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The Relationships between Fiber Parameters and Mechanical Properties of Timber Species

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Abstract. This study investigates the variations in mechanical properties and fiber parameters, along with wood densities, of 7 timber species commonly used in Sri Lanka's furniture industry as a promising one. Key parameters measured include wood density, compressive strength (both parallel and perpendicular to grain), and static bending properties, following the standards outlined in BS 373:1957. Mechanical tests have been conducted using a universal testing machine (UTM-100PC), while fiber parameters have been analyzed via a modified Franklin's method. The results indicate no significant correlations between fiber parameters (fiber length, diameter, and wall thickness) and mechanical properties such as compression and bending strengths, including modulus of rupture and modulus of elasticity. However, the fiber parameters have exhibited a decreasing trend with increasing wood density. Notably, timber species with higher density and elevated Runkel ratios have demonstrated greater strength values, suggesting the influence of fiber wall thickness relative to pore size on mechanical performance. The findings obtained imply that wood density and fiber structural ratios play a more critical role in determining strength than isolated fiber dimensions. The study contributes to a better understanding of the physical and mechanical behavior of local timber species and provides valuable data for optimizing timber selection and processing in Sri Lanka's furniture manufacturing sector.

Keywords: density, fiber properties, mechanical test, timber

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Научная статья

Взаимосвязь между параметрами волокон и механическими свойствами древесных пород

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Аннотация. Рассматриваются различия в механических свойствах и параметрах волокон, а также плотности древесины 7 пород, широко используемых в мебельной промышленности Шри-Ланки. К ключевым измеряемым параметрам в соответствии со стандартом BS 373:1957 относятся плотность древесины, прочность при сжатии (как параллельно, так и перпендикулярно волокнам) и при статическом изгибе. Механические испытания проводились с применением универсальной испытательной машины (UTM-100PC), а параметры волокон анализировались посредством модифицированного метода Франклина. Результаты демонстрируют отсутствие существенной корреляции между параметрами волокна (длина волокна, диаметр и толщина стенки) и механическими свойствами, такими как прочность на сжатие и изгиб, включая модуль разрыва и модуль упругости. Однако с увеличением плотности древесины параметры волокна демонстрируют тенденцию к ухудшению. Примечательно, что породы древесины с более высокой плотностью и повышенным коэффициентом Рункеля имеют большую прочность, что свидетельствует о влиянии соотношения толщины стенки волокна и просвета между волокнами на механические свойства. Полученные данные указывают на превалирующую роль при определении прочности волокон плотности древесины и структурных соотношений волокон по сравнению с размерами отдельных волокон. Исследование способствует пониманию физических и механических свойств местных пород древесины и оптимизации отбора и обработки древесины в процессе мебельного производства в Шри-Ланке.

Ключевые слова: плотность, характеристики волокна, механическое испытание, древесина

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Introduction

The history of wood architecture reveals that architects and craftsmen with natural creative skills have existed from the beginning of civilization. As a result of low quality and strength of wood which has been used by these ancestral architects and craftsmen, some of the wood creations have not lasted for long time [10, 12].

Wood is an excellent material for roof and other construction works, furniture, interior decorations, doors and window frames, paneling, partition borders, floorings, wood carvings, musical instruments etc. Mechanical properties are very important in deciding on the applicability and suitability of timbers for both structural and non-structural purposes. However these properties vary with the species and also with some other factors such as moisture content, the number and degree of defects, etc.

In hardwood, the anatomical organization is made up by vessels, fibers, parenchyma cells and wood rays. Fibers are the principal element that is responsible for the strength of wood [11]. Fiber length, fiber cell wall thickness, pore diameter and size of the pits are the characteristics associated with wood properties such as wood density, modulus of rupture, modulus of elasticity, shrinkage etc. Wood density is an important property for both solid wood and fiber products [6]. Softwood fibers are generally long (2–3 mm) [2–4], while hardwood fibers are shorter (1 mm) and less flexible [15].

The Runkel ratio, commonly used in pulp and paper industry to assess fiber quality, is not a primary criterion for selecting wood in traditional furniture production. Instead, furniture manufacturing typically focuses on macroscopic properties such as strength, density, workability, and aesthetic appeal. However, the Runkel ratio may have indirect relevance in the furniture industry, particularly for engineered wood products like MDF or particleboard, where fiber morphology affects material performance. In such contexts, the Runkel ratio can provide useful insights into fiber rigidity and cell wall thickness, contributing to quality. The Runkel ratio, the ratio between fiber cell wall thickness and pore size 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 of the mechanical properties and fiber parameters of 7 timber species commonly used in furniture industry in Sri Lanka have been studied during this research.

Materials and Methods

7 timber species commonly used for furniture manufacturing have been collected from the Southern and Central Provinces of Sri Lanka (Table 1).

Table 1

Timber species selected for the research

| Common name | Botanical name | Family | Timber class* | Province |
|------------------|---------------------------------|--------------|---------------|----------|
| Rose gum | <i>Eucalyptus grandis</i> | Myrtaceae | 2 | Central |
| Jackfruit | <i>Artocarpus heterophyllus</i> | Moraceae | Luxury | Southern |
| Arjuna | <i>Terminalia arjuna</i> | Combretaceae | Special | |
| Mahogany | <i>Swietenia macrophylla</i> | Meliaceae | Luxury | |
| Caribbean pine | <i>Pinus caribaea</i> | Pinaceae | 3 | Central |
| Ceylon satinwood | <i>Chloroxylon swietenia</i> | Rutaceae | Luxury | Southern |
| Teak | <i>Tectona grandis</i> | Lamiaceae | Super luxury | |

*Source: Timber classification by State Timber Corporation, Sri Lanka.

The samples for the tests have been prepared from defect-free sawn woods.

Determination of Wood Density. Each timber species sample has been replicated 10 times. Wood density has been determined based on the volume when green and oven-dry weight. The dry weight of timber samples has been obtained by placing them in an oven at 105 °C for 48 h (BS EN 373:1957). Basic density has been calculated using the following equation:

$$\text{Basic Density} = \frac{\text{Oven-dry wood weight (kg)}}{\text{Volume of green wood (m}^3\text{)}}.$$

The samples placed in normal room temperature conditions have shown good structural performance compared to the ones placed in hot and wet conditions [17].

Determination of Moisture Content. The samples (each measuring 20 × 20 × 20 mm) have been first weighed, and then oven-dried at 103 °C until a constant weight. The moisture content (r , %) of each sample has been determined using the equation below:

$$r = \frac{M_r - M_0}{M_0} \times 100,$$

where M_r is the weight of the moist sample; M_0 is the weight of the fully dried sample.

Measuring Fiber Dimensions. Fiber morphological analysis has been performed according to the modified Franklin's method [7]. The matchstick size splints have been 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 has been to ensure dehydrating and bleaching the samples. The glacial acetic acid has been used to dissolve lignin enabling easy separation of the fibers (Fig. 1).

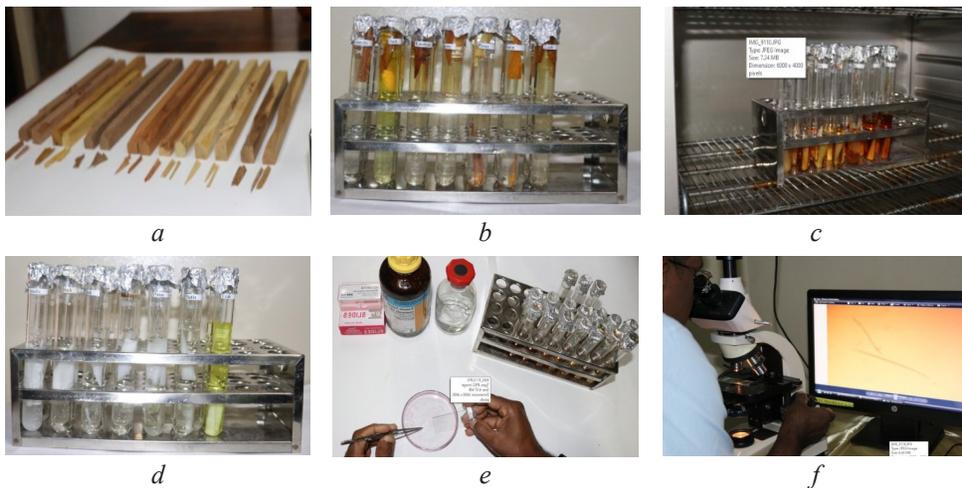


Fig. 1. The preparation of slides for measuring fiber properties:
a – matchstick size splints taken from timber samples; *b* – splints dipped into the mixture of glacial acetic acid and hydrogen peroxide; *c* – rack with test tubes kept at 60 °C;
d – test tubes after dissolving lignin; *e* – mounting the splints on the the slides with Canada balsam; *f* – measuring fiber dimensions

The material in boiling tubes has transformed into pulp after keeping it at a temperature of 65 °C for a period of 24 h. Then the remains have been rinsed in distilled water and shaken gently to ensure measurable individual cells of xylem tissues. The fibers have been carefully removed using a painting brush and mounted on

the slides using Canada balsam. They have then been covered with cover slips, named and kept in an oven at 30° C for 2 days to complete drying. The micrographs have been taken to measure the fiber thickness, pore diameter and wall thickness. The fiber dimensions have been measured subjectively to minimize the possible variations in the fibers due to such factors as the age and sampling height of the tree, etc. [13, 14].

Micrometrics SE Premium 4.1 software has been used to determine the fiber dimensions.

Calculating the Runkel Ratio. The Runkel ratio has been calculated using the following equation [14]:

$$\text{Runkel ratio} = \frac{D_2 - D_1}{D_2},$$

where D_2 is the cell thickness; D_1 is the pore diameter and $D_2 - D_1$ is the cell wall thickness.

Determination of Flexural Strength. The samples have been cut from defect-free, seasoned wood planks (average moisture content 12 %). 10 wood samples have been prepared representing each timber species. The dimensions of each replicate have been 20 × 20 × 300 mm. They have been prepared following the methods of testing the small clear samples as stated in BS 373:1957.

A universal testing machine (UTM-100PC) manufactured in Australia has been used for testing (Fig. 2). An assembling pressure of 6 MPa has been applied in this study [5, 19].



Fig. 2. The Universal testing machine (UTM-100PC)

Bending strength, modulus of rupture (MOR) and modulus of elasticity (MOE) values have been calculated using the equations below, respectively, corresponding to the test data:

$$\text{Bending Strength} = \frac{3F_1L_1}{2bd^2},$$

where F_1 is the serviceability force (N); L_1 is the length of the span (mm); b is the width of the sample (mm); d is the depth/thickness of the sample (mm).

$$\text{MOR} = \frac{3F_2L_1}{2bd^2},$$

where F_2 is the maximum force (N); L_1 is the length of the span (mm); b is the width of the sample (mm); d is the depth/thickness of the sample (mm).

$$\text{MOE} = \frac{F_3L_1^3}{4\delta bd^3},$$

where F_3 is the maximum load at proportionate state (N); L_1 is the length of the beam between supports (mm); b is the width of the sample (mm); d is the depth/thickness of the sample (mm); δ is the deflection of timber sample (mm).

Calculation of Compression Strength. The samples prepared for compression parallel and perpendicular to grain are shown in Fig. 3.

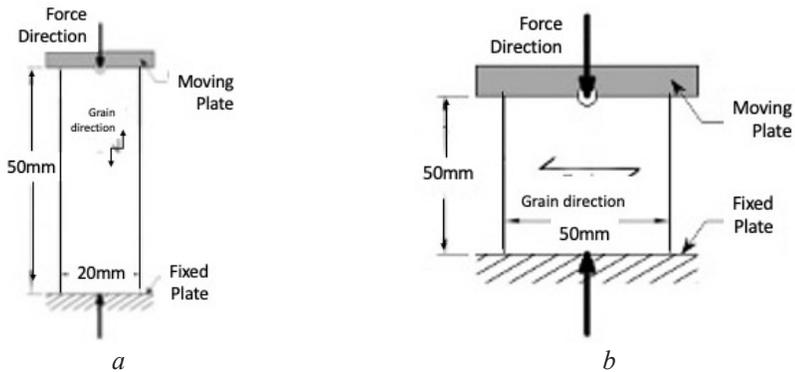


Fig. 3. The schematic presentation of compression tests: *a* – compression parallel to grain; *b* – compression perpendicular to grain

The load on timber section at proportionate state has been measured. The serviceability compressive strength has been calculated using the equation below.

$$\text{Serviceability compressive strength} = \frac{\text{Max load on the sample at proportionate state}}{\text{Load acting area}} \text{ N/mm}^2.$$

The direction of the load applied to the sample is shown in Fig. 4 and 5.

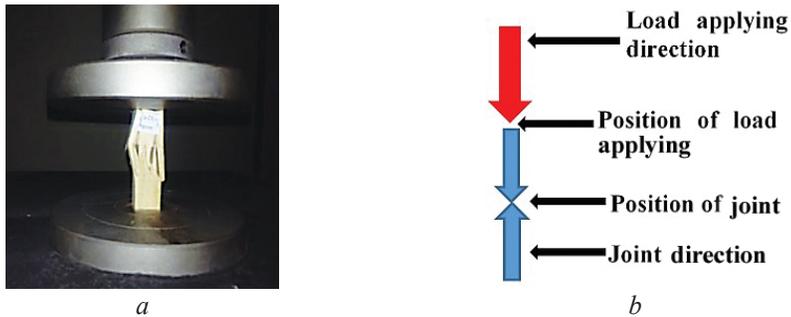


Fig. 4. The compression parallel to grain test: *a* – loading setup; *b* – load applying direction

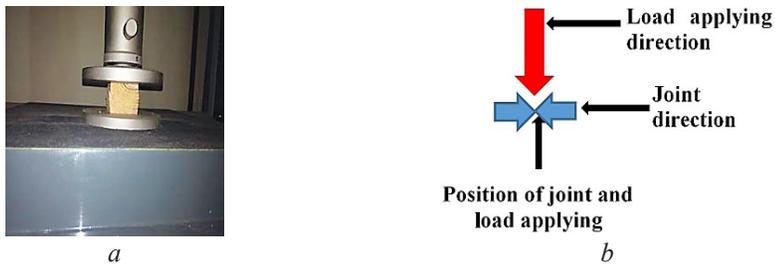


Fig. 5. The compression perpendicular to grain test: *a* – loading setup; *b* – load applying direction

Results and Discussion

The fiber parameters of 6 hardwood species and 1 softwood species have been compared as shown in Table 2.

Table 2

The fiber parameters of timber species

| Timber species | Basic density, kg/m ³ | Average | | | | The Runkel ratio |
|------------------|----------------------------------|------------------|--------------------|-------------------|--------------------------|------------------|
| | | fiber length, μm | fiber diameter, μm | pore diameter, μm | fiber wall thickness, μm | |
| Rose gum | 570 | 1,147.72 | 20.64 | 13.47 | 3.59 | 0.35 |
| Jackfruit | 645 | 2,070.94 | 22.35 | 12.34 | 5.00 | 0.45 |
| Arjuna | 756 | 1,613.15 | 18.43 | 11.15 | 3.64 | 0.39 |
| Mahogany | 570 | 1,431.68 | 20.48 | 13.82 | 3.33 | 0.33 |
| Caribbean pine | 465 | 3,387.86 | 44.53 | 27.79 | 8.37 | 0.38 |
| Ceylon satinwood | 980 | 1,225.43 | 11.28 | 4.92 | 3.18 | 0.56 |
| Teak | 720 | 1,203.77 | 22.14 | 14.12 | 4.01 | 0.36 |

The highest average fiber length (3,387.86 μm) has been recorded in Caribbean pine and the lowest (1,147.72 μm) – in rose gum. As for average fiber diameter, the highest value (44.53 μm) has been recorded in Caribbean pine and the lowest (11.28 μm) – in Ceylon satinwood. The highest average pore diameter (27.79 μm) has been recorded in Caribbean pine and the lowest (4.92 μm) – in Ceylon satinwood. As for average fiber wall thickness, the highest measurement (8.37 μm) has been recorded in Caribbean pine and the lowest (3.18 μm) – in Ceylon satinwood. The thickness of the fiber cell wall is the major factor governing density and mechanical strength of hardwood timbers [18]. In present study it shows the similar trend and the Runkel ratio varies from 0.35 to 0.56, with Ceylon satinwood having the highest (0.56) Runkel ratio (Fig. 6).

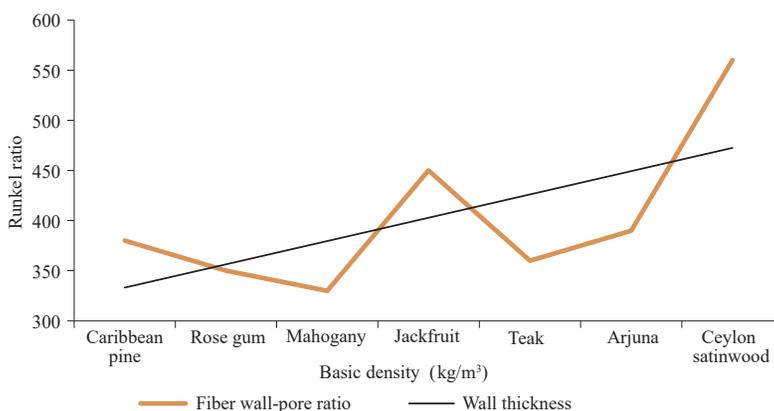


Fig. 6. The relationship between basic densities and the Runkel ratio in timber species under study

Average basic density values of 7 timber species are listed in a descending order: Ceylon satinwood – 980 kg/m³, arjuna – 756 kg/m³, teak – 720 kg/m³, jackfruit – 645 kg/m³, rose gum – 570 kg/m³, mahogany – 570 kg/m³, and Caribbean pine – 465 kg/m³. As depicted in Fig. 7, decreasing trends can be observed in the relationships between the fiber parameters and basic densities. Similar trend has been recorded in the research conducted by M. Kiaei and R.M. Roque in 2015 [8]. The effect of

fiber dimensions on the wood density of 3 parts (stem, branch and root wood) of alder wood has been determined by M. Kiaei and R.M. Roque in the stem, branch and root wood of *Alnus glutinosa* L. and the results emphasise that no significant differences have been found between fiber length, fiber diameter and pore diameter with wood density for each of the samples, while in the totality of the samples, there are significantly negative relationships between fiber length, fiber diameter and pore diameter with oven-dried wood densities.

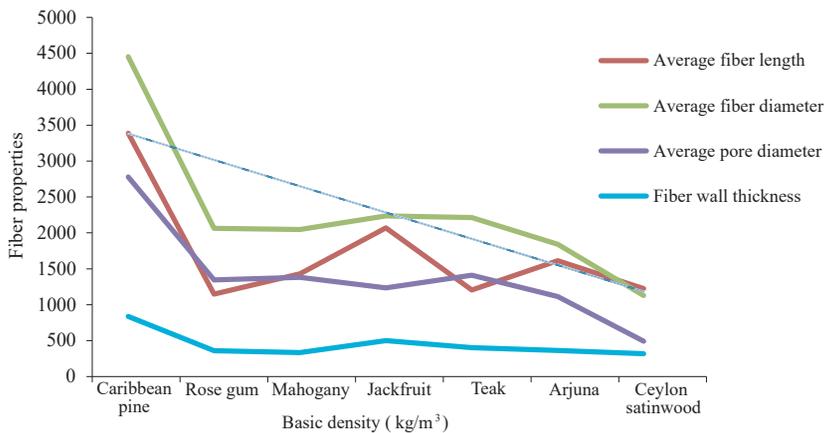


Fig. 7. The relationship between basic densities and fiber parameters in timber species under study

The mechanical properties of the selected 7 timber species are shown in Table 3.

Table 3

The mechanical properties of timber species under study

| Timber species | Compression (N/mm ²) | | MOR (N/mm ²) | Bending strength (N/mm ²) | MOE (N/mm ²) |
|------------------|----------------------------------|------------------------|--------------------------|---------------------------------------|--------------------------|
| | parallel to grain | perpendicular to grain | | | |
| Rose gum | 45.19 | 4.91 | 71.13 | 36.56 | 8,203.65 |
| Jackfruit | 41.02 | 13.42 | 64.47 | 36.55 | 5,765.51 |
| Arjuna | 33.81 | 7.39 | 52.86 | 21.21 | 4,615.56 |
| Mahogany | 30.31 | 8.20 | 60.16 | 32.58 | 5,775.78 |
| Caribbean pine | 45.78 | 5.53 | 59.90 | 28.56 | 7,149.67 |
| Ceylon satinwood | 46.36 | 16.65 | 106.6 | 50.85 | 10,819.05 |
| Teak | 47.40 | 9.20 | 84.36 | 44.36 | 8,538.29 |

The highest value of the compression parallel to grain (47.40 N/mm²) has been recorded in the teak sample and the lowest (30.31 N/mm²) – in mahogany. Ceylon satinwood and Caribbean pine, respectively, have shown the highest (16.65 N/mm²) and the lowest (5.53 N/mm²) values of compression perpendicular to grain. As for bending strength, the highest value (50.85 N/mm²) has been recorded in Ceylon satinwood while the lowest (21.21 N/mm²) has been revealed in arjuna. Ceylon satinwood and arjuna have shown the highest (106.6 N/mm²) and the least (52.86 N/mm²) MOR values, respectively. As for MOE, the highest value (10,819.05 N/mm²) has been recorded in Ceylon satinwood and the lowest (4,615.56 N/mm²) – in arjuna.

Table 4

Regression R-squared values of fiber parameters for timber species under study

| Mechanical properties | Fiber parameters | R-Sq, % | R-Sq (adjusted), % | Significant <i>P</i> value |
|------------------------------------|------------------|---------|--------------------|----------------------------|
| MOR | Length | 20.6 | 4.8 | 0.306 |
| Bending strength | | 21.1 | 5.4 | 0.299 |
| MOE | | 8.7 | 0 | 0.521 |
| Bending | Average diameter | 19.5 | 3.4 | 0.321 |
| MOR | | 23.4 | 8.1 | 0.237 |
| MOE | | 5.6 | 0 | 0.608 |
| Bending strength | Wall thickness | 11.2 | 0 | 0.463 |
| MOR | | 12.3 | 0 | 0.440 |
| MOE | | 2.1 | 0 | 0.754 |
| Compression parallel to grain | Length | 1.1 | 0 | 0.821 |
| | Diameter | 4.1 | 0 | 0.662 |
| | Wall thickness | 9.8 | 0 | 0.493 |
| Compression perpendicular to grain | Length | 6.9 | 0 | 0.569 |
| | Diameter | 31.6 | 17.9 | 0.189 |
| | Wall thickness | 10.6 | 0 | 0.477 |

No significant correlations among fiber parameters (fiber length, fiber diameter and fiber wall thickness) and strength values (compression parallel and perpendicular to grain) have been observed (significant *P* value > 0.05). Similarly no significant correlations have been found between fiber parameters (fiber length, fiber diameter and fiber wall thickness) and bending strength, MOR and MOE (significant *P* value > 0.05) (Table 4). Previous research conducted by J. Baar et al. in 2014 has revealed a weak correlation between wood density and MOR [1].

However according to the research conducted by P.K. Thulasidas et al. (2001) on the fiber length of teak, the wet site home-gardened one has exhibited shorter fiber length (1.16 mm) than the dry and plantation site ones with values equaling 1.24 mm each [4, 16]. Hence, the habitat also affects the results. Another research has shown that nutrient distribution has a significant positive correlation with wood quality, wood density and fiber length [5, 9].

Conclusion

This study has been aimed at assessing the relationships between fiber parameters and mechanical properties of 7 wood species: rose gum (*Eucalyptus grandis*), jackfruit (*Aartocarpus heterophyllus*), arjuna (*Terminalia arjuna*), mahogany (*Swietenia macrophylla*), Caribbean pine (*Pinus caribaea*), Ceylon satinwood (*Chloroxylon swietenia*) and teak (*Tectona grandis*). The highest average fiber length, fiber diameter, pore diameter and fiber wall thickness have been recorded in Caribbean pine (softwood species).

While the Runkel ratio is primarily used in the pulp and paper industry to evaluate fiber quality, it also holds contextual relevance in the furniture industry, particularly in relation to engineered wood products. Although studies indicate no significant correlations between fiber parameters (fiber length, diameter, and wall thickness) and mechanical properties such as compression strength (parallel and perpendicular to grain), modulus of rupture, and modulus of elasticity, wood's structural components

nevertheless exert influence. Mechanical properties arise from complex interactions among anatomical features, including cell wall thickness and density, which more directly affect strength and stiffness. Thus, fiber parameters contribute indirectly via their effects on wood structure and density, rather than through simple direct correlations. For instance, Ceylon satinwood exhibits the highest mechanical strength, density, and Runkel ratio, suggesting that in some species, denser fiber structures may correspond to stronger mechanical performance. Therefore, while not a standalone selection criterion, the Runkel ratio can still offer valuable supplementary insight into the internal structure of wood that may, in certain cases, align with desirable physical and mechanical properties for furniture applications.

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