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UNLEASHING THE POTENTIAL: INVESTIGATING TENSILE STRENGTH GRADE STRESSES IN STRUCTURAL-SIZED MALAYSIAN TROPICAL TIMBER IN ACCORDANCE TO BS EN 408

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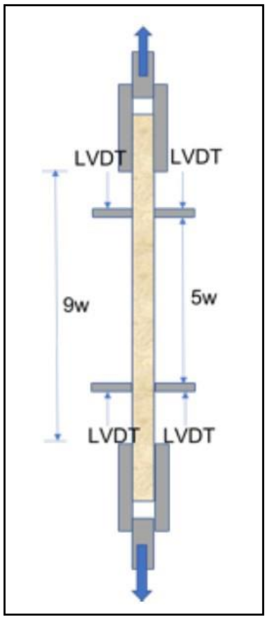
Graphical abstract



Abstract

There is no direct measurement of tensile strength have been determined for Malaysian tropical hardwood. The usual approach is to consider the tensile strength of timber as 60% of the small clear specimen's bending strength values, as specified in MS 544: Part 2:2001. However, this method proves inadequate for engineering applications as it fails to provide precise and accurate values. Therefore, in this study, nine (9) species of Malaysian tropical hardwoods were selected namely Balau (*Shorea spp.*), Kempas (*Koompassia Malaccensis*), Kelat (*Syzygium spp.*) Kapur (*Dryobalanops spp.*), Resak (*Vatica spp.*), Keruing (*Dipterocarpus spp.*), Mengkulang (*Heritiera spp.*), Light Red Meranti (*Shorea spp.*) and Geronggang (*Cratoxylum spp.*). The specimens were tested in structural sizes and subjected to tensile strength testing in accordance with BS EN 408:2010. Subsequently, the results were transformed into grade stresses following the guidelines of MS 544: Part 3. The lowest mean tensile strength (42.23N/mm^2) and Modulus of Elasticity (11972N/mm^2) was obtained by the lowest density timber Light Red Meranti while the highest mean tensile strength (84.46N/mm^2) and highest Modulus of Elasticity (21329N/mm^2) was obtained by the high density Kempas species although not excelled by the highest density of the investigated species. The evaluation also indicated that the grade stresses of the structural specimens in this study surpass those published in MS 544: Part 3.

Keywords: Tensile test, Malaysian timber, Structural size, Grade stresses, Density, Green infrastructure

Abstrak

Tiada pengukuran langsung kekuatan tegangan telah ditentukan untuk kayu keras tropika Malaysia. Pendekatan biasa adalah dengan menganggap kekuatan tegangan kayu

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sebagai 60% daripada nilai kekuatan lenturan spesimen kecil tanpa kecacatan, seperti yang ditetapkan dalam MS 544: Bahagian 2:2001. Walaubagaimanapun, kaedah ini terbukti tidak mencukupi untuk aplikasi kejuruteraan kerana ia gagal memberikan nilai yang tepat. Oleh itu, dalam kajian ini, sembilan (9) spesies kayu keras tropika Malaysia telah dipilih, iaitu Balau (Shorea spp.), Kempas (Koompassia Malaccensis), Kelat (Syzygium spp.), Kapur (Dryobalanops spp.), Resak (Vatica spp.), Keruing (Dipterocarpus spp.), Mengkulang (Heritiera spp.), Meranti Merah Muda (Shorea spp.) dan Geronggang (Cratoxylum spp.). Spesimen ini diuji dalam dimensi struktur dan diuji untuk kekuatan tegangan mengikut BS EN 408:2010. Seterusnya, hasil ujian ini diubah menjadi tegasan gred mengikut garis panduan MS 544: Bahagian 3. Kekuatan tegangan minima purata (42.23N/mm^2) dan Modulus Elastisiti (11972N/mm^2) diperoleh daripada jenis kayu Meranti Merah dengan ketumpatan terendah. Kekuatan tegangan purata tertinggi (84.46N/mm^2) dan Modulus Elastisiti tertinggi (21329N/mm^2) pula diperoleh daripada jenis kayu Kempas dengan ketumpatan tinggi walaupun tidak melebihi ketumpatan tertinggi daripada semua jenis kayu yang dikaji. Penilaian juga menunjukkan bahawa tegasan gred dimensi struktur dalam kajian ini melebihi nilai yang diterbitkan dalam MS 544: Bahagian 3.

Kata kunci: Kekuatan tegangan, Kayu Malaysia, Dimensi struktur, Tegasan gred, Ketumpatan, Infrastruktur hijau

1.0 INTRODUCTION

In the tropical rainforest of Malaysia, there are over 2500 species of wood. 10% of these species can be utilized as structural elements indefinitely if replanting is performed [1]. Timber stands out as a natural and renewable building material, with commendable ecological attributes such as carbon sequestration and low embodied energy. Compared to other structural materials like steel and concrete, the energy required for converting trees into wood and, subsequently, into structural timber is significantly lower. In modern construction practices, timber is used for a wide range of structural elements, including roof trusses, beams, and columns, to withstand tensile, shear, bending, and compression loads [2].

Furthermore, engineered timber products, such as glued laminated timber (glulam), cross-laminated timber (CLT), and laminated veneer lumber (LVL), have witnessed increased popularity due to their ability to enhance structural integrity and reduce the influence of defects [3]. For example, glulam and CLT can optimize the structural values of a renewable source by laminating a number of smaller pieces of wood and by diminishing the negative impact of knots and other small defects in each board [4]. These engineered structural products can be used as columns or beams which can be straight or curved shapes. In order for the timbers to be used as structural application, it is important to provide information on the mechanical properties of timbers [5]. The execution of auxiliary timber is affected by the essential wood properties, for example, ties [6]. Tensile strength holds significant importance in the design of structural engineered timber, particularly for applications such as roof trusses or the tension flange of an I-beam or box beam, where tension properties play a predominant role in bearing loads.

The current timber design practices in Malaysia rely on strength data obtained from small clear specimens, as per MS 544 Part 2. These clear specimens lack any defects, making it convenient to determine timber mechanical properties. While the stresses derived from this method are technically useful for determining timber mechanical properties, they do not provide accurate values for structural engineering applications due to various biological growth characteristics, such as knots, compression wood zones, and oblique fiber direction [4]. These growth characteristics, which originally served the needs of the tree, can significantly reduce the strength of the timber once it is sawn. Moreover, the presence and characteristics of knots and other defects vary from one timber board to another, making it challenging to accurately predict the true tensile strength value of the timber. Therefore, stresses obtained from small clear specimens need to be adjusted by reducing certain factors to reflect the structural size strength. The differences in size and the number of defects directly impact the performance of tensile strength.

During the mid-1960s, certain permissible properties for timber were subject to examination as an increased amount of data from full-size timber specimens became accessible [7]. This was particularly notable for tension parallel to grain. As a result, in 1968, ASTM D245 introduced a new provision that established tension values at 55% of the bending values for visually graded timber. Experiments have shown that the published bending values for small clear specimens might be overestimated, with an excess of up to 40% for MOE (Modulus of Elasticity) and 20% for MOR (Modulus of Rupture) [8]. By the 1970s, further tests conducted on full-size timber provided substantial evidence indicating that the values obtained from visually graded small clear specimens were no longer suitable [9]. Additionally, Mohd Jamil *et al.* [10] observed a weak correlation between small clear and structural size.

As per MS 544: Part 2:2001, the tensile strength is typically considered to be 60% of the bending strength for the same grade. However, there is a lack of sufficient recorded data for the tensile strength in structural sizes [11]. Having precise data for tensile strength is crucial for effective design and optimal utilization of timber. To address this need for reliable data, a study was conducted to investigate the tensile strength and grade stresses of selected Malaysian tropical timber using structural-sized specimens. Additionally, the study examined the relationship between density with tensile strength and MOE (Modulus of Elasticity).

2.0 METHODOLOGY

2.1 Material

Nine (9) type of timber species were selected in this study which is Balau (*Shorea spp.*), Kempas (*Koompassia Malaccensis*), Kelat (*Syzygium spp.*) Kapur (*Dryobalanops spp.*), Resak (*Vatica spp.*), Keruing (*Dipterocarpus spp.*), Mengkulang (*Heritiera spp.*), Light Red Meranti (*Shorea spp.*) and Geronggang (*Cratoxylum spp.*). They were chosen based on their availability in the market and their common commercial use in Malaysia, with the aim of representing a diverse range of wood strengths. Because all the timber was procured through a typical timber trading company, it is not possible to pinpoint their exact botanical genus. This choice was made to accurately reflect the typical utilization of timber in real-world scenarios. Nevertheless, it's important to note that all of these timber types come with a Chain of Custody (CoC) certification for their source, enabling the tracking of certified materials from the forest to the final product. This ensures that the origin of the wood can be traced throughout all stages of processing and distribution back to the actual forest. Table 1 presenting the strength group and density for each timber species according to MS 544: Part 2:2010. Each of these specimens underwent visual grading by a professional grader from the Malaysian Timber Industry Board (MTIB) and was classified under the Hardwood Structural Grade (HSG) following the standards of BS 5756:2007. Subsequently, the samples underwent a kiln drying process to maintain a moisture content of less than 19%.

The tension specimens were prepared from a complete structural cross-section, ensuring a clear length of at least nine times the larger cross-sectional dimension, following the guidelines of BS EN408:2010+A1:2012. The specific dimensions and quantities of the test specimens can be found in Figure 1 and Table 2. In total, 1800 specimens were tested for this comprehensive study.

Table 1 Strength Group of selected timber (source MS 544 Part 2)

Strength Group	Sample ID	Trade name	Air - dry Density (kg/m³)
SG 1	*BLU*	*Balau*	*850 - 1155*
SG 2	*KMP*	*Kempas*	*770 – 1120*
SG 3	*KLT*	*Kelat*	*495 - 1010*
SG 4	*KPR*	*Kapur*	*580 – 820*
SG 4	*RSK*	*Resak*	*655 - 1155*
SG 5	*KRG*	*Keruing*	*595 - 865*
SG 5	*MKG*	*Mengkulang*	*625 - 895*
SG 6	*LRM*	*Light Red Meranti*	*385 – 755*
SG 7	*GRG*	*Geronggang*	*350 - 610*

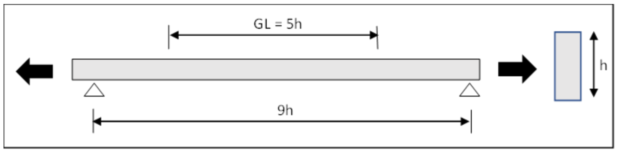


Figure 1 Requirement of the Specimens Size for Tensile Parallel to Grain Test According to EN 408: 2016 (h = thickness, GL = Gauge Length)

Table 2 Matrix of tensile test specimens

	Number of specimens per dimension			
Dimension(mm)	**20x80**	**25x100**	**30x120**	**15x75**
Clear Length (mm)	**720**	**900**	**1080**	**675**
Sample ID				
BLU	50	55	55	40
KMP	50	55	55	40
KLT	50	55	55	40
KPR	50	55	55	40
RSK	50	55	55	40
KRG	50	55	55	40
KRG	50	55	55	40
LRM	50	55	55	40
GRG	50	55	55	40

2.2 Testing Method

Tensile tests were conducted on structural-sized timber specimens using a 200-tonne capacity tensile machine located in the Heavy Structure Lab at School of Civil Engineering, College of Engineering, Universiti Teknologi Mara (UiTM), Shah Alam, Selangor (Figure 2). The clamping system employed in the tensile machine was non-hydraulic, which proved to be more suitable for timber material. Unlike hydraulic systems, the non-hydraulic clamping system allowed controlled clamping pressure to prevent crushing the timber during testing. Clamping pressures were determined during preliminary tests, tailored to the density of each timber species. For instance, Balau and Resak specimens required higher clamping pressure (4500 psi) compared to Light Red Meranti and Geronggang (3000 psi). The clamping pressure was set within specific limits to avoid damage during setup and slippage during testing.

Figure 2 (a) Tensile Machine 2000kN (b) Close Up Tensile Machine with Specimens Attached

The experimental setup involved clamping both ends of the tensile specimens, precisely positioned with LVDT sensors. The elongation of each specimen was assessed along a length equivalent to five times its width, carefully avoiding proximity to the grip ends. This measurement was performed using two sets of Linear Variable Differential Transformer (LVDT). Each set of LVDT is positioned at both surface of h and opposite to each other to minimize the effects of distortion as shown in Figure 3. The average elongation of both sets of LVDT are taken as the deformation of the sample.

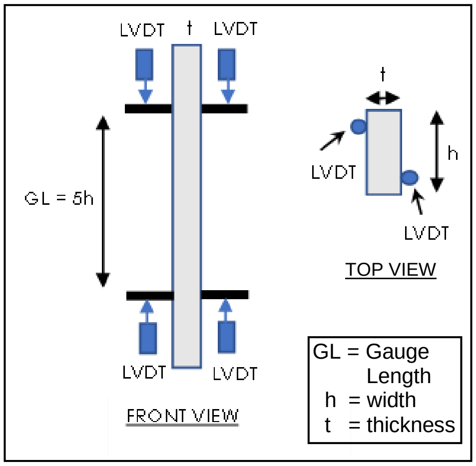


Figure 3 Position of LVDT for each specimen

Load was applied at a constant rate, adjusted to reach the maximum load (Fmax) within 5 ± 2 minutes. Preliminary tests were performed to ensure a consistent load rate for each timber species. The tests were conducted using split grips to ensure axial load and a computerized data acquisition system continuously recorded load and elongation readings until failure. The time to failure for each specimen was recorded, and any failure associated with the grips, such as slippage during testing, was noted.

3.0 RESULTS AND DISCUSSION

3.1 Tensile Strength, Modulus of Elasticity (MOE) and Density Properties

Nine (9) Malaysia tropical timber species were tested for tension tests. The results were computed based on the mean and coefficient of variation (COV) of tensile strength and MOE for each species. Additionally, moisture content (MC) and density were determined in relation to the tension test. Table 3 presents a concise overview of the mean tensile strength and MOE parallel to the grain for all species, along with their corresponding density and moisture content values.

Prior to conducting an in-depth analysis of the results, it is essential to highlight that the mean moisture contents of the individual species showed a relatively tight range, ranging from 13.7% to 15.7%. The overall mean moisture content across all species was 14.5%. Even though moisture content is the most important factor that can affect mechanical properties of solid-sawn and composite wood products, there are some contradictions about the effect of moisture content on tensile strength [12]. Next, the density results were discussed as density plays a significant role in influencing the scatter of wood strength and stiffness properties. The scatter of densities among individual species, expressed by the coefficient of variation, ranged from 8.4% (Kelat) to 14.8% (Geronggang), with an average of 11.4%. Notably, the scatter of densities among all investigated species was relatively low, considering the different sizes of the specimens. The lowest mean densities were recorded for Light Red Meranti and Geronggang, at 464 kg/m^3 and 482 kg/m^3, respectively, while the highest mean density was found for Resak. These density values fell within the ranges reported in 100 Malaysian Timber [13] for the respective species.

For tensile strength values, the scatter among individual species ranged from 26% (Keruing) to 37% (Geronggang), with an overall average of 32%. Although these scatter values are not low, they are within the expected range for timber material sampled from challenging growth origins and varies sizes. Notably, the strength scatter within each species was considerably higher than their respective density scatter. This indicates that parameters such as knots and the slope of grains have a significant influence on the observed scatter [12]. In terms of absolute strength values, both low density hardwoods, Light Red Meranti and Geronggang, displayed the lowest mean strengths at 42.3 N/mm^2 and 45.1 N/mm^2, respectively. On the other hand, the high density Kempas species exhibited the highest mean strength of 84.5 N/mm^2, surpassing even the highest density of the investigated species.

Table 3 Mean tensile strength, Modulus of Elasticity (MOE) and densities of nine (9) species

SAMPLE ID	MC (%)	DENSITY (kg/m^3)	TENSILE STRENGTH Mean (N/mm^2)	COV (%)	MODULUS OF ELASTICITY Mean (N/mm^2)	COV (%)
BLU	*15.3*	*952*	*62.56 ± 16.90*	*27.0*	*19716 ± 4985*	*25.2*
KMP	*13.7*	*886*	*84.46 ± 26.44*	*31.3*	*21329 ± 4631*	*21.7*
KLT	*15.7*	*908*	*66.32 ± 22.70*	*34.2*	*15905 ± 3907*	*24.6*
KPR	*14.9*	*762*	*67.15 ± 18.50*	*28.0*	*16238 ±3946*	*24.3*
RSK	*14.3*	*967*	*66.58 ± 23.03*	*34.6*	*17853 ± 4686*	*26.3*
KRG	*14.3*	*779*	*71.87 ± 19.03*	*26.4*	*17632 ±4683*	*26.5*
MKG	*14.4*	*675*	*76.27 ±25.58*	*33.5*	*18085 ±4475*	*24.7*
LRM	*13.7*	*464*	*42.23 ± 15.47*	*35.7*	*11972 ±3266*	*27.3*
GRG	*13.9*	*482*	*45.14 ± 16.73*	*37.1*	*11387 ± 2548*	*22.4*

In contrast, the modulus of elasticity displayed a significantly lower and more consistent scatter range both within and between species. The COV ranged from 21.7% (Kempas) to 27.3% (Light Red Meranti), with an average of 25%. Considering the vast sample of different species originating from various sizes, this COV can be considered moderate. In terms of absolute values, the mean MOE ranged from 11972 N/mm2 to 11387 N/mm2 for Light Red Meranti and Geronggang, respectively, while Kempas exhibited the highest mean MOE of 21329 N/mm2, also corresponding to the highest mean tensile strength.

3.2 Relationship between Density to Tensile Strength and Modulus of Elasticity

A statistical regression analysis was conducted to examine the relationships between density, tensile strength, and MOE, aiming to determine the influence of density on tensile strength and MOE values. Multiple proclamations have emphasized the significance of density in influencing timber properties, including strength and stiffness [14][15]. According to Ulker *et al.* [16], they state that as density decreases and cavity volume reduces, the strength properties of timber generally show an increase.

The statistical analysis was conducted using the Statistical Package for the Social Sciences (SPSS) software. This analysis yielded the "coefficient of correlation," denoted as R, along with its square, known as the "correlation of determination," R^2. The R^2 value indicates the proportion of the total variation in the predicted variable that can be accounted for by the predictor for each species. On the other hand, the correlation coefficient, R, ranges from -1 to 1, with a value close to 1 indicating a strong positive relationship, and a value of zero indicating the absence of any positive or negative relationship.

Figure 4 illustrates the relationship between density and tensile strength for all species. The analysis revealed a moderate positive correlation with a value of R = 0.43. This suggests that increasing density has a moderate effect on tensile strength, but the relationship is subject to considerable scatter. The results obtained are similar to the work done by Marcos *at al.* [17] who reported a moderate to weak positive correlations between tensile strength and density of Eucalyptus grandis and Eucalyptus urophyla.

To gain further insight into the relationship, it is intriguing to examine the correlation between density and tensile strength on a species-specific basis. For each species, the density-versus-tensile-strength relationship was plotted, and the three weakest correlations among the nine species were identified. Figure 5 depicts these three cases. Interestingly, Balau, Kelat, and Resak exhibited either no correlation or an extremely weak correlation between density and tensile strength. The correlation coefficients for Balau, Kelat, and Resak were found to be R = 0.05, 0.26, and 0.16, respectively. Notably, all three species belong to the heavier timber species investigated in this study, with mean densities of 952 kg/m^3, 908 kg/m^3, and 967 kg/m^3, respectively. Hence, it can be concluded that weaker relationship between timber density and tensile strength are obtained with increasing timber density for this study. However, Cown *et al.* [18] found a contradict results were strong density versus tensile strength correlation in softwood timber, Pinus radiata where prediction equation delivering a reduction of tensile strength by 11% when density is reduced by 10%. This finding may be due to the difference of fiber type and length in hardwood timber compared to softwood timber. According to Baar *et al.* [19], numerous hardwood species exhibit growth anomalies such as spiral and interlocking grains, which can lead to fiber deflection from the longitudinal direction. These anomalies, in turn, influence the tensile strength, MOE (Modulus of Elasticity), and density of the timber.

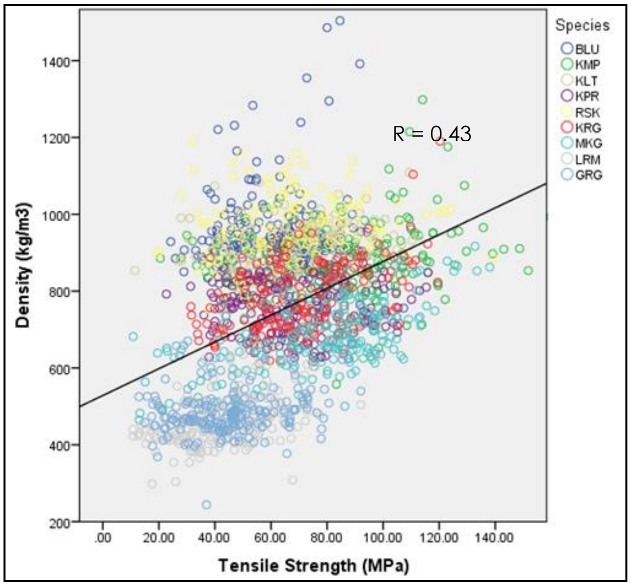
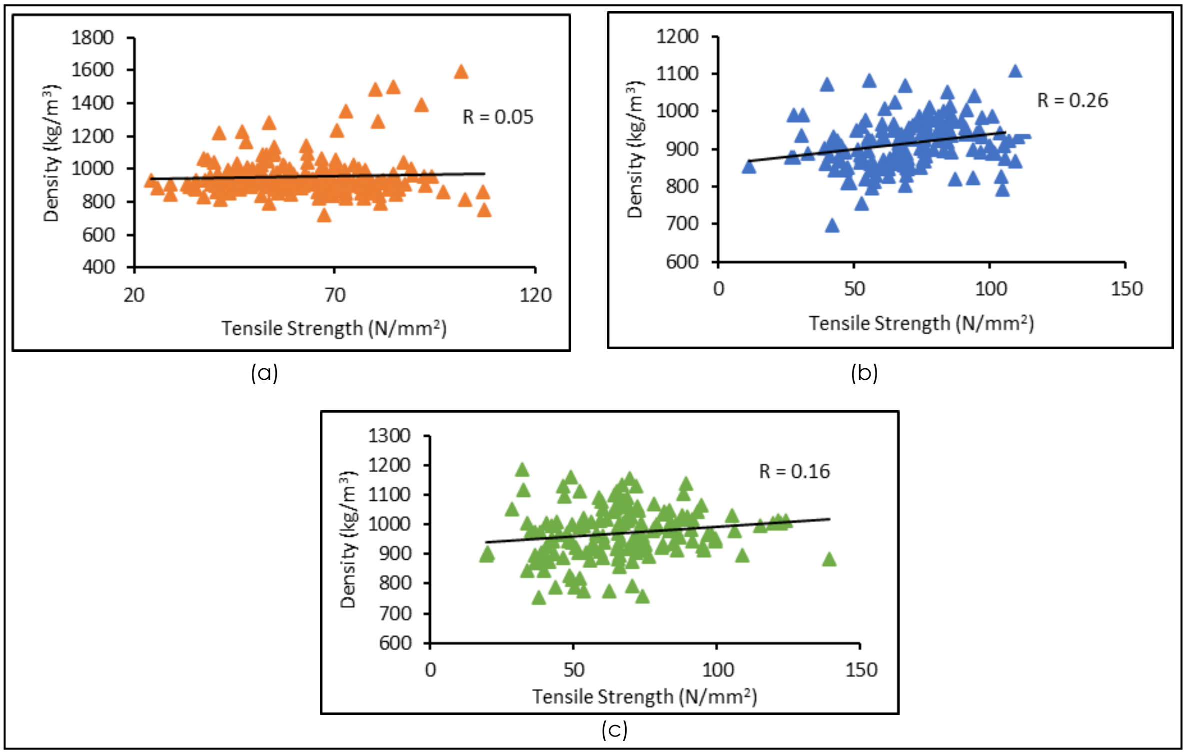


Figure 4 Relationship of density versus tensile strength based on individual specimens



(a)

(b)

(c)

Figure 5 Relationship of density versus tensile strength for (a) Balau, (b) Kelat and (c) Resak

A significance analysis using analysis of variance (ANOVA) at the 0.05% probability level was conducted to assess the statistical significance of the differences in tensile strength and MOE values among species. The outcome of the statistical analysis is presented in Table 4, indicating that there is a significant difference in the tensile strength and MOE values (p-value < 0.05).

Table 4 ANOVA of tensile strength and Modulus of Elasticity for the nine (9) timber species

Properties	F-Value	Pr > F
Tensile strength	82.776	0.000
MOE	122.027	0.000

Figure 6 illustrates the correlation between density and MOE for the individual data of all species. In this analysis, a moderately positive coefficient of correlation, R = 0.54, was derived. Since the density of Balau, Kelat, and Resak does not appear to have a significant effect on tensile strength, a regression analysis was performed for these three species to determine if density has any impact on MOE and it shows a correlation of coefficients of 0.014, 0.11 and 0.21 for Balau, Kelat and Resak respectively. Overall, it is challenging to categorize the tensile strength and MOE of hardwood species based solely on density. Similar findings were observed by Edward *et al.* [20] in analysis of mean values of tensile strength in softwood, indicating a lack of clear correlation between mechanical parameters, including MOE and relative tensile strain at break, with mean density of timber. This absence of a direct relationship can be attributed to the significant influence of defects such as knots and the angle of grain in determining tensile strength and MOE. The presence of knots disrupts the fiber structure and affects the grain orientation, leading to a decrease in the strength and stiffness of timber during tensile testing. Consequently, the influence of these defects plays a more dominant role in determining the mechanical properties of timber, overshadowing the influence of density alone.

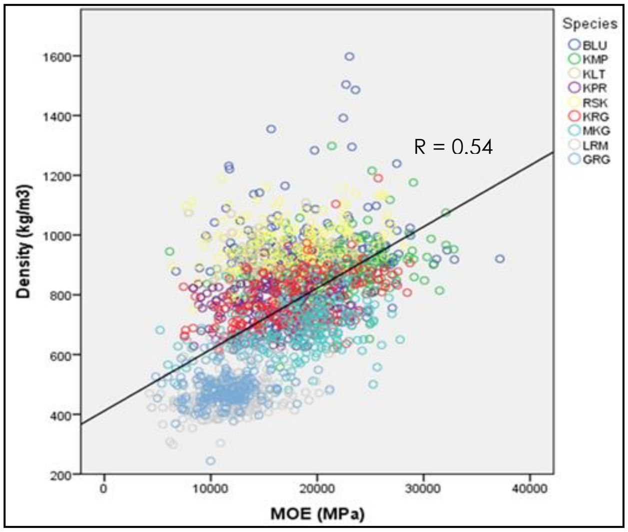


Figure 6 Relationship of density versus MOE based on individual specimens

3.3 Determination of Grade Stresses for Structural Size Specimens

Grade stresses refer to a fundamental stress that has been adjusted by a safety factor. It represents a stress level that the timber can safely and permanently withstand. The grade stresses from each species were computed by the result of 5th percentile value determined from cumulative distribution function and divided by factor of safety 2.5. Sall *et al.* [21] stated that the probability of 1 in 20 of the minimum strength is chosen as the characteristic strength as the confidence level for free from defect is less. Figure 7 shows the distribution of strength at 5th percentile.

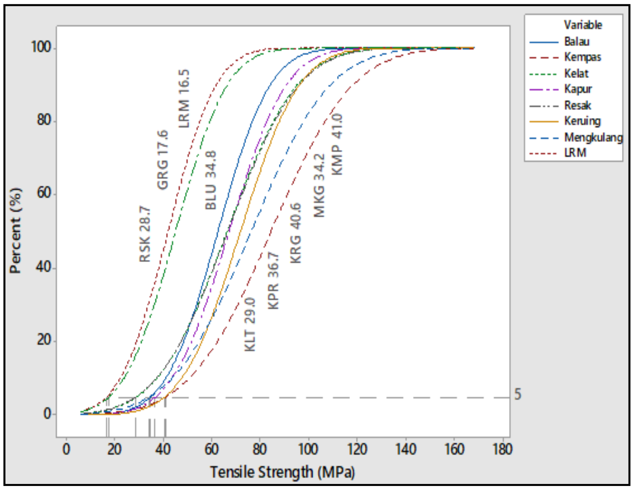


Figure 7 Relationship of density versus Modulus of Elasticity (MOE) based on individual specimens

The grade stresses in MS 544 Part 3 are based on the adoption of BS 5268:1996. Since there is a lack of strength data for structural sized specimens of Malaysian tropical hardwood, strength data from several Southeast Asian timbers present in BS 5268:1996 have been utilized. Table 5 displays both the experimental grade stresses and the grade stresses published in MS 544 Part 3. The lowest grade stress was 6.6 N/mm^2 obtained by the lowest density species Light Red Meranti, whereas the highest-grade stresses value of 16.4 N/mm^2 was related to high density species (Kempas).

Grade stresses published in MS 544 Part 3 provide very limited data on structural size based on the converting values from small clear specimens. The notes below the table indicate that the data provided were temporarily adopted from BS 5268: Part 2, Section 2. It is important to note that these values are believed to be considerably higher than those obtained from timber species found in Malaysia. However, this finding negates those statements. The results reveal that the grade stresses derived from this study surpass those reported in MS 544 Part 3, with the exception of Balau species, which showed no significant differences. Kempas, Kapur, Keruing, Mengkulang, and Light Red Meranti exhibited increases of 41%, 34.9%, 67%, 44.2%, and 8.2%, respectively, compared to the grade stresses published in MS 544 Part 3. Thus, with this data available, it can be seen that the value of grade stresses in tensile strength was underestimated.

Table 5 Summary of Grade Stresses by experimental and MS 544: Part 3 according to tensile

Species ID	Grade Stresses (N/mm^2)		Mean Modulus of Elasticity (N/mm^2)	
	MS 544: Part 3	**Experimental**	**MS 544: Part 3**	**Experimental**
BLU	14.1	13.9	20900	19716
KMP	11.6	16.4	19100	21329
KLT	-	11.6	-	15905
KPR	10.9	14.7	19200	16238
RSK	-	11.5	-	17853
KRG	9.7	16.2	19300	17632
MKG	9.5	13.7	14300	18085
LRM	6.1	6.6	10200	11972
GRG	-	7.0	-	11387

4.0 CONCLUSION

The tensile strength and grade stresses of various timbers, including Balau (Shorea spp.), Kempas (Koompassia Malaccensis), Kelat (Syzygium spp.), Kapur (Dryobalanops spp.), Resak (Vatica spp.), Keruing (Dipterocarpus spp.), Mengkulang (Heritiera spp.), Light Red Meranti (Shorea spp.), and Geronggang (Cratoxylum spp.), were investigated. The study revealed several key findings. Firstly, Light Red Meranti, the timber with the lowest density, exhibited the lowest mean tensile strength at 42.23 N/mm^2 and a modulus of elasticity (MOE) of 11972 N/mm^2. Conversely, Kempas, a high-density species, demonstrated the highest mean tensile strength at 84.46 N/mm^2 and the highest MOE at 21329 N/mm^2, despite not being the densest species examined. Additionally, a low positive correlation was found between density and both tensile strength and MOE, indicating that density had a minimal impact on tensile strength in this study. Finally, the grade stresses identified in this investigation surpassed the grade stresses published in MS 544 Part 3.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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