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MECHANICAL PROPERTIES OF MALAYSIAN TIMBERS: THE WEIGHTED MEAN AND COMBINED STANDARD DEVIATION VALUES

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OVERVIEW

The mechanical properties of timber are numerical values that signify the strength and elasticity characteristics of timber material in its solid form upon exertion of external forces. Depending on the mode of the applied force, the mechanical properties of timber can be characterised by various denotation e.g. modulus of rupture, modulus of elasticity, compressive strength parallel to the grain, shear strength parallel to the grain, compressive strength perpendicular to the grain, tensile strength parallel to the grain and Janka hardness. For instance, in the mechanical testing of timber, a component exerted by a mechanical force in bending mode is subjected to bending stress. The stress value at which the specimen fails is recorded as the bending strength of that specimen, and it is indicated by signs of mechanical failure such as loss of strength, permanent deformation, sound of breakage, or visible fracture (Figure 1).

A mechanical property is customarily represented by a mean value, derived from the mechanical test of a set of specimens. In the building construction and design of structural components, it is compulsory to determine the limitation of applied stresses. An accurate prediction of the mechanical properties of timber will increase the level of engineering safety, optimises the utilisation of material and assists on the budgetary decision. This article demonstrates the mathematical formulae to calculate the weighted mean and combined standard deviation values for more precise representation of the mechanical properties of Malaysian timbers.

Figure 1 Mechanical failure due to bending load is typically indicated by splintering fractures and loss of strength

THE MECHANICAL PROPERTIES OF MALAYSIAN TIMBER

The mechanical properties of Malaysian timbers are formally reported in the values of arithmetic mean, standard deviation and number of tested specimen. These three values represent the test results of a mechanical property of one sample batch consisted of a number of specimen having the same species and origin with approximately similar moisture content. The diagram in Figure 2 demonstrates how a set of arithmetic mean, standard deviation and number of specimen represent a mechanical property of a timber species. For example, there are more than thirty species of keruing (*Dipterocarpus* spp.) in the country and nine species have been officially tested for mechanical properties. Thus the mechanical properties of keruing are basically presented by nine different botanical species. Table 1 shows the mechanical properties of keruing of nine different species of *Dipterocarpus* spp. Mechanical properties such as modulus of elasticity, compressive strength, shear strength and Janka hardness of keruing, as well as all other timber groups are generally presented based on species. Each mechanical property is presented by a mean value accompanied by standard deviation and number of tested specimen.

The mechanical properties of Malaysian timbers are mostly recorded in Timber Trade Leaflet No. 34 (Lee et al. 1993). Some more recent data can be found in research journals, booklets and technical publications. Since the reporting and publications of the mechanical properties of Malaysian timbers involve only the arithmetic mean, standard deviation and number of specimen, the raw data of each tested specimen (also known as the ultimate stresses) are practically inaccessible. In fact, most of the original records were already destroyed (Mohd-Jamil 2017).

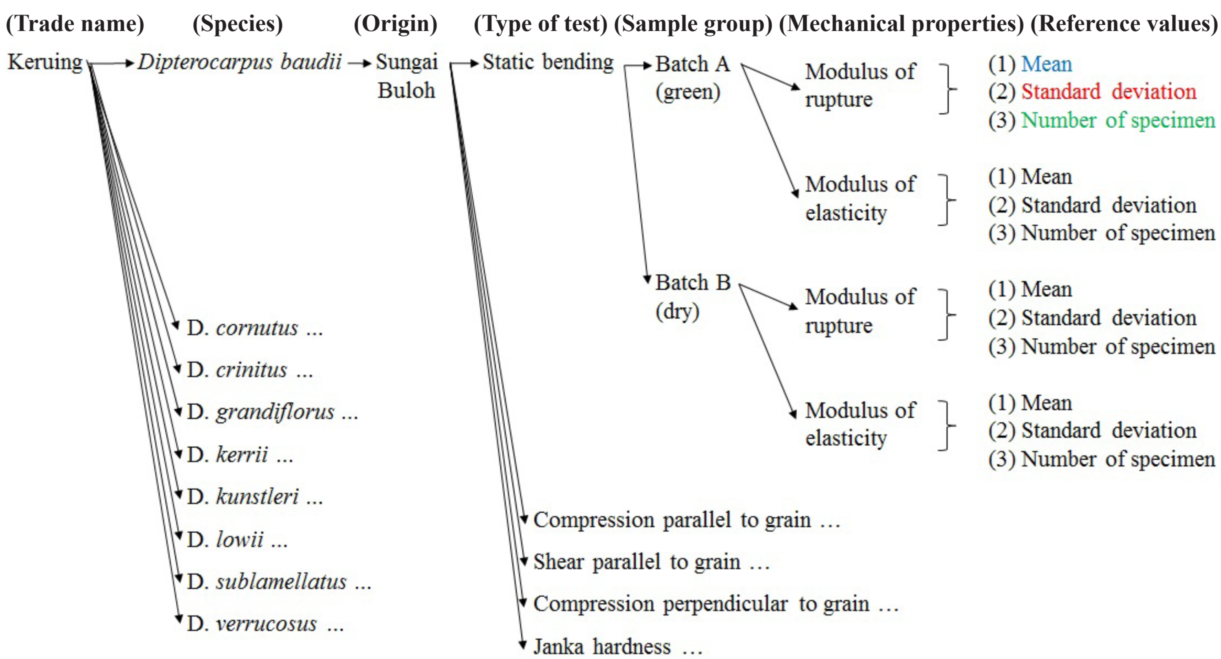

Figure 2 How a set of arithmetic mean, standard deviation and number of specimen signify the mechanical properties of keruing

THE IMPORTANCE OF THE WEIGHTED MEAN AND COMBINED STANDARD DEVIATION VALUES

The reporting of mechanical properties of timber based on individual species is strictly scientific. In the actual industrial practice, the supply, market price, and usage of most timbers are based on timber trade names, regardless of species. For instance, timbers of *Dipterocarpus* spp. are traded and utilised in a single group known as keruing. Likewise, timbers of *Hopea* spp. are traded and utilised in two different groups based on density, namely giam and merawan. Also, timbers of *Cotylelobium* spp. and *Vatica* spp. are grouped together as resak (Wong 2002). As a matter of fact, it is impossible to determine the exact botanical class of multi-species genera once converted into sawn timber.

In certain cases, the engineering values (also known as the basic and grade stresses) of the multi-species timbers such as keruing were derived from the mechanical properties of a single species i.e *Dipterocarpus kerrii* (MS 544 Part 2 2001), and yet, the trading, designing and applications of timber material was never based on botanical species. At present, if sawn timbers of any group are obtained and tested for mechanical properties, a comparison of the test results with the existing data will be inappropriate due to the multi-species content of the supply. Therefore, there is a need to recalculate the mechanical properties of Malaysian timbers which account for the strength variability among species.

For some timber species, the mechanical properties were reported through various assessments. For example, the mechanical properties of *Acacia mangium* planted in Malaysia were reported in four different tests i.e. 15-y-old samples of Bidor, 15-y-old samples of Setiu (Mohd-Jamil et al. 2018), 16-y-old samples of Ulu Sedili, and 20-y-old samples of Kemasul (Mohamad Omar & Mohd-Jamil 2011). The mechanical properties obtained from these assessments were reported in the values of mean, standard deviation and the number of tested specimen. However, the test results of individual specimen are not accessible to public. In order to obtain the precise data distribution of *Acacia mangium* planted in Malaysia, the correct algebraic computation is required.

Similarly, the mechanical properties of 15-y-old *Khaya ivorensis* planted in Malaysia were reported based on three sample batches of different locations i.e. Bukit Hari, Bidor and Setiu (Mohamad Omar et al. 2018, Mohd-Jamil et al. 2018). Since *Khaya ivorensis* has not been incorporated into the Malaysian strength grouping system, thus the basic and grade stresses of the timber need to be established. Yet, the timber mechanical properties of *Khaya ivorensis* which represent the overall values of all tested samples are still indeterminate.

To place the Malaysian hardwood timbers in the European strength classes system, mechanical properties such as modulus of rupture and modulus of elasticity must be derived from structural size specimen tests. There are only two means to achieve the goal. One is to conduct the destructive structural size test, or, the other way is to manipulate the existing data so that they are equivalent to the properties obtained from structural size specimen test (Mansfield-Williams 2010). It is stated in the standard procedure that the conversion factor only applies to timbers of a similar strength characteristics (EN 384 2018). Since the mechanical properties of Malaysian timbers were reported based on botanical species, there is a prospect to improve those values by considering the actual variation of data in each trade group. Therefore, there is an urgent need to reanalyse the mechanical properties of Malaysian timbers based on trade name assemblage.

THE WEIGHTED MEAN FORMULA

The mean of a data set, $\overline{x}$ is the sum of the values, x_i divided by the number of values, n.

$$\overline{x} = \frac{\sum_i^n x_i}{n}$$

However, in cases where a certain x_i contributes to $\overline{x}$ more than others, the formula of weighted mean can be applied. The weighted mean is the arithmetical mean of N samples having a different number of values, n. Thus, since the values of the ultimate stresses, x_i are not available, the formula of weighted mean is applied to determine the arithmetical mean of mechanical properties of multi-species timber. The weighted mean, $\overline{W}$ for N samples is calculated via the equation:

$$\overline{W} = \frac{\sum_{i=1}^{N} \overline{x}_i n_i}{\sum_{i=1}^{N} n_i} \tag{1}$$

where N is the number of samples, $\overline{x}_i$ is the mean value of sample N_i, and n_i is the number of specimen in sample N_i. The calculation example of the weighted mean of modulus of rupture (air-dry) of *Dipterocarpus* spp. is demonstrated in Appendix 1.

THE COMBINED STANDARD DEVIATION FORMULA

The standard deviation value is a measure of dispersion of a set of values, x_i. However, since x_i is not available, the formula of combined standard deviation is applied. Based on the basic principle of standard deviation of a sample, a reverse algebraic approach is applied to calculate the combined standard deviation value of N samples. The principle of standard deviation of a sample of n number of specimen, denoted by s:

$$s = \sqrt{\frac{1}{n-1}\sum(\bar{x} - x_i)^2}$$

$$s^2 = \frac{1}{n-1}(\sum\bar{x}^2 - 2\bar{x}\sum x_i + \sum x_i^{\,2})$$

$$s^2 = \frac{1}{n(n-1)}(n\bar{x}\sum\bar{x} - 2n\bar{x}\sum x_i + n\sum x_i^{\,2})$$

and since $\sum x_i = \sum\bar{x} = n\bar{x}$

Hence, $s^2 = \frac{1}{n(n-1)}(n\sum x_i^{\,2} - (n\bar{x})^2)$

And for each sample N_i :

$$\sum x_i^{\,2} = \frac{1}{n}[s^2 n\,(n-1) + (n\bar{x})^2] \tag{2}$$

Thus the combined standard deviation, s_c for N samples is calculated via the formula:

$$s_c = \sqrt{\frac{1}{n_t(n_t - 1)}\left[n_t\sum x_i^{\,2} - (n\bar{x})^2\right]} \tag{3}$$

where n_t is the total number of specimen of N samples, $\sum x_i^{\,2}$ is the parametric value based on the Eq. 2, accounted for N samples, and $n\bar{x}$ is the product of mean and the number of specimen, accounted for N samples. The calculation example of the combined standard deviation of modulus of rupture (air-dry) of keruing is demonstrated in Appendix 2.

Based on the mean ultimate mechanical properties of eight species of keruing (*Dipterocarpus* spp.) namely *D. baudii*, *D. cornutus*, *D. crinitus*, *D. grandiflorus*, *D. kerrii*, *D. lowii*, *D. sublamellatus* and *D. verrucosus* published in Trade Leaflet No. 34, using the given formulae, the weighted mean and combined standard deviation of modulus of rupture in air-dry condition, consisted of 187 specimens, are 98.3 N mm^{-2} and 17.2 N mm^{-2} respectively. The distributions of data following the calculations of weighted mean and combined standard deviation is illustrated in Figure 3. The calculated weighted mean and combined standard deviation of other mechanical properties of keruing are summarised in Table 2.

In summary, the mathematical formulae demonstrated calculations of weighted mean and combined standard deviation values for more precise representation of the timber mechanical properties regardless of species. Nevertheless, the results of the computation are by no means the concluding values. In the future, new test results could be integrated into the data using the same formulae provided that the arithmetic mean, standard deviation and number of tested specimen are available. In addition, the similar procedure can be applied to other multi-species Malaysian timbers.

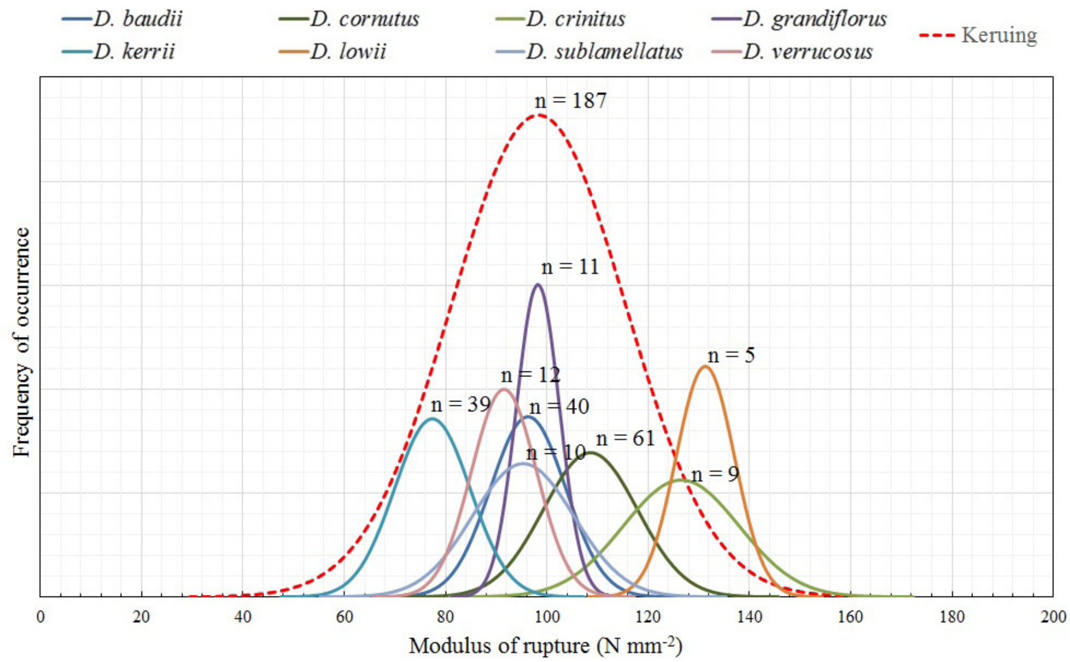

Figure 3 Data distribution of modulus of rupture (air-dry) of keruing (weighted mean = 98.3, combined standard deviation = 17.2)

SUMMARY

To calculate the mean and standard deviation values for a mechanical property of timber that involved different samples, the weighted mean and combined standard deviation formulae are recommended. The formulae are presented to facilitate scientists, engineers and safety officers in determining the actual dispersal of timber strength data. The calculation examples, based on the modulus of rupture of different species of keruing (*Dipterocarpus* spp.) are provided in the appendices. The computation is an accurate arithmetical operation, depending on the precision of the decimal number of the existing records. The formulae can be applied to any mechanical property provided that three important parameters of each sample are available i.e. the arithmetic mean, standard deviation and number of specimen.

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Table 1 The mechanical properties of different species of *Dipterocarpus* spp. (Lee et al. 1993)

Botanical name	Vernacular name	Average moisture content	Specific gravity	Modulus of rupture	Modulus of elasticity	Compressive strength parallel to the grain	Shear strength parallel to the grain	Compressive strength perpendicular to the grain (stress at limit of proportionality)	Janka hardness
		%		N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N
D. baudii	Keruing bulu	65	0.62 (147)(0.032)	71 (88)(7.9)	15000 (87)(1150)	39.5 (147)(4.51)	7.5 (41)(0.70)	4.21 (62)(1.007)	4230 (63)(-)
		15.5	0.68 (92)(0.031)	96 (40)(7.8)	17100 (40)(1120)	52.9 (92)(3.91)	9.3 (21)(0.79)	4.69 (38)(0.772)	4890 (36)(-)
D. cornutus	Keruing gombang	51	0.65 (159)(0.032)	76 (92)(8.0)	16700 (92)(1510)	39.1 (159)(4.70)	7.8 (40)(0.57)	3.65 (65)(0.586)	4140 (70)(-)
		15.4	0.71 (108)(0.045)	109 (61)(9.8)	20200 (61)(2000)	59.7 (108)(4.51)	9.2 (26)(1.60)	4.34 (43)(0.634)	5430 (44)(-)
D. crinitus	Keruing mempelas	41	0.77 (29)(0.017)	96 (15)(4.4)	20000 (15)(1160)	51.1 (29)(3.04)	9.3 (18)(0.79)	5.65 (13)(0.559)	6050 (13)(-)
		15.8	0.81 (24)(0.045)	128 (9)(12.1)	22300 (9)(1860)	62.6 (24)(4.19)	12.3 (12)(1.23)	9.17 (23)(1.421)	7830 (22)(-)
D. grandiflorus	Keruing belimbing	54	0.66 (21)(0.017)	84 (9)(3.4)	16300 (9)(1320)	45.0 (21)(1.95)	8.2 (7)(0.43)	5.86 (7)(0.862)	5380 (7)(-)
		18.1	0.69 (19)(0.025)	98 (11)(4.5)	17600 (11)(1840)	51.8 (19)(3.24)	10.3 (9)(0.72)	5.38 (10)(0.690)	5160 (8)(-)
D. kerrii	Keruing gondol	89	0.57 (110)(0.054)	46 (56)(3.2)	10200 (56)(1650)	24.2 (110)(2.21)	6.4 (63)(0.72)	-	2850 (64)(-)
		16.5	0.64 (92)(0.059)	76 (39)(7.9)	12900 (39)(2590)	43.4 (92)(5.42)	11.0 (52)(0.86)	-	4720 (50)(-)
D. kunstleri	Keruing gombang merah	70	0.58 (22)(0.022)	65 (11)(7.2)	14500 (11)(1460)	31.9 (22)(3.46)	7.2 (10)(0.85)	3.24 (9)(0.455)	3030 (9)(-)
D. lowii	Keruing shol	45	0.70 (18)(0.031)	84 (12)(3.6)	18400 (12)(920)	47.0 (18)(3.51)	8.7 (12)(0.34)	4.83 (9)(0.303)	5030 (9)(-)
		15.3	0.73 (12)(0.026)	133 (5)(6.1)	20000 (5)(1420)	68.1 (12)(3.21)	11.3 (7)(1.09)	7.35 (10)(1.018)	7290 (8)(-)

Continue...

Continue Table 1

Botanical name	Vernacular name	Average moisture content	Specific gravity	Modulus of rupture	Modulus of elasticity	Compressive strength parallel to the grain	Shear strength parallel to the grain	Compressive strength perpendicular to the grain (stress at limit of proportionality)	Janka hardness
		%		N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N
D. sublamellatus	Keruing kerut	56	0.61 (31)(0.025)	60 (18)(6.7)	15400 (18)(1390)	32.6 (31)(5.04)	6.7 (20)(0.84)	3.24 (29)(0.483)	3200 (28)(-)
		15.8	0.67 (30)(0.061)	95 (10)(10.6)	18200 (10)(1960)	50.3 (30)(3.17)	11.3 (13)(1.01)	5.17 (26)(1.041)	5160 (22)(-)
D. verrucosus	Keruing merah	61	0.61 (25)(0.035)	62 (12)(3.9)	14100 (12)(1250)	32.6 (25)(2.15)	6.6 (7)(0.92)	3.79 (8)(0.276)	3290 (8)(-)
		16.5	0.69 (21)(0.061)	91 (12)(6.8)	17000 (12)(1460)	50.2 (21)(4.50)	9.2 (8)(0.64)	5.10 (7)(0.214)	5780 (7)(-)

Note: In each column, the figure in the centre is the mean value. The figures (in brackets) on the left and right are the number of specimen and the standard deviation respectively.

Table 2 The weighted mean and combined standard deviation of mechanical properties of *Dipterocarpus* spp.

Trade name	Tested species	Condition of specimens	Specific gravity	Modulus of rupture	Modulus of elasticity	Compressive strength parallel to the grain	Shear strength parallel to the grain	Compressive strength perpendicular to the grain (stress at limit of proportionality)	Janka hardness
				N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N mm^{-2}	N
Keruing	*D. baudii* *D. cornutus* *D. crinitus* *D. grandiflorus* *D. kerrii* *D. kunstleri* *D. lowii* *D. sublamellatus* *D. verrucosus*	Green	0.605 (562)(0.178)	66.59 (313)(22.86)	14508 (312)(4876)	35.20 (562)(12.59)	7.03 (218)(2.46)	3.86[b] (202)(1.46)	3750[c] (271)(n.a.)
		Air-dry	0.688[a] (398)(0.062)	98.34[a] (187)(17.17)	17645[a] (187)(3432)	53.20[a] (398)(8.14)	10.45[a] (148)(1.45)	5.56[ab] (157)(1.89)	5466[c] (197)(n.a.)

Note: In each column, the figure in the centre is the weighted mean value. The figures (in brackets) on the left and right are the total number of specimen and the combined standard deviation respectively.
[a]Data of *Dipterocarpus kunstleri* are not available.
[b]Data of *Dipterocarpus kerri* are not available.
[c]Standard deviation values are not available.

APPENDIX 1

Calculation example: The weighted mean of modulus of rupture (air-dry) of *Dipterocarpus* spp.

Based on values in Table 1, using Eq.1:

$$\overline{W} = \frac{\sum_{i=1}^{N} \overline{x}_i n_i}{\sum_{i=1}^{N} n_i} \tag{1}$$

$$\overline{W} = \frac{\sum_{i=1}^{8} [(96 \times 40) + (109 \times 61) + (128 \times 9) + (98 \times 11) + (76 \times 39) + (133 \times 5) + (95 \times 10) + (91 \times 12)]}{\sum_{i=1}^{8} (40 + 61 + 9 + 11 + 39 + 5 + 10 + 12)}$$

$$\overline{W} = \underline{\underline{98.3}} \text{ N mm}^{-2}$$

Thus, based on 187 specimens, the weighted mean of modulus of rupture of *Dipterocarpus* spp. in air-dry condition is 98.3 N mm^{-2}.

APPENDIX 2

Calculation example: The combined standard deviation of modulus of rupture (air-dry) of *Dipterocarpus* spp.

Based on values in Table 1, using Eq.2:

$$\sum x_i^{\ 2} = \frac{1}{n}[s^2 n\,(n-1) + (n\bar{x})^2] \qquad (2)$$

Determining $\sum x_i^{\ 2}$ for *D. baudii*:

$$\sum x_1^{\ 2} = \frac{1}{40}[7.8^2(40)(39) + (40\times 96)^2] = 3.71\times 10^5$$

Determining $\sum x_i^{\ 2}$ for *D. cornutus*:

$$\sum x_2^{\ 2} = \frac{1}{61}[9.8^2(61)(60) + (61\times 109)^2] = 7.31\times 10^5$$

Determining $\sum x_i^{\ 2}$ for *D. crinitus*:

$$\sum x_3^{\ 2} = \frac{1}{9}[12.1^2(9)(8) + (9\times 128)^2] = 1.49\times 10^5$$

Determining $\sum x_i^{\ 2}$ for *D. grandiflorus*:

$$\sum x_4^{\ 2} = \frac{1}{11}[4.5^2(11)(10) + (11\times 98)^2] = 1.06\times 10^5$$

Determining $\sum x_i^{\ 2}$ for *D. kerrii*:

$$\sum x_5^{\ 2} = \frac{1}{39}[7.9^2(39)(38) + (39\times 76)^2] = 2.28\times 10^5$$

Determining $\sum x_i^{\ 2}$ for *D. lowii*:

$$\sum x_6^{\ 2} = \frac{1}{5}[6.1^2(5)(4) + (5\times 133)^2] = 8.86\times 10^4$$

Determining $\sum x_i^{\ 2}$ for *D. sublamellatus*:

$$\sum x_7^{\ 2} = \frac{1}{10}[10.6^2(10)(9) + (10\times 95)^2] = 9.13\times 10^4$$

Determining $\sum x_i^{\,2}$ for *D. verrucosus*:

$$\sum x_8^{\,2} = \frac{1}{12}[6.8^2(12)(11) + (12\times 91)^2] = 9.99\times 10^4$$

Applying $\sum x_i^{\,2}$ values of N samples in Eq. 3:

$$s_c = \sqrt{\frac{1}{n_t(n_t - 1)}\left[n_t \sum x_i^{\,2} - (n\bar{x})^2\right]} \qquad (3)$$

$$s_c = \sqrt{\frac{1}{187(186)}\left[187\left((3.71+7.31+1.49+1.06+2.28+0.89+0.91+1.00)\times 10^5\right) - \left((40\times 96)+(61\times 109)+(9\times 128)+(11\times 98)+(39\times 76)+(5\times 133)+(10\times 95)+(12\times 91)\right)^2\right]}$$

$$s_c = \underline{\underline{17.17}}\ \mathrm{N\ mm^{-2}}$$

Thus, based on 187 specimens, the combined standard deviation of modulus of rupture of *Dipterocarpus* spp. in air-dry condition is 17.17 N mm^{-2}.

The mechanical properties of Malaysian timbers are formally reported based on botanical species in the values of arithmetic mean, standard deviation and number of tested specimen. There appears a need to represent the mechanical properties of timbers which take into account the variability among the multiple species of a timber of a trade name. An accurate description of the mechanical properties of timber will ultimately increases the level of engineering safety, optimises the utilisation of material and assists on the budgetary decision. This article demonstrates the mathematical formulae to calculate the weighted mean and combined standard deviation values for more precise representation of the mechanical properties of timber.

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