pmatrix} p_{y1} \\ \vdots \\ p_{yn} \end{pmatrix} = \begin{pmatrix} r_{y1} \\ \vdots \\ r_{yn} \end{pmatrix}$$

There are causal and parallel relations between two factors or more if these factors are discussed from a causal point of view. Further, for parallel relation there are also two cases:



Variables X_1, X_2 and X_3 are correlated



Variables X_1, X_2 and X_3 are independent

Where "$\leftarrow$" is called path line, and "$\curvearrowright$" is called correlation line.

Path coefficient P_{yi} reflects direct influence of X_i upon Y, also called direct path coefficient therefore. X_i, as shown above, is probably correlated with other variables X_j ($j = 1, \ldots i-1, i+1, \ldots, n$). Therefore the correlation coefficient between X_i and Y may include more or less influences of the other variables X_j upon Y. The influence is regarded as indirect influence in path analysis, expressed by indirect path coefficients (I):

$$I = r_{ij} * P_{jy}.$$

Where: I = the indirect path coefficient for the path from cause factor $X_i \rightarrow X_j \rightarrow Y$;
r_{ij} = correlation coefficient of X_i and X_j;
P_{jy} = the direct path coefficient for the path from $X_j \rightarrow Y$;

With direct and indirect path coefficients of all variables upon Y, thus, it is possible to discuss the influences of various causal factors X_i upon effect factor Y.

Results and discussion

Table 1 lists the correlation coefficients between 18 anatomical, physical, and mechanical parameters studied. More than half of them listed reaches the significant level. It

Table 1. Correlation coefficients between 18 parameters studied[a]

Y_1	1.0000																	
Y_2	0.4628	1.0000																
Y_3	−0.7989	−0.3535	1.0000															
Y_4	0.7608	0.4943	−0.7256	1.0000														
Y_5	−0.7191	−0.5470	0.8644	−0.6067	1.0000													
Y_6	−0.6835	−0.6516	0.7506	−0.7783	0.7936	1.0000												
X_1	−0.5997	−0.7008	0.7280	−0.6328	0.8991	0.7940	1.0000											
X_2	−0.6136	−0.6826	0.3305	−0.5847	0.3218	0.6699	0.3910	1.0000										
X_3	0.7136	0.6858	−0.6705	0.7582	−0.5898	−0.8488	−0.6036	−0.8685	1.0000									
X_4	−0.2567	−0.2272	0.6624	−0.3482	0.7846	0.5367	0.7244	−0.1474	−0.1807	1.0000								
X_5	0.4116	0.5516	−0.6887	0.3969	−0.8516	−0.6753	−0.7809	−0.2361	0.4938	−0.8381	1.0000							
X_6	−0.0121	−0.1023	−0.3915	0.0369	−0.5401	−0.1908	−0.4784	0.5359	−0.2358	−0.8640	0.5040	1.0000						
X_7	−0.4435	−0.3681	0.7445	−0.4203	0.8958	0.5848	0.8195	−0.0240	−0.2881	0.8997	−0.7896	−0.7915	1.0000					
X_8	−0.1347	−0.2976	0.0620	−0.2238	0.1011	0.2598	0.2846	0.5530	−0.4513	−0.0054	−0.1075	0.2241	0.0094	1.0000				
X_9	−0.2325	−0.3600	−0.1143	−0.3531	−0.2014	−0.0414	−0.2402	0.5112	−0.3663	−0.6410	0.2060	0.8127	−0.4446	−0.0193	1.0000			
X_{10}	−0.5885	−0.6346	0.4420	−0.4799	0.5408	0.6743	0.5790	0.7449	−0.7251	0.1253	−0.3461	0.1111	0.3248	0.4426	0.2622	1.0000		
X_{11}	−0.6481	−0.6414	0.3174	−0.0732	0.2593	0.5433	0.3058	0.9599	−0.8175	−0.2498	0.1714	0.6351	−0.1074	0.4850	0.6189	0.6200	1.0000	
X_{12}	0.6311	0.7476	−0.2890	0.5249	−0.3365	−0.5520	−0.3844	−0.9363	0.7742	0.1546	0.2383	−0.5254	−0.0040	−0.5248	−0.5660	−0.6748	0.9598	1.0000

Critical values for significant level } =0.4555 (significant at 0.05 level); =0.5751 (significant at 0.01 level)

[a] From Table 1 to Table 9: Y_1 = radial shrinkage; Y_2 = tangential shrinkage; Y_3 = differential shrinkage; Y_4 = volumetric shrinkage; Y_5 = specific gravity; Y_6 = tensile strength; X_1 = fiber length; X_2 = fiber diameter; X_3 = microfibrillar angle; X_4 = fiber proportion; X_5 = parenchyma proportion; X_6 = vessel proportion; X_7 = percentage of cell wall material; X_8 = narrow ray proportion; X_9 = wide ray proportion; X_{10} = ray height; X_{11} = tangential diameter of earlywood vessels; X_{12} = vessel frequency in earlywood

Table 2. Path analysis of radial shrinkage Y_1

	$X_1 \to Y_1$	$X_2 \to Y_1$	$X_3 \to Y_1$	$X_4 \to Y_1$	$X_5 \to Y_1$	$X_6 \to Y_1$	$X_{10} \to Y_1$
$X_1 \to$	−0.0099	−0.3324	−0.1069	0.0834	0.1021	−0.3113	−0.0247
$X_2 \to$	−0.0039	−0.8502	−0.1539	−0.0170	0.0309	0.3487	0.0317
$X_3 \to$	0.0060	0.7384	0.1771	−0.0208	−0.0646	−0.1534	0.0309
$X_4 \to$	−0.0072	0.1253	−0.0320	0.1151	0.1096	−0.5621	−0.0653
$X_5 \to$	0.0077	0.2007	0.0875	−0.0964	−0.1307	0.3281	0.0147
$X_6 \to$	0.0047	−0.4556	−0.0418	−0.0994	−0.0659	0.6506	−0.0047
$X_{10} \to$	−0.0057	0.6333	−0.1284	0.0144	0.0452	0.0723	−0.0426

can be noticed that some correlation coefficients can not reflect real relationships between these parameters. The best example is the one between specific gravity and microfibrillar angle (−0.5898), which is significant at the 0.01 level. The main cause may be that some anatomical parameters (such as fiber length and diameter) affecting specific gravity are correlated to microfibrillar angle. Therefore it is necessary to adopt path analysis.

Shrinkage

Several anatomical parameters were selected for path analysis (Table 2). The direct path coefficients for the paths from the factors to radial shrinkage are −0.8502 (fiber diameter), 0.6506 (vessel proportion), 0.1771 (microfibrillar angle), −0.1307 (parenchyma proportion), 0.1151 (fiber proportion), −0.0426 (ray height) and −0.0099 (fiber length) in sequence. This indicates that the most important factor influencing radial shrinkage is fiber diameter. The next is vessel proportion. The remaining factors show few effects. As seen in Table 1, the correlation coefficient between microfibrillar angle and radial shrinkage is the highest one (0.7136), while the direct path coefficient from $X_3 \to Y$ is very low (0.1771). Further it is known from the path analysis (Table 2) that the indirect path coefficient for the path from microfibrillar angle → fiber diameter → radial shrinkage, or $X_3 \to X_2 \to Y_1$, is as high as 0.7384. This indicates that the correlation coefficient between microfibrillar angle and radial shrinkage includes a large indirect influence of fiber diameter upon radial shrinkage. Therefore the correlation coefficient between microfibrillar angle and radial shrinkage, or the importance of microfibrillar angle in affecting radial shrinkage, is exaggerated.

Table 3 showed that the most important anatomical parameter affecting tangential shrinkage is also fiber diameter (−0.9103). The following are fiber proportion (−0.7641), microfibrillar angle (−0.6027), fiber length (−0.5801), parenchyma proportion (0.5516), vessel proportion (0.3023) and ray height (−0.0481) respectively.

The key anatomical parameter for differential shrinkage is microfibrillar angle (−0.8056) (Table 4). In addition, fiber proportion (0.4771) and vessel proportion (−0.3730) also show some effects on it.

The major factors controlling volumetric shrinkage are fiber proportion (−2.0962), parenchyma proportion (−1.3455) and vessel proportion (−1.1329), in one word, tissue proportions (Table 5).

Table 3. Path analysis of tangential shrinkage Y_2

	$X_1 \rightarrow Y_2$	$X_2 \rightarrow Y_2$	$X_3 \rightarrow Y_2$	$X_4 \rightarrow Y_2$	$X_5 \rightarrow Y_2$	$X_6 \rightarrow Y_2$	$X_{10} \rightarrow Y_2$
$X_1 \rightarrow$	−0.5801	−0.3559	0.3638	0.5535	−0.5096	−0.1446	−0.0278
$X_2 \rightarrow$	−0.2268	−0.9103	0.5234	−0.1126	−0.1541	0.1620	0.0358
$X_3 \rightarrow$	0.3502	0.7906	−0.6027	−0.1381	0.3222	−0.0713	0.0348
$X_4 \rightarrow$	−0.4202	0.1342	0.1089	−0.7641	−0.5469	−0.2612	−0.0060
$X_5 \rightarrow$	0.4530	0.2149	−0.2976	−0.6404	0.5516	0.1524	0.0166
$X_6 \rightarrow$	0.2775	−0.4878	0.1421	−0.6601	0.3291	0.3023	−0.0053
$X_{10} \rightarrow$	−0.3359	0.6781	0.4370	0.0957	−0.2258	0.0336	−0.0481

Table 4. Path analysis of differential shrinkage Y_3

	$X_1 \rightarrow Y_3$	$X_2 \rightarrow Y_3$	$X_3 \rightarrow Y_3$	$X_4 \rightarrow Y_3$	$X_5 \rightarrow Y_3$	$X_6 \rightarrow Y_3$	$X_{10} \rightarrow Y_3$
$X_1 \rightarrow$	−0.1814	0.0166	0.4863	0.3456	−0.1394	0.1784	0.0220
$X_2 \rightarrow$	−0.0709	0.0424	0.6997	−0.0703	−0.0421	−0.1999	−0.0282
$X_3 \rightarrow$	0.1095	−0.0368	−0.8056	−0.0862	0.0881	0.0880	−0.0275
$X_4 \rightarrow$	−0.1314	−0.0062	0.1456	0.4771	−0.1496	0.3221	0.0048
$X_5 \rightarrow$	0.1417	−0.0100	−0.3978	−0.3998	0.1785	−0.1881	−0.0131
$X_6 \rightarrow$	0.0868	0.0227	0.1900	−0.4122	0.0900	−0.3730	0.0042
$X_{10} \rightarrow$	−0.1051	−0.0316	0.5841	0.0598	−0.0618	−0.0414	0.0376

Table 5. Path analysis of volumetric shrinkage Y_4

	$X_1 \rightarrow Y_4$	$X_2 \rightarrow Y_4$	$X_3 \rightarrow Y_4$	$X_4 \rightarrow Y_4$	$X_5 \rightarrow Y_4$	$X_6 \rightarrow Y_4$	$X_{10} \rightarrow Y_4$
$X_1 \rightarrow$	−0.3803	−0.0202	−0.2929	−1.5185	1.0507	0.5420	−0.0136
$X_2 \rightarrow$	−0.1487	−0.0517	−0.4214	0.3090	0.3177	−0.6071	0.0175
$X_3 \rightarrow$	0.2296	0.0449	0.4852	0.3788	−0.6644	0.2671	0.0171
$X_4 \rightarrow$	−0.2755	0.0076	−0.0877	−2.0962	1.1277	0.9788	−0.0076
$X_5 \rightarrow$	0.2970	0.0122	0.2396	1.7568	−1.3455	−0.5713	0.0083
$X_6 \rightarrow$	0.1819	−0.0277	−0.1144	1.8111	−0.6786	−1.1329	−0.0026
$X_{10} \rightarrow$	−0.2202	0.0385	−0.3518	−0.2627	0.4657	−0.1259	−0.0235

Shrinkage is an important index of dimensional stability of wood and wood products (Panshin, de Zeeuw 1980). Some studies on wood shrinkage in relation to its structure by Boyd (1977), Ellwood (1962) and Zhou (1963) found that tracheid diameter and wall thickness show remarkable effects on radial and tangential shrinkage of wood. Differential shrinkage of wood is complex, and many explanations were proposed (Cheng 1980; Quirk 1984; Panshin, de Zeeuw 1980).

Some investigators thought that differing microfibrillar angle in the radial and tangential walls is the key cause of differential shrinkage of wood. Cheng (1980) and Panshin & de Zeeuw (1980) reported that volumetric shrinkage is directly related to the amount of cell wall material, which, in turn, is mainly controlled by tissue proportions, as revealed in Table 7. So it is easily understood that tissue proportions are the major factors controlling volumetric shrinkage.

Table 6. Path analysis of specific gravity Y_5 (1)

	$X_1 \to Y_5$	$X_2 \to Y_5$	$X_4 \to Y_5$	$X_5 \to Y_5$	$X_6 \to Y_5$
$X_1 \to$	0.2959	0.1656	−0.3672	0.4284	0.3764
$X_2 \to$	0.1157	0.4234	0.0747	0.1295	−0.4216
$X_4 \to$	0.2144	−0.0624	−0.5069	0.4597	0.6798
$X_5 \to$	−0.2311	−0.1000	0.4248	−0.5486	−0.3968
$X_6 \to$	−0.1416	0.2270	0.4379	−0.2766	−0.7868

Table 7. Path analysis of percentage of cell wall material Y_7

	$X_1 \to Y_7$	$X_2 \to Y_7$	$X_4 \to Y_7$	$X_5 \to Y_7$	$X_6 \to Y_7$
$X_1 \to$	0.3176	0.0577	−0.1476	0.2370	0.3548
$X_2 \to$	0.1242	0.1476	0.0300	0.0717	−0.3974
$X_4 \to$	0.2301	−0.0217	−0.2037	0.2544	0.6407
$X_5 \to$	−0.2480	−0.0348	0.1707	−0.3035	−0.3740
$X_6 \to$	−0.1519	0.0791	0.1760	−0.1531	−0.7416

Table 8. Path analysis of specific gravity Y_5 (2)

	$X_1 \to Y_5$	$X_2 \to Y_5$	$X_4 \to Y_5$	$X_5 \to Y_5$	$X_6 \to Y_5$	$X_7 \to Y_5$
$X_1 \to$	0.0938	0.1289	−0.2732	0.2775	0.1506	0.5216
$X_2 \to$	0.0367	0.3296	0.0556	0.0839	−0.1687	−0.0153
$X_4 \to$	0.0679	−0.0486	−0.3772	0.2979	0.2720	0.5726
$X_5 \to$	−0.0732	−0.0778	0.3161	−0.3554	−0.1588	−0.5025
$X_6 \to$	−0.0449	0.1766	0.3259	−0.1792	−0.3148	−0.5037
$X_7 \to$	0.0768	0.0079	−0.3394	0.2806	0.2496	0.6364

Specific gravity

As shown in Table 6, tissue proportions are key anatomical factors controlling specific gravity of wood, among which vessel proportion is of the greatest importance to specific gravity (−0.7868). If anatomical factors effecting percentage of cell wall material were studied in Table 7, it was found that like specific gravity, tissue proportions are also the major factors influencing percentage of cell wall material, among which vessel proportion is the most important one (−0.7416). If percentage of cell wall material is considered as an anatomical factor in path analysis, together with tissue proportions in Table 8, the most important factor effecting specific gravity, as expected, is percentage of cell wall material rather than tissue proportions. It is known that the direct path coefficients for the paths from tissue proportions to specific gravity in Table 8 are apparently lower than those in Table 6, while indirect path coefficients for the paths from tissue proportions (X_4, X_5 and X_6) → percentage of cell wall material (X_7) → specific gravity (Y_5) are all high (0.5726, −0.5025 and −0.5037 respectively). This indicates that percentage of cell wall material is the direct

Table 9. Path analysis of tensile strength Y_6

	$X_1 \rightarrow Y_6$	$X_2 \rightarrow Y_6$	$X_3 \rightarrow Y_6$	$X_4 \rightarrow Y_6$	$X_5 \rightarrow Y_6$	$X_6 \rightarrow Y_6$
$X_1 \rightarrow$	0.1969	−0.1704	0.5221	0.1989	−0.0906	0.1370
$X_2 \rightarrow$	−0.1189	−0.2079	0.2492	0.2470	−0.0916	0.2267
$X_3 \rightarrow$	0.1427	0.0599	−0.8651	−0.0496	0.0753	0.0675
$X_4 \rightarrow$	−0.1538	−0.1871	0.1563	0.2746	−0.0973	0.2475
$X_5 \rightarrow$	−0.0942	0.1642	−0.4272	−0.2301	0.1160	−0.1444
$X_6 \rightarrow$	0.1614	0.1646	0.2040	−0.2373	0.0585	−0.2864

factor effecting specific gravity while tissue proportions influence it indirectly through percentage of cell wall material. On the other hand, it implies that tissue proportions, as anatomical parameter, could reflect and replace percentage of cell wall material.

Hill (Maeglin 1976) found that vessel proportion and fiber proportion in red oak are closely correlated with mechanical properties of wood and the two factors are the best estimators of mechanical properties. Similar results were also reported by Daniel and Barker (1979).

Tensile strength

Table 9 indicates that microfibrillar angle is the key anatomical factor influencing tensile strength (−0.8651). The other factors show little influence on it. Fiber length, usually regarded as an important factor influencing tensile strength, actually shows few effect on tensile strength (0.1969) although the correlation coefficient between them the two is high (0.7940). The main cause in this case is that the correlation coefficient between fiber length and tensile strength includes a large indirect effect by microfibrillar angle. The indirect path coefficient for the path from fiber length (X_1) → microfibril angle (X_3) → tensile strength (Y_6) is as high as 0.5221.

Tensile strength is one of the most important mechanical properties. Guo (1982) found microtensile strength of wood in red pine is closely correlated with microfibrillar angle and tracheid length. Ifju and Kennedy (1962) reported that microtensile strength of annual increments in Douglas-fir was correlated with tracheid length, specific gravity, microfibrillar angle and cellulose content, which accounted for 78 percent of the variation when earlywood and latewood were considered individually. Hillis (1989) also pointed out the importance of microfibrillar angle to strength and other properties of wood.

It is well-known that specific gravity is closely related to mechanical properties of wood, and usually is considered a good index of properties (Armstrong et al. 1984; Panshin, de Zeeuw 1980). The regression equations for specific gravity-mechanical property relationships have been developed based upon worldwide data (Armstrong et al. 1984). Kellogg and Ifju (1962) found that specific gravity is linearly related to tensile strength based on the results of study relating the physical characteristics of 20 species to difference in the properties of wood in tension parallel to the grain. The same result was found in East-Liaoning Oak. The regression equation between specific gravity (S) and tensile strength (T), $T = -1{,}176.52 + 3{,}494.76\ S$, is shown in

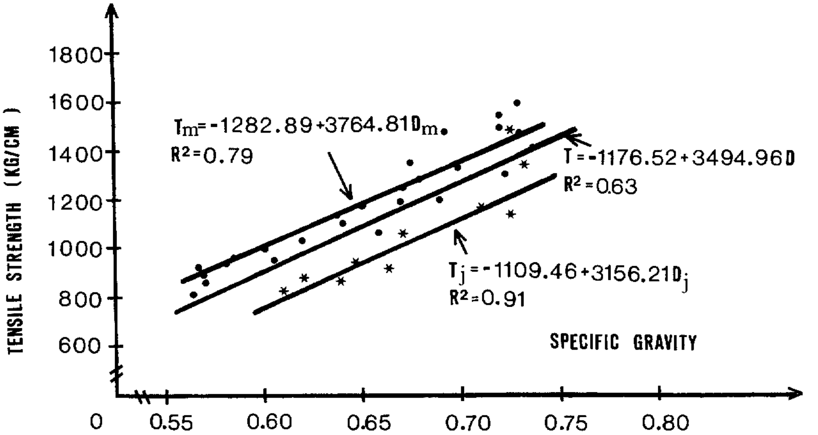


Fig. 1. Relationship between tensile strength (T) and specific gravity (D). * juvenile wood; • mature wood

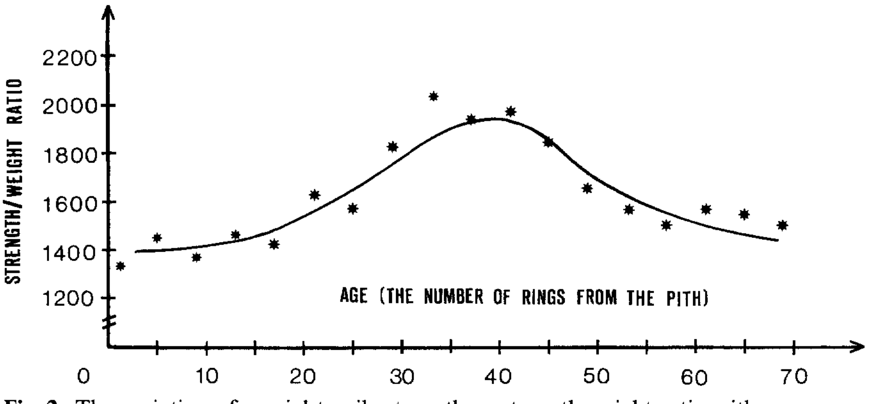


Fig. 2. The variation of special tensile strength or strength weight ratio with age

Fig. 1. It was found that the regression equation in juvenile wood (T_j) was different from that in mature wood (T_m) if they were considered separately. Tensile strength of mature wood with a specific gravity value is usually higher than that of juvenile wood with the same specific gravity value. Further it was found that specific strength, or tensile strength/weight ratio, shows an optimum curve, as shown in Fig. 2. This indicates that the relationship between specific gravity and the strength varies with the age (ring number from the pith), It is clear that there are different tensile strength values for woods with the same specific gravity values, as high as 2,230 kg/cm^2 and as low as 1,330 kg/cm^2 for East-Liaoning Oak wood with specific gravity of 1.0000, for instance. Therefore specific gravity is not always a good estimator of tensile strength. Leclercq (1980) and Hunt et al. (1989) also found that specific gravity is a poor predictor of strength.

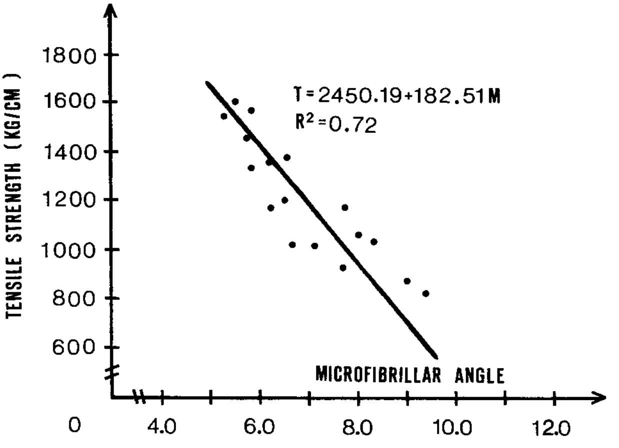


Fig. 3. Relationship between tensile strength (T) and microfibrillar angle (M)

As alreadly shown in Table 9, microfibrillar angle is of the greatest importance to tensile strength. The regression equation for microfibrillar angle and tensile strength relationship is given in Fig. 3. It is evident that the determination coefficient R^2 (0.72) is higher than that in Fig. 1. It shows that microfibrillar angle, as an estimator of tensile strength, is better than specific gravity in East-Liaoning Oak.

Specific gravity, from an anatomical point of view, serves only as a relative measure of cell wall material per unite volume (Panshin, de Zeeuw 1980). It can serve as an estimator of strength for softwoods which are simple in composition (Maeglin 1976). For hardwoods with a more complex structure, however, specific gravity, as an index of strength, is not as good as in softwoods since there may be great differences in structure for hardwoods with the same specific gravity values. In addition, both in softwoods and hardwoods, certain anatomical characters (such as microfibrillar angle etc.) show few effects on specific gravity although they influence strength significantly. On the other hand, certain parameters like extractives add weight (or specific gravity) without appreciably modifying strength (Kellogg, Ifju 1962). Therefore specific gravity can sometimes be a misleading criterion (Hillis 1989).

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