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ASSESSMENT OF THE RELATIONSHIPS BETWEEN FIBER AND MECHANICAL PROPERTIES OF TREE SPECIES

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ABSTRACT

The variations in mechanical and fiber properties and wood density of seven commonly used timber species in the furniture industry of Sri Lanka were studied. Wood density, compressive strength (parallel to grain and perpendicular to grain), and static bending proportional limit properties were measured. Specifications stated in BS 373: 1957 were used as the standards for the tests. The mechanical property test was performed using a Universal Testing Machine (UTM 100 PC). Fiber analysis was done according to modified Franklin's method. Regarding density, all fiber properties decreased according to the trend graph. Similarly, no significant correlations were found among fiber properties (fiber length, fiber diameter, and fiber wall thickness) and bending proportional limit, MOR, and MOE. A higher Runkel ratio in high-density timber species was associated with higher strength values.

Keywords: density; fiber properties; mechanical test; timber.

INTRODUCTION

The history of wood architecture reveals that architects and artisans with natural creative skills have existed from the beginning of civilization. Due to the low quality and strength of the wood used by these ancestral architects and artisans, some of their creations have not lasted long (Ruwanpathirana and Muthumala, 2010).

The wood is an excellent material for roofs and other construction works, furniture, interior decorations, doors and window frames, paneling, partition borders, floorings, wood carvings, musical instruments, etc. Mechanical properties are fundamental in determining the suitability of timbers for both structural and non-structural purposes. However, these properties vary with species and other factors, such as moisture content, defect number, and degree.

In hardwood, the cells that make up the anatomical organization are the vessels, fibers, parenchyma cells, and wood rays. Fibers are the principal element that is responsible for the strength of the wood (Panshin and Zeeuw, 1980). Fiber length, fiber cell wall thickness, lumen diameter, and pit size are characteristics associated with wood properties such as wood density, modulus of rupture, modulus of elasticity, shrinkage, etc. Wood density is a vital wood property for both solid wood and fiber products (De Guth, 1980). Softwood fibers are generally long (2-3 mm) (Bardage, 2001, Brandstrom *et al*., 2003), while hardwood fibers are shorter (1 mm) and less flexible (Tabarsa, 2001).

The Runkel ratio, the ratio between fiber cell wall thickness and lumen, determines the suitability of a fibrous material for pulp and paper production. If a wood species has a high Runkel ratio, its fibers are stiff and less flexible, and have poor bonding abilities. The variations in mechanical and fiber properties of seven timber species commonly used in the furniture industry in Sri Lanka were studied in this experiment.

MATERIALS AND METHODS

Commonly used seven tree species for furniture manufacturing were collected from the Southern and Central provinces of Sri Lanka (Table 1).

Tab. 1 Selected timber species for identifying the joint efficiencies.

Common Name	Botanical Name	Family	Timber Class*	Collected Province
Grandis	*Eucalyptus grandis*	Myrtaceae	Class-2	Central
Jack	*Artocarpus heterophyllus*	Moraceae	Luxury	Southern
Kumbuk	*Terminalia arjuna*	Combretaceae	Special	Southern
Mahogany	*Swietenia macrophylla*	Meliaceae	Luxury	Southern
Pine	*Pinus caribaea*	Pinaceae	Class-3	Central
Satin	*Chloroxylon* swietenia	Rutaceae	Luxury	Southern
Teak	*Tectona grandis*	Lamiaceae	Super Luxury	Southern

*Source: Timber classification of State Timber Corporation, Sri Lanka

Determination of wood density

Each tree species was replicated ten times. Wood density was determined based on green volume and oven-dry weight. The dry weight of the timber samples was taken by placing them in an oven at 105 ^{0}C for 48 hours (BS EN 373:1957). The density was calculated using Equation 1.

$$\text{Density} = \frac{\text{Weight of oven-dried wood (kg)}}{\text{Volume of wood (m}^3\text{)}} \quad (1)$$

Samples placed at normal room temperature conditions showed better structural performance than those under hot, wet conditions (Vivek et al, 2016).

Determination of moisture content

The specimens (each 20 x 20 x 20 mm) were first weighed and then oven-dried at 103 0C until constant weight. The moisture content (r) of each sample was determined using Equation 02 given below.

$$r = \frac{M_r - M_0}{M_0} \times 100 \quad (2)$$

Where: r is the moisture content of the sample (%), M_r is the moist weight of the sample, and M_0 is the fully dried mass of the sample.

Measuring the fiber dimensions

Fiber morphological analysis was done using the modified Franklin's method (Franklin, 1945). In preparation for the timber slides containing fibers, the matchstick-sized splints were taken from the tangential section of timber samples and put into boiling tubes containing a mixture of glacial acetic acid and 30% hydrogen peroxide (1:1 by volume). The purpose of using hydrogen peroxide was to ensure dehydration and bleaching of the samples. The glacial acetic acid was used to dissolve the lignin, enabling easy separation of the fibers (Fig. 1). The material in the boiling tubes transformed into a pulp when the temperature was maintained at 65°C for 24 h. Then, the remains were rinsed in distilled water and shaken gently to ensure that individual cells of xylem tissue were measurable. Fibers were carefully removed with a paintbrush and mounted on slides with Canada balsam. They were then covered with cover slips, named, and kept in an oven at 30 0C for two days to complete drying. Microscopic views were taken to measure fiber thickness, lumen diameter, and wall thickness. The fiber dimensions were measured subjectively to minimize the possible variations in the fibers, which could occur due to factors such as the age of the tree and the sampling height of the tree, etc. (Smook, 2003; H'ng *et al.*, 2016). Micrometrics SE Premium 4.1 software was used to determine the fiber dimensions.

Calculation of Runkel ratio

Runkel ratio was calculated using the Equation 3 (Smook, 2003).

$$\text{Runkel ratio} = \frac{D_2 - D_1}{D_2} \qquad (3)$$

Where: D_2- Cell thickness, D_1-Lumen diameter;
D_2-D_1=Cell wall thickness.

Fig.1 Preparation of slides for measuring fiber properties – A, Matchstick size splints taken from timber samples; B, Small timber samples dipped in the mixture; °C, Rack with test tubes kept at 60°C; D, Test tubes after dissolving the lignin; E, Mounting the slides with Canada balsam; F, Determination of fiber dimensions.

Determination of flexural strength

Specimens were cut from defect-free, seasoned wood planks (average moisture content 12%). 10 wood specimens were made, one for each tree species. The size of each replicate was 20 x 20 x 300 mm. Specimens were prepared according to the testing methods for small transparent specimens as stated in BS 373:1957.

The Universal Testing Machine (UTM-100), manufactured in Australia, was used for testing (Fig. 2). An assembly pressure of 6 MPa was used in this study (Castro & Paganini, 1997; Min-Chyuan et al., 2011).

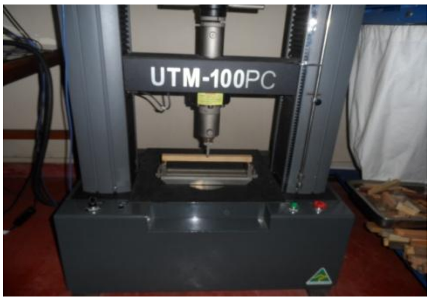


Fig. 2 Universal Testing (UTM-100PC-Australia).

Bending proportional limit strength, Modulus of Rupture (MOR), and Modulus of Elasticity (MOE) values were calculated using Equations 4, 5, and 6, respectively, corresponding to the test data.

$$\text{Bending proportional limit Strength} = \frac{3F_1L_1}{2bd^2} \quad (4)$$

Where: F_1 = Serviceability Force (N);
L_1 = Length of the span (mm);
b = Width of the specimen (mm);
d = Depth/Thickness of the specimen (mm).

$$\text{MOR} = \frac{3F_2L_1}{2bd^2} \quad (5)$$

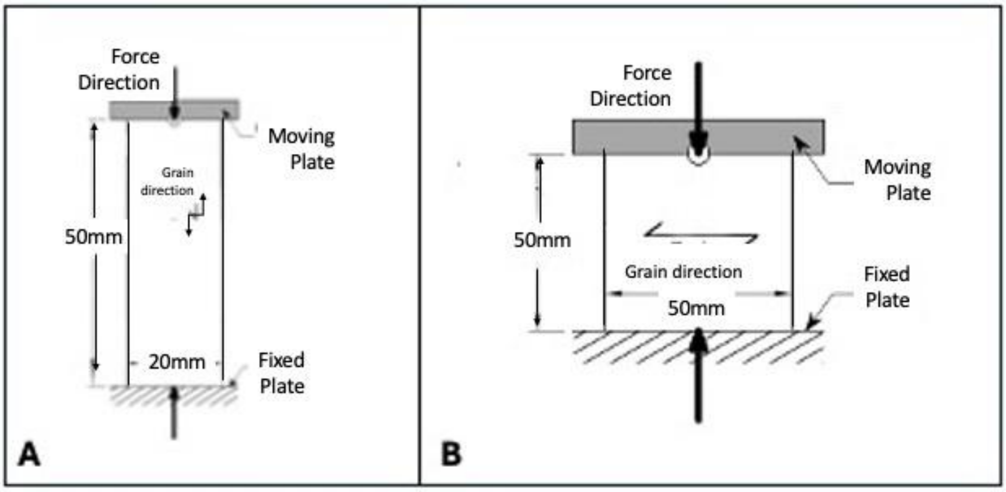
Where: F_2= Maximum Force (N);
L_1 = Length of the span (mm);
b = Width of the specimen (mm);
d = Depth/Thickness of the specimen (mm).

$$\text{MOE} = \frac{F_3{L_1}^3}{4\delta bd^3} \quad (6)$$

Where: F_3= Maximum load at proportionate state (N);
L_1= Length of the beam between supports (mm);
b = width of the specimen (mm);
d= Depth/ Thickness of the specimen (mm);
δ= Deflection of timber specimen (mm);

Calculation of Compression Strength

Prepared specimen for compression parallel to grain are shown in Fig. 3 (a).



Fi. 3 Schematic presentation of compression tests (a) Compression parallel to grain (b) Compression perpendicular to grain specimen.

The load was applied to the timber section at a proportional state. Serviceability compressive strength was calculated using Equation 07. The Force direction of the specimen is shown in Fig. 4 and Fig.5.

$$\text{Serviceability compressive strength of the specimen} = \frac{\text{Max.Load act on specimen at Proportionate state}}{\text{Load acting area}} \ \text{N/mm}^2 \qquad (7)$$

Compression parallel to grain

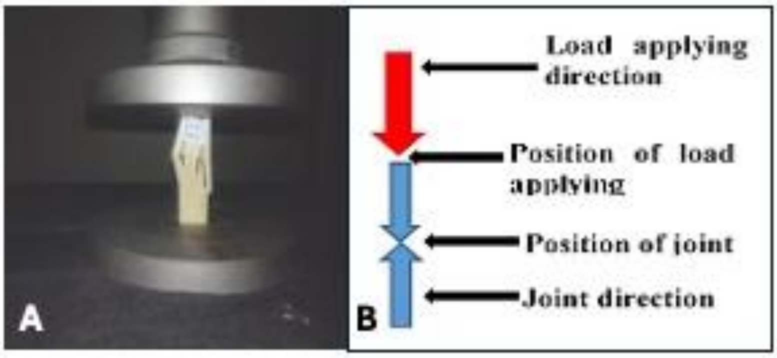


Fig. 4 Compression parallel to grain test. (a) Loading setup (b) Load applying direction.

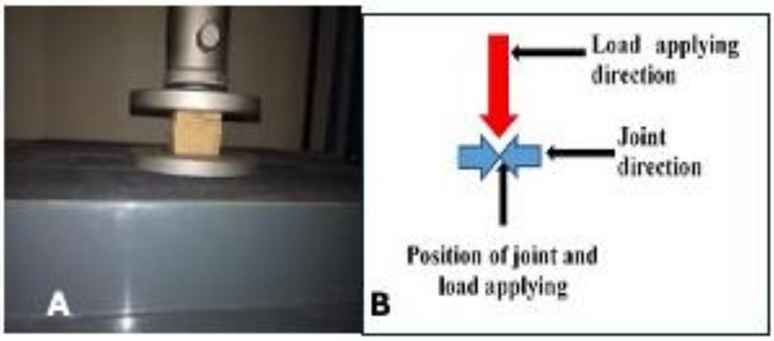


Fig. 5 Loading setup used in Compression perpendicular to grain test.

Joint direction is highlighted in the figure 4 and 5 as above.

RESULTS AND DISCUSSION

The fiber properties of six hardwood species and one softwood species were compared as shown in Table 2.

Tab. 2 Fiber properties of timber species.

Timber species	Density (kg/m^3)	Average fiber length (40X) µm	Average Fiber diameter (40X) µm	Average Lumen diameter (40X) µm	Fiber wall thickness (40X) µm	Runkel Ratio
Grandis	570	1147.72	20.64	13.47	3.59	0.35
Jack	645	2070.94	22.35	12.34	5.00	0.45
Kumbuk	756	1613.15	18.43	11.15	3.64	0.39
Mahogany	570	1431.68	20.48	13.82	3.33	0.33
Pine	465	3387.86	44.53	27.79	8.37	0.38
Satin	980	1225.43	11.28	4.92	3.18	0.56
Teak	720	1203.77	22.14	14.12	4.01	0.36

The highest average fiber length (3387.86 mm) was recorded in Pine, and the least (1147.72 mm) was from Grandis. Concerning average fiber diameter, the highest value (44.53 mm) was recorded in Pine, and the lowest (11.28 mm) was from Satin. The highest average lumen diameter (27.79 mm) was recorded in Pine, and the least (4.92 mm) was from Satin. For average fiber wall thickness, the highest measurement (8.37 mm) was recorded in Pine, and the lowest (3.18 mm) was in Satin. The thickness of the fiber cell wall is the primary factor governing the density and mechanical strength of hardwood timbers (Wiedenhoeft, 2010). The present study shows a similar trend; the Runkel ratio varies from 0.35 to 0.56. Satin recorded the highest (0.56) Runkel ratio (Figure 6).

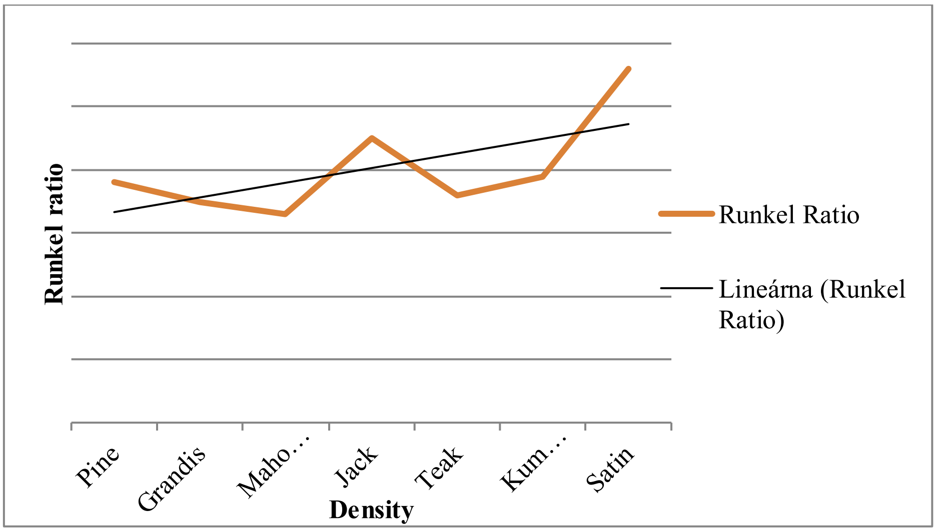


Fig. 6. Relationship between densities vs. runkel ratio.

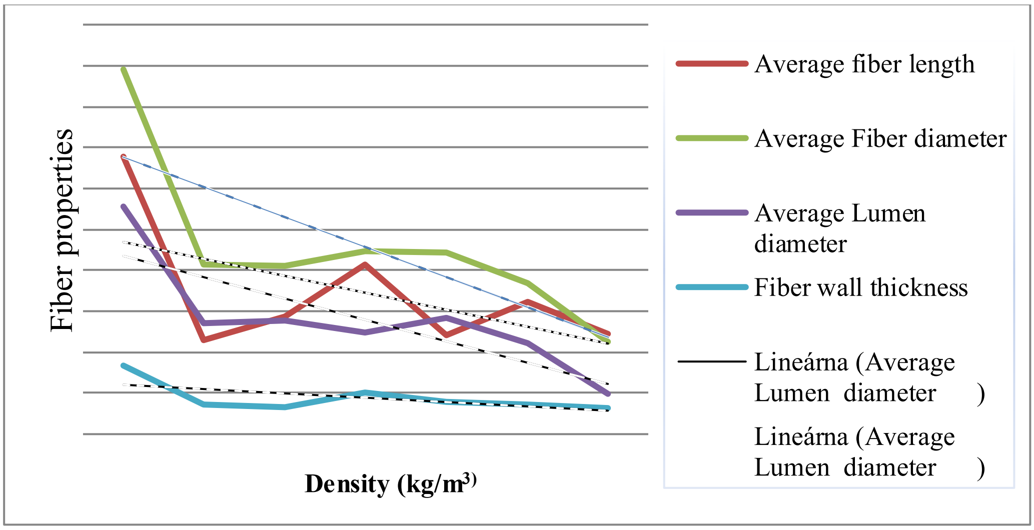


Fig. 7. Relationship between densities vs. fiber properties.

Average density values of seven tree species varied as Satin (980 kg/m3), Kumbuk (756 kg/m3), Teak (720 kg/m3), Jack (645 kg/m3), Grandis (570 kg/m3), Mahogany (570 kg/m3), and Pine (465 kg/m3) in descending order. As depicted in Figure 6, decreasing trends were observed in the relationships between the fiber properties and the densities. A similar trend was observed in previous research by Kiaei and Moya (2015). The effect of fiber dimension on the wood density of three parts (stem, branch and root wood) of alder wood was determined by Kiaei and Moya in the stem, branch, and root wood of *Alnus glutinosa* L and results emphasis that a significant differences were not found between fiber length, fiber diameter and lumen diameter with wood density for each of wood samples. In contrast, in the total of wood samples, there is a significantly negative relationship between fiber length, fiber diameter, and lumen diameter with wood oven-dried densities. Mechanical properties of the seven selected tree species are shown in Table 3.

Tab. 3 Strength values of the mechanical tests.

Timber species	Compression parallel to grain (N/mm^2)	Compression perpendicular to grain (N/mm^2)	MOR (N/mm^2)	Bending (N/mm^2)	MOE (N/mm^2)
Grandis	45.19	4.91	71.13	36.56	8203.65
Jack	41.02	13.42	64.47	36.55	5765.51
Kumbuk	33.81	7.39	52.86	21.21	4615.56
Mahogany	30.31	8.20	60.16	32.58	5775.78
Pine	45.78	5.53	59.90	28.56	7149.67
Satin	46.36	16.65	106.60	50.85	10819.05
Teak	47.40	9.20	84.36	44.36	8538.29

The proportional limit is the deformation of a material or structural element when a load is applied perpendicular to its length, causing it to curve or deflect. In contrast, Modulus of Rupture (MOR) is a material property that measures the maximum stress a material can withstand in bending, proportional to its proportional limit before it breaks, often determined through a flexural test. While the bending proportional limit describes behavior under load, MOR quantifies the breaking point under that load, making it especially important for assessing the strength of brittle materials like wood, concrete, or ceramics. The highest strength value in the compression parallel to grain test (47.40 N/mm^2) was recorded in the Teak specimen, and the lowest (30.31 N/mm^2) was in the Mahogany specimen. Satin and Pine, respectively, recorded the highest (16.65 N/mm^2) and the lowest (5.53 N/mm^2) strength values of the compression perpendicular to grain tests. About the bending proportional limit strength, the highest value (50.85 N/mm^2) was recorded in Satin, while the lowest (21.21 N/mm^2) was shown in Kumbuk. Satin and Kumbuk recorded the highest (106.6 N/mm^2) and the lowest (52.86 N/mm^2) modulus of rupture strength values. For the modulus of elasticity, the highest stiffness value (10819.05 N/mm^2) was recorded in Satin, and the lowest (4615.56 N/mm^2) was shown in Kumbuk.

Tab. 4 Regression R-sq. values of fiber properties of test tree species.

Mechanical Test	Fiber properties	R-Sq.	R-Sq. (adj)	Sig. P value
MOR	Fiber length	20.6%	4.8%	0.306
bending proportional limit	Fiber length	21.1%	5.4%	0.299
MOE	Fiber length	8.7%	0.0%	0.521
bending proportional limit	Average fiber diameter	19.5%	3.4%	0.321
MOR	Average fiber diameter	23.4 %	8.1 %	0.237
MOE	Average fiber diameter	5.6%	0.0%	0.608
bending proportional limit	Fiber wall thickness	11.2%	0.0%	0.463
MOR	Fiber wall thickness	12.3%	0.0%	0.440
MOE	Fiber wall thickness	2.1%	0.0%	0.754
Com. parallel to grain	Fiber length	1.1%	0.0%	0.821
Com. parallel to grain	Fiber diameter	4.1%	0.0%	0.662
Com. parallel to grain	Fiber wall thickness	9.8%	0.0%	0.493
Com. perpendicular to grain	Fiber length	6.9%	0.0%	0.569
Com. perpendicular to grain	Fiber diameter	31.6%	17.9%	0.189
Com. perpendicular to grain	Fiber wall thickness	10.6%	0.0%	0.477

No significant correlations among fiber properties (fiber length, fiber diameter, and fiber wall thickness) with strength values (compression parallel to grain and compression perpendicular to grain) are observed (Sig. P value > 0.05). Similarly, no significant correlations were found among fiber properties (fiber length, fiber diameter, and fiber wall thickness) vs. bending proportional limit, MOR, and MOE (Sig. P value > 0.05) (See Figure 7). A previous study by Jan Baar *et al.* in 2014 revealed a weak correlation between density and the MOR.

However, according to the research conducted by Bhat *et al*. (2001), regarding the fiber length of Teak, the wet-site home-garden exhibited shorter fibers (1.16 mm) than the dry and plantation sites, with values of 1.24 mm each (Bhat *et al.,* 2001). Hence, selected sites of the specimens also contributed to these results. Another study showed that nutrient distribution had a significant positive correlation with wood quality, wood density, and fiber length (Rizki and Andrian, 2015).

CONCLUSION

The relationships between fiber properties and mechanical properties of seven tree species: Grandis (Eucalyptus grandis) and Jack (Aartocarpus heterphyllus), Kumbuk (Terminalia arjuna), Mahogany (Swietenia macrophylla), Pine (Pinus caribaea), Satin (Chloroxylon swietenia), and Teak (Tectona grandis) were assessed in the study. The highest average fiber length, fiber diameter, lumen diameter, and fiber wall thickness were recorded in Pine (Softwood species). No significant correlations among fiber properties (fiber length, fiber diameter, and fiber wall thickness) and compression tests (compression parallel to grain and compression perpendicular to grain) were observed. Satin shows the highest mechanical strength, the highest runkler ratio, and the highest density value.

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