The Prediction of Wood Properties from Anatomical Characteristics: The Case of Common Commercial Malaysian Timbers

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This study established a predictive relationship between the material properties and the anatomical characteristics of common commercial Malaysian timbers. Anatomical databases were analysed using a one-way analysis of variance (ANOVA), a Duncan test, and the Spearman and Pearson correlation tests, and then modelled using multiple regression (stepwise method with constant excluded). The correlation tests revealed that the properties and anatomical characteristics of the wood were strongly correlated. The predictability of the resulting equation models was quite high. The equation models were able to relate various anatomical characteristics to wood texture, porosity, density, radial shrinkage, modulus of elasticity, and compression parallel to grain. This finding suggests that the relationship between the properties and the anatomical characteristics of wood can be described successfully using multiple regression equation models.

Keywords: Wood anatomical characteristics; Wood properties; Multiple regression equation models; Predictability

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INTRODUCTION

Malaysian commercial timbers are generally categorised on the basis of their density. These timbers are divided into heavy hardwoods (800 to 1120 kg/m^3), medium hardwoods (720 to 880 kg/m^3), and light hardwoods (400 to 700 kg/m^3). Each given class of timber has its very own physical, mechanical, and machining properties as well as drying, durability, treatability, defect, and usage properties, all of which are well documented (MTIB 1986; MTC 2006). However, information on the detailed anatomical characteristics of the timbers is scarce (Menon 1955; 1959; Richter and Dallwitz 2009).

In comparison to many other materials, wood is unique. It is anisotropic, with a sophisticated structure that is complicated by three major microscopic components, *i.e.*, vessel elements, fibers, and parenchyma. The structure of whole wood is unique in that each of its three major planes, that is, longitudinal (cross cut direction), radial (quarter sawn direction), and tangential (flat sawn direction), possesses distinctive features. Each plane has its own anatomical, physical, and mechanical properties in relation to both the wood itself and to the wood machining process, which is affected by its distinct and complicated structures. These complications pose challenges to anyone working with wood.

Moreover, unlike many other materials, wood cannot be cut in any direction. It is sensitive to ambient temperatures and unpredictable internal stresses and possesses varied characteristics (Ratnasingam and Tanaka 2002). For this reason, an understanding of wood anatomy is very important to the understanding of wood as a material. Working with wood at the level of its most fundamental characteristics may help to decrypt this riddle and illuminate the connections between its various material properties. One of the ways to approach this challenge is through use of mathematical modeling, which has been exploited by several other wood scientists in the past. Numerous studies have uncovered relationships between anatomical characteristics and material properties using regression analyses (Dagnelie 1969-1970; 1975; Ezell 1979; Fujiwara 1992; Fujiwara *et al.* 1991; Kiaei 2011; Leclercq 1980), correlation analyses (Beery *et al.* 1983; Chowdhury *et al.* 2012; Kaeiser and Boyce 1964; Myer 1921; Purkayastha *et al.* 1974; Schulz 1957; Taylor 1969; 1975; Zink-Sharp *et al.* 1999), correlation and regression analyses (Jeong 2013; Uetimane and Ali 2011), transformation normalised and regression analyses (Ziemińska *et al.* 2013), and covariance and regression analyses (Walton and Armstrong 1986). Furthermore, these scientists investigated a wide variety of wood species, namely beechwood (Leclercq 1980), Japanese hardwoods (Fujiwara *et al.* 1991; Fujiwara 1992), ntholo (Uetimane and Ali 2011), elder pine (Kiaei 2011), beach sheoak (Chowdhury *et al.* 2012), Australian angiosperms (Ziemińska *et al.* 2013), hard maple and Northern red oak (Zink-Sharp *et al.* 1999), North American hardwoods (Beery *et al.* 1983), American commercial timbers (Myer 1921; Walton and Armstrong 1986), sweetgum (Ezell 1979), sycamore and black willow (Taylor 1975), loblolly pine (Jeong 2013), champ (Purkayastha *et al.* 1974), red beech (Schulz 1957), and Eastern cottonwood (Kaeiser and Boyce 1964). These analyses incorporated both the macro aspects (vessel and fiber void volume, tissue proportion of vessel and fiber, parenchyma, ray volume, annual ring width, and vessel arrangement and frequency) as well as the micro aspects (dimensions, pore volume, wall thickness, percentage of fiber wall material, tracheid length, vessel diameter, and tangential latewood cell wall thickness) of wood anatomy, and related these features to the wood's physical properties (oven-dry density, air-dry density, basic density, specific gravity, volume shrinkage, and ray width) and mechanical properties (static bending, compression, bearing stress, proportional limit stress, transverse tensile strength, and ultimate tensile strength). A few studies involved the prediction of wood properties from the anatomical characteristics through the use of regression equation models, and some among them were highly efficient and precise. The resultant equations had coefficients of determination (R^2) in the range of 0.730 to 0.950 (Fujiwara 1992; Fujiwara *et al.* 1991; Jeong 2013; Leclercq 1980; Uetimane and Ali 2011). Such equations are indicative of the manner in which groups of anatomical characteristics influence the wood properties which are expressed by regression coefficient (value for the regression equation for predicting the dependant variable from independent variable), while the efficiency and precision of the predictability of the given relationships are expressed by R^2.

Based on the aforementioned literature, it is evident that the current understanding of the relationship between the internal (anatomical) and external (physical and mechanical) aspects of wood has been well studied, but research into such a relationship for tropical timbers from Malaysia has not been attempted before. Some of the questions that have yet to be answered, therefore, are as follows: which anatomical traits influence which wood properties, the extent and manner of the influence, how efficiently and precisely the resulting equations predict these variables, and how accurately these equations describe the characteristics of a given species of wood. Given these research interests, this study discusses the relationship between the anatomical characteristics and material properties of wood, and more specifically, which anatomical traits influence which wood properties, and how strongly, as expressed by means of mathematical equations. This study investigated a select fifty species of hardwoods which comprise the most common commercial timbers of Malaysia and which can be divided into three classes: heavy, medium, and light. Each timber class is uniquely described by a set of equations, as well as by anatomical characteristics and wood properties that are characteristic of the class.

EXPERIMENTAL

This study was carried out using data drawn from several databases, upon which basis mathematical analyses were conducted, equations were generated, and, finally, the most suitable equations were selected.

Database Acquisition and Pre-Analytic Preparation

The anatomical details of the common commercial timbers of Malaysia were retrieved from the archive of the Forest Research Institute of Malaysia (FRIM) (Menon 1955; 1959). Some undocumented yet essential data were retrieved from the database compiled by Richter and Dallwitz (2009). Data on the physical and mechanical properties of the timbers were retrieved from the Malaysia Timber Council (MTC 2006) and the Malaysian Timber Industry Board (MTIB 1986), respectively. The information contained in the databases used were derived from wood of matured trees (of more than 50 years), as stated in the source information used to create these databases. Then, a spreadsheet was constructed using Microsoft Excel (Microsoft Corporation, USA) to accommodate the data retrieved from the various databases. The spreadsheet was divided into three major sections: anatomical characteristics (vessel element characteristics: grouping, size, percentage of solitary, no. per square millimetre; fiber characteristics: wall thickness; ray characteristics: width, distinct size, no. per millimetre); physical properties (wood density, wood porosity, wood texture, radial and tangential shrinkage); mechanical properties (modulus of elasticity (MOE), modulus of rupture (MOR), compression perpendicular and parallel to grain, shear strength). The wood porosity value was a calculated value, and the ordinal variables such as fiber wall thickness and wood texture were presented as an index for ease of analysis. The description of wood anatomy was based on the International Association of Wood Anatomists' (IAWA) list of microscopic features for hardwood identification (IAWA Committee 1989), and some modifications were made for ease of sorting the data from the FRIM archive. The spreadsheet is shown in Table 1.

Statistical Analysis and Modeling of Data

The statistical analysis was divided into three major parts: first, a one-way analysis of variance (ANOVA) with post hoc analysis *via* Duncan's new multiple range test (Duncan test) was run to compare the anatomical characteristics, physical properties, and mechanical properties of the three timber classes in search of significant interactions; second, the relationship between anatomical characteristics and material properties of wood were identified using two-tailed Spearman's rank correlation test and Pearson's product-moment correlation test; third, the relationships between anatomical characteristics and material properties of wood were analysed *via* a stepwise multiple regression method (with constant excluded) to generate the equation models that described the interactions. The stepwise method is known to be a sophisticated multiple regression approach as it ensures that the model ends up with the smallest possible set of independent variables and thus always results in the most parsimonious model (Brace *et al.* 2012). This selection method is more advanced than the forward selection method suggested previously by Dagnelie (1975). All statistical methods were carried out at a 95% confidence level using the statistics program SPSS, version 19.0 (IBM Corporation, USA).

Selection of the Most Suitable Multiple Regression Equation Models

From the analyses, 10 equations were generated for each timber class. For testing the predictability, equation models were used to compute the wood properties, called "predicted values", which were then plotted against the recorded wood properties, called "recorded values" in the scatter plot graph. A linear curve was drawn, and the R^2 linear value for scatter plot graph was determined. The three highest R^2 linear values were selected, and these were used to pinpoint the top three equations for each timber class. This method was unlike the method used by previous researchers who had used the R^2 value and P-value to select the most relevant equations (Leclercq 1980; Fujiwara *et al.* 1991; Fujiwara 1992; Jeong 2013; Uetimane and Ali 2011). Wood scientists such as Lerlercq (1980) and Fujiwara (1992) generated the plots just to show the precision and efficiency of the models but did not generate any R^2 linear value to correspond to the plot and help identify the most suitable models. Because the generated equation was merely a model, it was essential to put it in practice to determine its efficiency and precision. This was the reason that the selection method was introduced. Moreover, the adjusted R^2 value of the equation was preferred over the conventional R^2 because the former more closely reflected the "real world" practice and was therefore a more useful estimate than the latter, which was an overestimate (Brace *et al.* 2012). This adjusted R^2 has been previously exploited by Ali (2011) in his study.

RESULTS AND DISCUSSION

Differences between Timber Classes

Before the equations that were found could be interpreted, it was essential to understand the differences between the three classes of timber, namely, the heavy, medium, and light hardwoods. The results showed that only half of the 18 tested variables were significant: one variable related to anatomical characteristics (fiber thickness index), three variables related to physical properties (wood texture index, wood density, and wood porosity), and five variables related to mechanical properties (MOE, MOR, compression perpendicular to grain, compression parallel to grain, and shear strength).

It was clearly shown that there was not much variation in anatomical characteristics among the three classes of timber, while physical and mechanical properties showed significant variation. Furthermore, from the mathematical point of view, the physical and mechanical properties were most appropriately conceptualised as dependent variables, while the anatomical characteristic were better suited as the independent variables in the multiple regression models.

Table 1. Database of Anatomical Characteristics and Wood Properties

No.	Commercial Timber	Anatomical Characteristics								Physical Properties						Mechanical Properties				
		Vessel Elements					Rays							Shrinkage						
	Trade Name	Grouping (No. of Cells)	Mean Tangential Diameter of Lumina (µm)	Solitary (%)	No. per Square Millimetre	Fiber Thickness Index	Width (No. of Cells)	Average Maximum Height (No. of Cells)	No. per Millimetre	Density (kg/m^3)	Specific Gravity (computed)	Porosity of Wood	Wood Texture Index	Radial (%)	Tangential (%)	Modulus of Elasticity, MOE (N/mm^2)	Modulus of Rupture, MOR (N/mm^2)	Compression Perpendicular to Grain (N/mm^2)	Compression Parallel to Grain (N/mm^2)	Shear Strength (N/mm^2)
Heavy Hardwood																				
1	Balau	3.5	205.0	77.5	7.0	6.0	3.5	43.5	7.0	1002.5	1.0	0.3	2.0	1.9	3.7	20100.0	142.0	9.8	76.0	15.0
2	Red Balau	3.5	205.0	77.5	7.0	6.0	3.5	43.5	7.0	840.0	0.8	0.4	4.5	1.8	3.4	15900.0	121.0	5.5	60.7	12.7
3	Bitis	4.5	175.0	20.0	6.5	6.0	1.0	30.0	14.5	1010.0	1.0	0.3	4.0	2.8	4.0	23800.0	171.0	12.5	90.3	15.4
4	Chengal	3.0	170.0	70.0	12.5	4.0	3.5	17.0	7.0	947.5	0.9	0.4	2.0	1.1	2.6	19600.0	149.0	12.0	75.2	13.9
5	Giam	3.0	150.0	69.5	18.0	6.0	5.0	39.0	6.5	1042.5	1.0	0.3	2.5	3.5	1.7	16500.0	122.0	11.2	58.9	15.9
6	Kekatong	3.0	210.0	42.5	7.1	4.0	3.5	35.0	7.0	1017.5	1.0	0.3	4.0	1.6	2.7	18400.0	135.0	11.4	67.0	15.6
7	Keranji	3.0	210.0	65.0	5.4	5.0	2.5	22.0	9.5	1002.5	1.0	0.3	4.0	1.7	2.7	20100.0	134.0	14.5	72.0	16.0
8	Merbau	2.5	280.0	69.5	3.7	3.0	2.5	14.0	7.5	777.5	0.8	0.5	7.0	0.9	1.6	15400.0	116.0	9.2	58.2	12.5
9	Resak	1.0	120.0	90.0	32.5	5.0	4.5	59.5	8.0	905.0	0.9	0.4	2.0	1.5	3.4	16250.0	93.0	8.2	51.3	11.0
10	Tembusu	4.5	210.0	31.5	5.2	5.5	1.0	11.5	15.0	857.5	0.9	0.4	2.0	1.1	1.6	13950.0	100.0	8.0	56.3	12.2
Medium Hardwood																				
11	Kapur	1.0	235.0	90.5	10.3	3.0	4.0	40.0	6.5	700.0	0.7	0.5	6.0	1.8	4.5	15850.0	120.0	5.5	65.7	12.1
12	Kasai	5.0	240.0	35.5	3.7	3.0	1.0	20.0	11.0	825.0	0.8	0.5	6.0	2.8	3.5	17000.0	106.0	7.4	51.4	13.9
13	Keledang	3.5	265.0	50.0	4.0	3.5	4.5	40.0	5.0	722.5	0.7	0.5	7.0	0.9	2.2	13850.0	100.0	4.9	53.2	11.2
14	Kelat	5.0	147.5	21.0	26.0	5.5	3.5	38.5	12.0	752.5	0.8	0.5	4.0	1.9	3.3	17600.0	116.0	6.0	59.0	12.8
15	Kempas	4.0	305.0	45.0	4.6	5.0	3.5	29.5	6.0	945.0	0.9	0.4	7.0	2.0	3.0	18600.0	122.0	7.5	65.6	12.4
16	Keruing	1.0	290.0	90.0	5.6	5.5	4.0	55.0	8.0	770.0	0.8	0.5	7.0	2.4	5.4	19650.0	112.0	6.8	59.2	10.8
17	Kulim	5.0	196.0	10.0	17.5	6.0	2.5	79.0	14.0	807.5	0.8	0.5	4.0	1.7	3.2	14900.0	107.0	5.1	57.0	10.3
18	Mata Ulat	1.0	62.5	90.0	21.5	6.0	3.5	12.5	12.5	975.0	1.0	0.4	2.0	2.1	2.5	16300.0	102.0	6.8	53.1	10.7
19	Mengkulang	5.0	335.0	40.0	3.4	5.0	3.5	55.0	4.0	760.0	0.8	0.5	5.5	1.5	3.4	14000.0	100.5	5.8	56.4	11.5
20	Merawan	3.0	180.0	65.0	14.5	3.0	4.0	55.0	7.0	737.5	0.7	0.5	4.0	1.1	2.8	15250.0	91.0	5.3	48.4	9.2
21	Merpauh	4.5	260.0	52.5	4.3	4.0	2.0	22.0	6.0	760.0	0.8	0.5	6.0	1.1	1.8	16150.0	101.0	6.8	50.1	13.2
22	Punah	4.0	276.5	13.0	6.8	6.0	3.0	36.0	11.0	712 .5	0.7	0.5	6.0	3.2	4.5	15400.0	87.0	5.7	49.4	9.7
23	Rengas	3.0	255.0	45.0	3.3	4.0	1.5	21.0	10.5	800.0	0.8	0.5	5.0	1.0	1.8	14900.0	111.0	7.7	59.4	13.2

24	Simpoh	1.0	193.5	90.0	9.9	5.0	3.5	150.0	10.5	747.5	0.7	0.5	8.0	2.2	3.9	14300.0	76.0	5.0	39.4	8.2
25	Tualang	6.0	304.0	47.5	4.3	5.0	3.5	20.0	6.0	832.5	0.8	0.4	7.0	1.5	1.7	17800.0	121.0	8.0	62.0	16.3
Light Hardwood																				
26	Bintangor	1.0	240.0	90.0	6.5	5.0	1.5	16.5	10.5	665.0	0.7	0.6	7.0	1.8	2.9	14300.0	74.0	3.2	36.7	10.8
27	Durian	6.0	335.0	30.0	2.9	3.5	4.5	67.5	9.5	642.5	0.6	0.6	7.0	1.9	2.8	12650.0	80.5	4.2	43.2	8.0
28	Jelutong	3.0	175.0	10.0	3.4	1.0	4.5	24.5	6.5	460.0	0.5	0.7	4.0	0.8	2.0	8100.0	50.0	2.7	27.0	5.8
29	Kedondong	4.0	195.0	57.5	12.8	3.5	2.5	20.0	7.5	737.5	0.7	0.5	4.0	2.1	3.7	12500.0	81.0	6.4	43.4	11.4
30	Kungkur	2.5	250.0	45.0	3.9	4.0	2.5	22.0	7.5	657.5	0.7	0.6	6.0	0.6	0.9	10700.0	89.0	6.6	44.1	12.8
31	Machang	3.0	225.0	55.0	2.9	2.0	1.5	18.5	9.0	577.5	0.6	0.6	4.0	1.1	1.8	10900.0	73.5	6.1	40.2	12.7
32	Medang	3.0	150.0	35.0	17.5	5.0	4.0	40.0	7.0	615.0	0.6	0.6	4.0	1.5	3.1	11350.0	78.5	3.2	43.5	7.6
33	Melunak	3.0	185.0	40.0	16.0	5.0	5.0	20.0	8.0	642.5	0.6	0.6	4.0	1.4	2.5	12000.0	85.0	4.3	43.6	10.8
34	Mempisang	4.5	195.0	37.5	14.0	4.0	7.0	70.0	5.0	645.0	0.6	0.6	7.0	2.8	3.6	14100.0	82.5	4.1	46.1	9.7
35	Light Red Meranti	2.5	295.0	57.5	4.8	2.0	5.0	50.0	5.0	570.0	0.6	0.6	8.0	2.1	5.6	11000.0	73.0	2.5	41.4	8.7
36	Dark Red Meranti	3.0	375.0	67.5	7.3	5.0	5.0	52.5	5.0	650.0	0.7	0.6	6.0	1.6	3.7	12550.0	83.0	4.0	45.9	9.7
37	White Meranti	3.0	265.0	67.5	6.3	5.0	5.5	37.0	5.5	745.0	0.7	0.5	6.0	1.2	2.2	15450.0	111.0	7.4	55.7	11.8
38	Yellow Meranti	3.0	235.0	70.0	6.2	2.5	6.0	62.5	5.0	655.0	0.7	0.6	6.0	1.1	3.5	11050.0	77.5	3.0	45.3	9.3
39	Meranti Bakau	3.0	375.0	67.5	7.3	5.0	5.0	52.5	5.0	675.0	0.7	0.6	7.0	1.0	2.7	14700.0	68.0	3.4	35.9	6.7
40	Mersawa	1.0	255.0	90.0	7.3	3.5	4.5	41.3	5.5	625.0	0.6	0.6	6.0	1.4	3.5	10900.0	51.5	5.6	27.5	7.3
41	Nyatoh	3.5	185.0	17.5	10.1	3.5	2.0	35.0	12.5	737.5	0.7	0.5	5.5	2.0	3.1	15250.0	104.0	6.8	54.1	11.5
42	Penarahan	3.5	155.0	27.5	6.4	3.0	2.0	30.0	10.0	550.0	0.6	0.6	4.0	2.2	3.2	9380.0	51.0	5.7	43.6	9.6
43	Perupok	2.5	138.0	67.8	15.5	5.5	1.5	20.0	13.5	560.0	0.6	0.6	3.0	2.4	2.9	12400.0	77.5	5.5	43.2	8.2
44	Pulai	5.5	180.0	7.4	9.0	3.0	2.5	29.0	6.5	355.0	0.4	0.8	5.5	2.3	2.8	7100.0	43.0	N.A	24.8	6.3
45	Ramin	2.8	165.0	35.0	7.5	2.0	2.0	25.0	12.0	657.5	0.7	0.6	4.0	1.8	3.7	14200.0	111.0	N.A	60.6	10.2
46	Rubberwood	6.0	202.5	N.A	2.0	3.5	3.5	N.A	10.0	600.0	0.6	0.6	6.0	0.8	1.2	9200.0	66.0	4.7	32.3	11.0
47	Sepetir	3.5	185.0	45.0	5.1	2.0	4.5	32.5	6.0	657.5	0.7	0.6	4.0	1.5	2.9	13600.0	92.0	5.9	46.2	13.6
48	Sesendok	4.5	275.0	15.0	3.4	1.0	3.0	27.5	8.0	485.0	0.5	0.7	7.0	1.2	1.3	8500.0	39.0	1.8	20.8	5.4
49	Terap	3.5	295.0	52.5	2.9	4.0	5.0	35.0	5.0	480.0	0.5	0.7	7.0	1.8	3.7	11150.0	67.5	3.1	34.9	9.2
50	Terentang	3.0	130.0	40.0	31.0	1.0	3.5	30.5	7.0	440.0	0.4	0.7	2.0	1.9	4.4	7000.0	42.0	2.2	22.4	7.5

Note: N.A = Not available

This was in line with the previous study by Dagnelie (1969-1970), who suggested that, were the wood properties portrayed as the dependant variables with connections to with several independent variables, such as anatomical characteristics, then the problem of the relationship between them could be resolved. On this basis, a conceptual multiple regression model was outlined as such:

$$y_{\text{physical/mechanical property}} = \alpha + \beta x_{\text{anatomical characteristic 1}} + \beta x_{\text{anatomical characteristic 2}} + \ldots + \varepsilon$$

Correlations between Anatomical Characteristics and Material Properties

It is necessary to know the relationship between the properties and anatomical characteristics of wood prior to the development of the multiple regression models. Furthermore, the multiple regression tests that were carried out during the latter procedure were meant for normally distributed variables, and it is essential to know the correlation before arriving at this stage. The data were analysed using both Spearman's and Pearson's correlation tests, as the former is not used for normally distributed variables, while the latter is. The pattern of data was not well known at this stage, so it was essential to perform analyses using both conventional correlation tests.

When the two correlation tests were compared, it was revealed that the wood properties (such as texture, density, porosity, tangential and radial shrinkage, compression perpendicular and parallel to grain, and shear strength) were correlated with anatomical characteristics (such as vessel diameter, vessel per square millimetre, vessel percentage of solitary, fiber thickness, ray width, ray height, and ray per millimetre). The coefficient of correlation was within the range of 0.280 to 0.760, which shows that different anatomical traits had different influence on wood properties. The strongest correlation occurred between wood texture and vessel diameter, while the weakest correlation ocurred between modulus of elasticity and vessel percentage of solitary. Previous studies by Myer (1921), Schulz (1957), Taylor (1969), and Ezell (1979) found correlations between ray volume and density, and between fiber proportion and specific gravity. However, Kaeiser and Boyce (1964) found that these ray traits were not in any way correlated with specific gravity. Purkayastha *et al.* (1974) and Uetimane and Ali (2011) noted that fiber wall thickness, length, and diameter were correlated with density and compression parallel and perpendicular to grain. Chowdhury *et al.* (2012) documented a correlation between air-dry density and vessel diameter, fiber diameter and wall thickness, and proportion of fiber and cell wall tissue. Furthermore, Beery *et al.* (1983) stated that transverse stiffness was significantly correlated with ray traits. Zink-Sharp *et al.* (1999) reported that the bearing stress failure of a single-bolted connection was influenced by ray size and vessel size. The polarity of the coefficient of correlation was not considered at this stage, since it was necessary for the multiple regressions test to be described. The details of the statistical analysis are shown in Table 2.

Relationship between Anatomical Characteristics and Properties of Wood

To more completely detect and describe the relationships between wood properties and anatomical characteristics, a stepwise multiple regression was used. With the constant excluded from the multiple regression model, the model was further improved. As in previous steps, the adjusted R^2 was chosen over the conventional R^2 as a measure of the appropriateness of the model.

Table 2. Correlations between Wood Properties and Anatomical Characteristics

Significant Correlation		Coefficient of Correlation	
Wood properties	Anatomical Characteristics	Spearman Correlation (two-tailed test)	Pearson Correlation (two-tailed test)
Texture Index	Ray no. per millimetre	-0.368	-0.344
	Vessel element mean tangential diameter of lumina	0.759	0.734
	Vessel element no. per square millimetre	-0.497	-0.570
	Ray average maximum height	Non-significant	0.327
Density	Fiber thickness index	0.599	0.619
Porosity	Fiber thickness index	-0.587	-0.616
	Vessel element percentage of solitary	Non-significant	-0.303
Modulus of Elasticity	Fiber thickness index	0.581	0.612
	Vessel element percentage of solitary	0.284	Non-significant
Modulus of Rupture	Fiber Thickness Index	0.487	0.524
Tangential shrinkage	Ray average maximum height	0.510	0.405
	Vessel element no. per square millimetre	0.330	Non-significant
Radial shrinkage	Fiber thickness index	0.321	0.340
	Vessel element no. per square millimetre	0.388	Non-significant
Compression perpendicular to grain	Fiber thickness index	0.379	0.413
	Ray average maximum height	-0.353	Non-significant
	Ray width	0.403	-0.338
Compression parallel to grain	Fiber thickness index	0.452	0.522
Shear strength	Fiber thickness index	0.309	0.385
	Ray average maximum height	-0.333	-0.297
	Ray width	0.303	Non-significant

The multiple regression tests resulted in ten successful models for each timber class. The models described the wood properties on the basis of the anatomical characteristics of the wood. The R^2 of the models ranged from 0.873 to 0.993, while the estimated standard error ranged from 0.047 to 4285.947. The R^2 value in this study was higher than that found in previous studies (Leclercq 1980; Fujiwara *et al.* 1991; Fujiwara 1992; Uetimane and Ali 2011; Jeong 2013). The R^2 value indicated that the model was very successful in describing the data; however, it was still essential to observe it in practice before drawing definitive conclusions. The details of all the models are shown in Table 3.

The model describes the relationship clearly. The anatomical characteristics of the wood, namely vessel diameter, vessel grouping, vessel percentage of solitary, vessel per square millimetre, fiber thickness, ray width, ray height, and ray per millimetre, were the factors that determined the properties of the wood. A previous study by Leclercq (1980) found that wood properties were explained by diameter, pore volume, length, and fiber wall thickness. The material properties of the wood, namely basic density, were explained by fiber wall thickness, percentage of fiber wall tissue, ray volume, and ray cell wall tissue (Fujiwara *et al.* 1991; Fujiwara 1992).

Table 3. Multiple Regression Equation Models of the Relationship between Wood Properties and Anatomical Characteristics for Three Timber Classes

Wood Properties	Multiple Regression Equation Model (Stepwise method; Constant excluded)		Adjusted Coefficient of Determination (Adjusted R^2)	Standard Error of Estimate
Heavy Hardwood				
Texture	y_{HWTI}	$= 0.018x_{VD}$	0.900	1.180
Density	y_{HD}	$= 119.692x_{FTI} + 1.678x_{VD}$	0.977	144.229
Porosity	y_{HP}	$= 0.002x_{VD} + 0.006x_{VPSM}$	0.985	0.047
Radial shrinkage	y_{HRS}	$= 0.359x_{FTI}$	0.898	0.620
Tangential shrinkage	y_{HTS}	$= 0.536x_{FTI}$	0.918	0.819
Modulus of elasticity	y_{HMOE}	$= 3447.597x_{FTI}$	0.945	4285.947
Modulus of rupture	y_{HMOR}	$= 13.598x_{FTI} + 0.303x_{VD}$	0.958	26.732
Compression parallel to grain	y_{HCPaG}	$= 7.434x_{FTI} + 0.148x_{VD}$	0.961	13.286
Compression perpendicular to grain	y_{HCPeG}	$= 0.050x_{VD}$	0.886	3.545
Shear strength	y_{HSS}	$= 1.527x_{FTI} + 0.032x_{VD}$	0.975	2.234
Medium Hardwood				
Texture	y_{MWTI}	$= 0.020x_{VD} + 0.021x_{RH}$	0.973	0.966
Density	y_{MD}	$= 5.397x_{VPS} + 79.732x_{VG} + 25.597x_{RPM}$	0.993	66.889
Porosity	y_{MP}	$= 0.002x_{VD} + 0.012x_{VPSM}$	0.980	0.067
Radial shrinkage	y_{MRS}	$= 0.383x_{FTI}$	0.892	0.630
Tangential shrinkage	y_{MTS}	$= 0.655x_{FTI}$	0.873	1.183
Modulus of elasticity	y_{MMOE}	$= 43.779x_{VD} + 387.040x_{VPSM} + 40.001x_{VPS}$	0.986	1943.878
Modulus of rupture	y_{MMOR}	$= 0.329x_{VD} + 2.836x_{VPSM}$	0.981	14.437
Compression parallel to grain	y_{MCPaG}	$= 0.175x_{VD} + 1.457x_{VPSM}$	0.984	6.93383
Compression perpendicular to grain	y_{MCPeG}	$= 0.693x_{FTI} + 0.012x_{VD}$	0.951	1.405
Shear strength	y_{MSS}	$= 0.043x_{VD} + 0.318x_{VPSM} – 0.035x_{RH}$	0.971	2.013
Light Hardwood				
Texture	y_{LWTI}	$= 0.023x_{VD}$	0.961	1.096
Density	y_{LD}	$= 37.298x_{RPM} + 54.301x_{RW} + 2.443x_{VPS}$	0.980	85.597
Porosity	y_{LP}	$= 0.0920x_{VG} + 0.003x_{VPS} + 0.018x_{RPM}$	0.962	0.116
Radial shrinkage	y_{LRS}	$= 0.227x_{VG} + 0.075x_{RPM} + 0.034x_{VPSM}$	0.924	0.471
Tangential shrinkage	y_{LTS}	$= 0.038x_{RH} + 0.083x_{VPSM} + 0.017x_{VPS}$	0.916	0.913
Modulus of elasticity	y_{LMOE}	$= 667.093x_{RPM} + 1029.056x_{RW} + 818.375x_{FTI}$	0.975	1889.519
Modulus of rupture	y_{LMOR}	$= 5.747x_{RPM} + 8.222x_{RW}$	0.943	18.347
Compression parallel to grain	y_{LCPaG}	$= 3.214x_{RPM} + 4.279x_{RW}$	0.954	8.935
Compression perpendicular to grain	y_{LCPeG}	$= 0.337x_{RPM} + 0.519x_{FTI}$	0.875	1.676
Shear strength	y_{LSS}	$= 0.752x_{RPM} + 0.937x_{RW}$	0.929	2.554

Note:

x_{VG} = Vessel Element Grouping
x_{VD} = Vessel Element Mean Tangential Diameter of Lumina
x_{VPS} = Vessel Element Percentage of Solitary
x_{VPSM} = Vessel Element No. Per Square Millimetre
x_{FTI} = Fiber Thickness Index
x_{RW} = Ray Width
x_{RH} = Ray Average Maximum Height
x_{RPM} = Ray No. Per Millimetre

The findings of Uetimane and Ali (2011) suggested that tissue proportion, fiber dimensions, and vessel traits influenced the wood properties. Jeong (2013) stated that the wood properties were predicted by different combinations of anatomical characteristics. In line with previous research, therefore, the results of this study indicated that single as well as a combination of anatomical characteristics can be used to describe the variation in wood properties.

Moreover, the developed model was also able to explain the strength of the correlation between wood properties and anatomical characteristics using a regression coefficient. For example, in the case of the model that described the shear strength of medium hardwood, that is, $y_{MSS} = 0.043x_{VD} + 0.318x_{VPSM} - 0.035x_{RH}$, the vessel diameter and vessel per square millimetre were positively correlated with shear strength, while ray height was negatively correlated with shear strength. The regression coefficient for the relationship between vessel per square millimetre and shear strength was 0.318, meaning that, holding all other variables constant, every unit increase in vessel per square millimetre resulted in a 0.318 increase in shear strength, on average. Moreover, for every unit increase in ray height, there was a 0.035 decrease in shear strength, on average. Among all the correlations found, that of vessel per square millimetre possessed the most variation, while ray height had the least. These results indicated that it was possible to describe wood properties by means of a combination of these correlations.

Predictability of Multiple Regression Equation Model

Table 4. Most Suitable Multiple Regression Equation Models

Wood Properties	Multiple Regression Equation Model (Stepwise method; Constant excluded)		Adjusted Coefficient of Determination (Adjusted R^2)	R^2 Value of Scatter Plot Graph
Heavy Hardwood				
Texture	y_{HWTI}	$= 0.018x_{VD}$	0.900	0.548
Porosity	y_{HP}	$= 0.002x_{VD} + 0.006x_{VPSM}$	0.985	0.430
Radial shrinkage	y_{HRS}	$= 0.359x_{FTI}$	0.898	0.445
Medium Hardwood				
Texture	y_{MWTI}	$= 0.020x_{VD} + 0.021x_{RH}$	0.973	0.673
Density	y_{MD}	$= 5.397x_{VPS} + 79.732x_{VG} + 25.597x_{RPM}$	0.993	0.373
Compression parallel to grain	y_{MCPaG}	$= 0.175x_{VD} + 1.457x_{VPSM}$	0.984	0.259
Light Hardwood				
Texture	y_{LWTI}	$= 0.023x_{VD}$	0.961	0.572
Density	y_{LD}	$= 37.298x_{RPM} + 54.301x_{RW} + 2.443x_{VPS}$	0.980	0.361
Modulus of elasticity	y_{LMOE}	$= 667.093x_{RPM} + 1029.056x_{RW} + 818.375x_{FTI}$	0.975	0.380

Notes:
x_{VG} = Vessel Element Grouping
x_{VD} = Vessel Element Mean Tangential Diameter of Lumina
x_{VPS} = Vessel Element Percentage of Solitary
x_{VPSM} = Vessel Element No. Per Square Millimetre
x_{FTI} = Fiber Thickness Index
x_{RH} = Ray Average Maximum Height
x_{RW} = Ray Width
x_{RPM} = Ray No. Per Millimetre

The question regarding the efficiency and precision of predictability of the model must also be answered. This exercise was conducted with the aim of confirming the utility out of the model by putting it to practice. The models were used to compute the wood properties, and the predicted values were plotted against the recorded values.

The three models with the highest R^2 values were selected from each timber class, and these were considered the models with the best predictability. The R^2 linear values of the scatter plots ranged from 0.259 to 0.673, showing a good predictability of the models. The models with the highest predictability were y_{HWTI}, y_{HP}, and y_{HRS} of the heavy class, y_{MWTI}, y_{MD}, and y_{MCPaG} of the medium class, and y_{LWTI}, y_{LD}, and y_{LMOE} of the light class. From these models, it was clear that wood texture was the best identifying feature for timber class, although it was not the most successful model based on R^2 value alone. The models and linear scatter plots with the highest computed predictability are shown in Table 4 and Fig. 1, respectively.

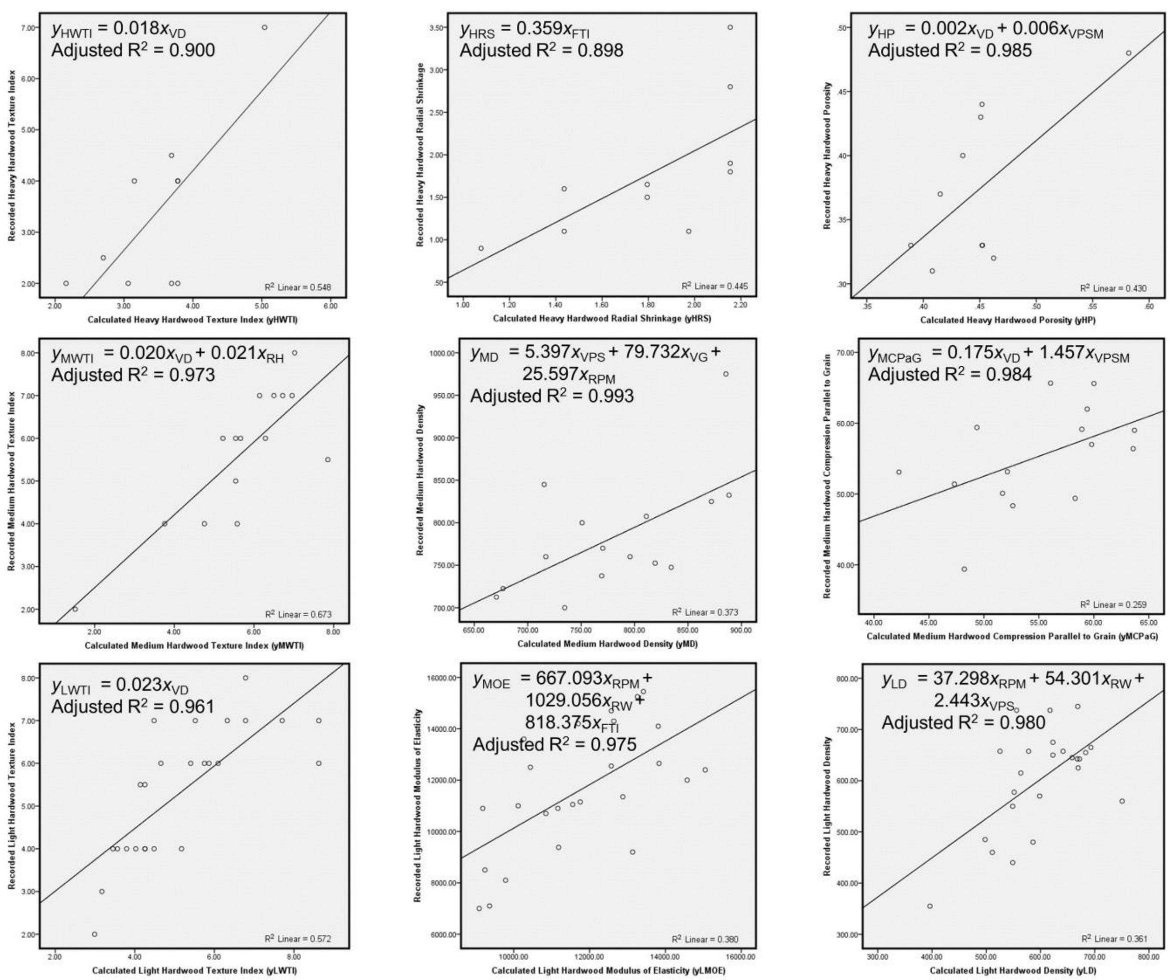

Fig. 1. Linear scatter plot graphs of recorded values against predicted values of the most suitable multiple regression equation models

In addition, the models were applied to lesser-known commercial timbers of Malaysia. However, the results turned out to be a disappointment. The data on the anatomical characteristics of these woods, which were retrieved from Richter and Dallwitz (2009), were not well documented, and this affected the predictability of the model. Evidently, the works done on the lesser-known commercial timbers is incomplete and of poor quality, as publication on the properties of these timbers are very limited. This is an area for future research, and, given that the current and future supply of wood resources is unsustainable (NATIP 2009; MPIC 2011), it will be important to look into these lesser-known commercial timbers.

Possible Exploitation of Multiple Regression Equation Model

In addition to the model's utility as a means to describe, explain, and predict the wood properties based on the anatomical characteristics, it can also be used as a tool to narrow down and pinpoint the anatomical characteristics that govern certain properties of the wood. Furthermore, the model is able to improve the understanding of wood properties. For example, the models concerning the modulus of elasticity of the three timber classes, $y_{HMOE} = 3447.597x_{FTI}$, $y_{MMOE}= 43.779x_{VD} + 387.040x_{VPSM}, + 40.001x_{VPS}$, and $y_{LMOE} = 667.093x_{RPM} + 1029.056x_{RW} + 818.375x_{FTI}$, demonstrated that for the heavy class, MOE was governed by fiber thickness, whereas for the medium class it was predicted by vessel properties, and for the light class by both ray and fiber properties. Wood texture was an important feature for the wood, and from the models it was clear that diameter of vessel was a key trait.

In all, the availability of these successful predictive models will increase the efficiency of the exploitation of timber resources. The relationships between wood properties and anatomical characteristics have been established by means of the development of predictive mathematical models. The Malaysian hardwood has been well-known for its wide variation in characteristics, and these models have managed to narrow down these characteristics as shown in Table 3. These models will also allow for better prediction of wood properties and more efficient use of Malaysian timbers.

CONCLUSIONS

1. The relationships between the anatomical characteristics and the properties of Malaysian commercial timbers were successfully described and explained by multiple regression models developed.
2. These models narrowed down the important wood anatomical characteristics that strongly governed wood properties.
3. The predictability of the models was high in efficiency and precision; however, the models were not as applicable to lesser-known commercial timbers.
4. The primary benefit of these models is the ability to better predict the properties of Malaysian hardwoods, which will improves its utilization.

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