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ORIGINAL ARTICLE

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Mechanical stress grading of tropical timbers without regard to species

Received: March 12, 2004 / Accepted: June 22, 2004

Abstract Some reports have shown that for single species the correlation between modulus of elasticity (MOE) and modulus of rupture (MOR) in bending is quite high. Tropical timbers consist of hundreds of species that are difficult to identify. This report deals with the mechanical stress grading of tropical timber regardless of species. Nine timber species or groups of species with a total number of 1094 pieces measuring 60 × 120 × 3000 mm, were tested in static bending. The MOE was measured flat wise, while MOR was tested edge wise. Statistical analysis of linear regression with a dummy model and analysis of covariance were used to analyze the role of MOE and the effect of species on prediction of MOR. The analysis showed that using MOE as a single predictor caused under/overestimation for one or more species and/or groups of species. The accuracy of prediction would be increased with species identification. An allowable stress and reference resistance for species and/or groups of species were provided to compare with the prediction of strength through timber grading. The timber strength class for species and/or groups of species was also established to support the application of mechanical timber grading.

Key words Regardless of species · Mechanical stress grading · Tropical timbers · Allowable stress · Reference resistance

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Introduction

Being a natural material, wood has large variations of strength and stiffness properties among species and even among pieces in one species. The variations of strength and stiffness are caused by defects or imperfections like knots (number, size, and location in each piece of timber), slope of grain, and interlocked grain. To guarantee structural safety, prediction of timber strength is necessary. The strength characteristics of a piece of timber should be evaluated by nondestructive methods. It can be done through visual grading or mechanical grading or by combination of such methods. For simplicity and economy, pieces of timber of similar mechanical properties are placed in categories called stress grades.[1]

Most tropical countries are blessed with a biodiversity of natural resources which means that hundreds or thousands of timber species are available for construction. In such cases, the application of visual grading is complicated due to the difficulties of species identification and checking of the imperfection condition. Predicting the strength of wood on a large scale through density shows a poor coefficient of determination (R^2). A study on Norway spruce (*Picea abies*) reported that the R^2 value of the relationship between density and bending strength was in the range of 0.16–0.40 while the R^2 value of the relationship between the density and knots was 0.38. However, the stiffness, which is normally expressed as the modulus of elasticity (MOE), is by far recognized as the best predictor of strength.[2] The most common method of sorting machine-graded lumber is to measure MOE.[1] The R^2 value of the relationship between MOE and bending strength [modulus of rupture (MOR)] of Norway spruce was in the range of 0.51–0.72.[2,3] Previous studies have showed the R^2 value between MOE in flatwise timber and MOR was 0.61 for *Acacia mangium* timber and 0.53 for mixed tropical wood.[5] Combining MOE with knots and other data gained slight improvement in the relationship between MOE and MOR.[2]

In the application to timber grading and strength classes, the strength of a piece of timber regardless of species could be predicted and classified through measuring the

MOE. Most species are grouped together and the timber performances from such species are treated similarly. With reference to the availability of timber for structural purposes consisting of many species in tropical countries, the application of mechanical stress grading needs to be evaluated.

The objective of this study was to evaluate the application of mechanical grading to tropical timber, which consists of timber from natural forest, timber from plantation forest, hardwood as well as softwood. It is expected that the results can be utilized in structural timber design.

Materials and methods

The number of the specimens was 1094 pieces of tropical wood consisting of timber from natural forest [60 pieces of kapur (*Dryobalanops aromatica* Gaertner f.), 192 pieces of a group of meranti or *Shorea* sp., and 314 pieces of mixed unknown species namely "borneo" timber] hardwood from plantation forest [120 pieces of *Acacia mangium*, Willd.[4] 60 pieces of falcata (*Paraserianthes falcataria*, L. Nielsen), 60 pieces of rubber wood (*Hevea brasiliensis*, Willd), and 60 pieces of *Maesopsis eminii*, Engler], and softwood from plantation forest [168 pieces of *Pinus merkusii*, Junghuhn & de Vriese, and 60 pieces of agathis (*Agathis dammara*, Lambert Rich)]. The specimens were 60 × 120 × 3000 (L) mm when air-dried. For any piece of lumber, the imperfection condition was evaluated based on the visual grading system of Indonesian Standard for Construction Timber (SNI 03-3527).[6] Based on the diameter of the knots, slope of the grain, length of the wane, and other visual grading parameters, the timber was classified into the three categories of class A, class B, and that rejected as structural timber. Only timber that was classified as timber suitable for building construction was used as specimens.

The MOE in flatwise configuration with center-point loading was measured using a simple machine with a deflectometer that can magnify the reading about 40 times. In the measurement of MOE flat wise, the span was 2730 mm and the applied load was 25 kg. Before measuring the MOE flat wise, the machine was calibrated based on a certified dial gauge. The specimens were then tested in flexural bending with three-point loading edge wise with a universal testing machine with a capacity of 100 tons, following the procedure of ASTM D 198.[7] With consideration of the loading system, adjustment factors were applied to the MOE and MOR calculations based on the equilibrium moisture content in Indonesia of 15% and ASTM 2915.[8]

Regression analysis was used to analyze the relationship between MOE flat wise and MOR of the timber. Based on the regression analysis, the allowable stress for the tropical wood and the stress classification were established. The effects of timber species on the MOR of timber were analyzed using analysis of covariance (ANCOVA) with MOE as the covariant variable and the model as shown in Eq. 1:

$$Y_{ij} = \mu + \tau_i + \beta\left(X_{ij} - \overline{X}\right) + \varepsilon_{ij} \quad (1)$$

where Y_{ij} is the measured MOR of species i and sample number j, μ is the average MOR, τ_i is the additive effect of species, β is the regression coefficient that expresses the dependency of MOR on MOE, X_{ij} is the measured MOE, $\overline{X}$ is the average MOE, and ε_{ij} is the error of sample number j of species i.

The hypothetical test was conducted through an F test by considering:

Ho: $\tau_i = 0$, there is no significant effect of species or group of species to MOR.

For

H_1: $\tau_i \neq 0$, there is at least one species that shows a significantly different MOR value to the others.

The prediction of strength characteristics of the timber was analyzed through a model as described by Eq. 2:

$$Y_{ij} = z_{ij}a_j + f\left(X_{ij}\right) + \varepsilon_{ij} \quad (2)$$

where z_{ij} is the dummy variable of species i, a_i is a constant of the dummy variable and, $f(X_{ij})$ is a function of the relationship between MOR and MOE. Two hypotheses were used as:

1. Ho: $\beta_1 = \beta_2 = \beta_3 \ldots = \beta_k = 0$, species and MOE provide no significant effect to MOR.
   H_1: $\exists\, \beta_k \neq 0$, at least one species and/or MOE provide significant effect to MOR.
2. Ho: species provide no significant effect on MOR when MOE is included in the analytical model.
   H_1: at least one species provides significant effect on MOR when MOE is included in the analytical model.

Strength characteristics based on the allowable stress design (ASD) and load and resistance factor design (LRFD) were established following ASTM D 2915[8] and ASTM D 5457,[9] respectively.

Results and discussion

Modulus of elasticity and bending strength performance of the timber

MOE and MOR of timber are the two parameters usually used in the evaluation of the bending performance of timber in structural sizes. The MOE and MOR of timber may vary among the species, trees, logs, and even among the sawn timber of one log.[10] Variations of strength and stiffness are, in general, caused by density and imperfections, i.e., knots, slope of grain, and interlocked grain.

The lowest value of MOE was 4.1 GPa found in *Acacia mangium* from the plantation forest and the highest was 28.5 GPa found in mixed unknown timber from natural forest as shown in Table 1. The weakest value of MOR was 10.8 MPa found in agathis from plantation forest and the strongest was 134.3 MPa found in shorea sp. from natural forest. Generally, the range of MOE and MOR values of timber from natural forest is wider than that of timber from

Table 1. Modulus of elasticity (MOE) and modulus of rupture (MOR) performance of tested timber

Specimens	MOE (Gpa)				MOR (MPa)				Moisture content (%)			
	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD
Hardwood from natural forest	5.3	28.5	15.1	4.1	13.8	134.3	59.8	20.3	13.9	18.4	15.5	1.4
Borneo timber	8.3	28.5	15.3	4.1	30.0	108.0	62.8	15.4	14.3	18.4	15.5	1.5
Shorea sp.	5.3	25.9	14.9	3.9	13.8	134.3	55.1	26.1	13.9	16.7	14.9	1.3
Kapur	8.4	28.3	14.2	4.7	23.0	107.6	56.1	22.2	14.1	17.9	16.1	1.3
Planted fast-growing hardwood	4.1	22.1	9.8	2.9	11.6	92.0	41.6	13.1	12.9	18.8	15.6	1.1
Acacia mangium	4.1	15.8	8.9	2.6	11.6	92.0	42.2	15.8	12.9	16.8	15.2	1.2
Falcata	6.2	13.0	8.7	1.4	15.3	48.0	32.7	8.1	13.2	17.9	14.8	0.9
Rubber wood	6.3	17.6	10.6	3.0	29.4	56.7	43.9	7.9	14.4	18.7	16.3	1.0
Maesopsis eminii	5.5	22.1	12.0	3.4	28.5	70.8	45.8	10.2	13.9	18.8	16.2	1.4
Total hardwood	4.1	28.5	13.6	4.5	11.6	134.3	54.7	20.1	12.9	18.8	15.6	1.2
Planted fast-growing softwood	5.6	21.7	12.6	3.3	10.8	67.2	37.1	11.8	13.8	18.7	15.8	1.2
Pinus merkusii	5.6	21.7	12.9	3.6	15.4	55.9	34.2	8.6	14.5	17.6	15.9	1.0
Agathis	7.6	16.6	12.0	2.3	10.8	67.2	44.6	12.3	13.8	18.7	15.7	1.3
Tropical timber (total)	4.1	28.5	13.3	4.3	10.8	134.3	50.6	20.0	12.9	18.8	15.7	1.1

SD, standard deviation

Table 2. Goodness of fit (percent) of parametric distribution to the plots of tropical timber

Specimens	MOE			MOR		
	Normal	Log-normal	Weibull	Normal	Log-normal	Weibull
Timber from natural forest	67	100	47	84	68	100
Borneo timber	69	100	56	100	51	56
Shorea sp.	100	79	92	55	100	73
Kapur	60	100	50	71	100	72
Planted fast-growing hardwood	85	85	100	97	100	98
Acacia mangium	100	100	71	65	100	69
Falcata	85	80	100	100	86	100
Rubber wood	65	100	56	95	100	86
Maesopsis eminii	69	100	55	88	100	82
Hardwood	84	99	100	90	100	100
Planted fast-growing softwood	100	87	75	66	100	60
Pinus merkusii	100	91	87	91	100	73
Agathis	94	83	100	100	82	90
Tropical timber (total)	91	96	86	73	100	86

plantation forest. The wide range of such values of timber from natural forest may be due to the cultivation system. Shorea sp. is a group of species occurring in the mixed unknown tropical wood commonly known as "Borneo" timber. It is reasonable to expect that the range of MOE and MOR of mixed tropical timber is wider than that of timber from plantation forest where the trees are well cultivated and homogenous.

Parametric distributions, namely, normal, log-normal, and Weibull distributions were applied to evaluate the distribution. Based on the frequency analysis, the apparent distribution was also analyzed to obtain the goodness of fit of the parametric distributions, i.e., normal distribution, log-normal distribution, and the cumulative Weibull distribution.[11] It is not easy to recognize the fit of the parametric distributions to the actual frequency plots of the timber generalized for all timber. Some species have a high goodness of fit to the normal distribution, some to the log-normal distribution, and others to the Weibull distribution as shown in Table 2. The parametric distribution and actual frequency of the MOE and MOR of the tropical timber are shown in Figs. 1 and 2. Selecting the best fit distribution for the actual frequency values is important, especially for the lower tail values in the establishment of allowable MOE and MOR. In ASTM D 5457, the distribution of timber is assumed to be a Weibull distribution while the European standard tends to assume a log-normal distribution.[12] With reference to Fig. 1, for the lower tail values, the log-normal and Weibull distributions provide better fits than the normal distribution, but for the other plots the log-normal distribution seems better than the Weibull distribution.

Table 3. The parameters of parametric distribution and their fifth percentile limit

Specimens	MOE						MOR					
	Log-normal			Weibull			Log-normal			Weibull		
	λ	ξ	$R_{0.05}$	η	α	$R_{0.05}$	λ	ξ	$R_{0.05}$	η	α	$R_{0.05}$
Timber from natural forest	2.68	0.26	9.1	16.5	4.5	9.3	4.04	0.33	29.8	66.6	3.4	26.5
Borneo timber	2.69	0.26	9.4	16.8	4.6	9.6	4.11	0.24	39.4	68.5	4.9	38.7
Shorea sp.	2.67	0.26	8.8	16.3	4.4	8.5	3.91	0.45	20.7	62.2	2.5	20.6
Kapur sp.	2.60	0.32	7.8	15.7	3.8	8.5	3.95	0.38	26.6	62.7	3.0	28.8
Planted fast-growing hardwood	2.24	0.30	5.7	10.8	4.1	5.3	3.68	0.31	22.4	46.2	3.6	21.3
Acacia mangium	2.15	0.28	5.1	9.8	4.2	4.9	3.68	0.36	19.6	47.2	3.1	16.3
Falcata	2.16	0.16	6.5	9.4	6.8	6.6	3.46	0.24	19.5	36.0	4.2	17.9
Rubber wood	2.32	0.27	6.2	11.6	4.3	6.0	3.77	0.18	30.9	47.1	6.4	31.2
Maesopsis eminii	2.45	0.37	7.2	13.2	4.4	7.7	3.80	0.22	30.0	49.5	5.3	30.5
Hardwood	2.56	0.33	7.2	15.1	3.6	7.0	3.94	0.36	26.3	61.1	3.2	24.2
Planted fast-growing softwood	2.51	0.25	7.8	13.8	4.7	7.6	3.56	0.31	19.8	41.1	3.7	19.6
Pinus merkusii	2.52	0.27	7.6	14.2	4.3	7.3	3.50	0.25	21.2	37.4	4.7	21.3
Agathis	2.47	0.19	8.4	12.9	6.2	8.4	3.74	0.33	18.7	50.1	2.7	14.2
Tropical timber (total)	2.54	0.32	7.2	14.7	3.8	7.1	3.85	0.38	23.5	56.6	3.1	22.8

λ, Mean of log-normal distribution; ξ, standard deviation of log-normal distribution; η, scale parameter of Weibull distribution; α, shape parameter of Weibull distribution; $R_{0.05}$, fifth percentile limit

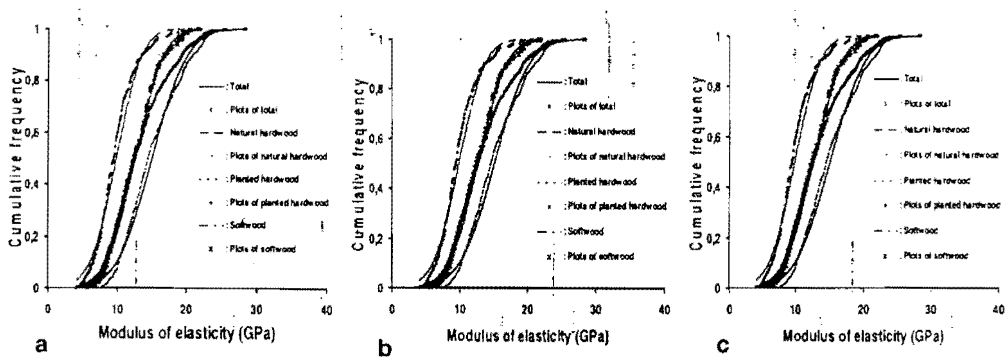

Fig. 1a–c. Parametric distributions of modulus of elasticity (MOE) for group of species of tropical timbers. **a** Normal distribution. **b** log-normal distribution. **c** Weibull distribution

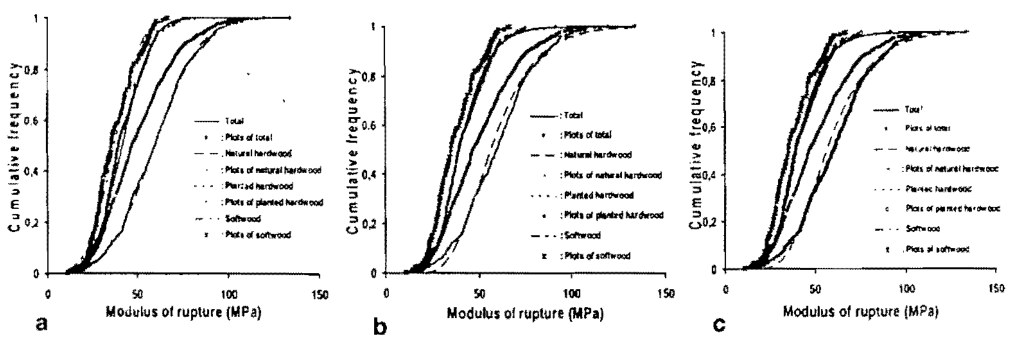

Fig. 2a–c. Parametric distributions of modulus of rupture (MOR) for group of species of tropical timbers. **a** Normal distribution. **b** log-normal distribution. **c** Weibull distribution

For each species or group of species, the mean and the standard deviation of the log-normal distribution, the shape and scale parameter of the Weibull distribution, as well as the fifth percentile limit were calculated and are presented in Table 3. An observation to the lower tail of the distribution is important in order to reduce error in the establishment of allowable stress. Although the goodness of fit of the parametric distributions to the actual frequency of MOE and MOR of the timber could not be specified as shown in Table 2 and Figs. 1 and 2; the difference of the fifth percentile limit of both the log-normal and Weibull distributions were relatively small as shown in Table 3. As described above, the fifth percentile limit of the MOE and MOR of timber from natural forest was also higher than planted timber. The MOE of planted softwood was higher than that of planted hardwood, while the strength of planted hard-

Table 4. The allowable bending stress (in MPa) for allowable stress design (ASD)

Specimens	Parametric (distribution)		Nonparametric		
	5% PE Weibull	5% PE log-normal	5% PE	5% TL	δ
Timber from natural forest	12.62	14.19	13.09	12.62	0.036
Borneo timber	18.43	18.76	19.48	18.10	0.071
Shorea sp.	9.81	9.86	9.90	9.48	0.042
Kapur	13.71	12.67	14.75	14.52	0.015
Planted hardwood	10.14	10.67	10.71	10.38	0.032
Acacia mangium	7.76	9.33	8.57	7.86	0.083
Falcata	8.52	9.29	8.43	8.19	0.030
Rubber wood	14.86	14.71	15.26	15.10	0.010
Maesppsis eminii	14.52	14.29	14.86	14.43	0.028
Hardwood	11.52	12.52	11.62	11.48	0.011
Softwood	9.33	9.43	9.29	8.95	0.028
Pinus merkusii	10.14	10.10	10.38	10.14	0.022
Agathis	6.76	8.90	7.04	6.62	0.061
Topical timber (total)	10.86	11.19	10.91	10.76	0.014

PE, point estimate; TL, tolerance limit; δ, relative difference between nonparametric point estimate (NPE) and nonparametric lower tolerance limit (NTL) which was expressed as (NPE-NTL)/NPE

wood was higher than that of planted softwood. These properties may be affected by the different characteristics of the timbers. Two distinct conditions that might affect MOE and MOR are the presence of tracheid in softwoods and vessels in hardwoods and the different formations of knots in both.[12]

Establishment of allowable stress and reference resistance in LRFD of species or group of species

The basic concept of ASD is that the working stress in the member of a structure should be lower or the same as the product of allowable stress of the member and corresponding duration of loading.[9] The allowable stress is the strength characteristic with the reduction of the safety factor. For example, in Indonesia, as well as in the USA, the safety factor of bending strength is 1/2.1.[8,13] Based on ASTM[8] and European Standards,[14] the strength characteristic of the timber is the fifth exclusion limit ($R_{0.05}$) of the population distribution. The strength characteristic of timber is analyzed using parametric and/or nonparametric procedures.[8]

As mentioned above, the distributions of the timber could not be easily distinguished. For parametric procedures, the allowable strength of timber species and group of species could be obtained from Table 3 with reference to Table 2 for the goodness of fit. There are two statistical ways for nonparametric procedures, i.e., nonparametric point estimate (NPE) based on interpolated data, and nonparametric lower tolerance limit (NTL) based on order statistics. The width of the confidence interval is a sufficiently small fraction of the mean with the values in the range of 0.016 to 0.067. In such a condition, the allowable value of modulus of elasticity is the mean of MOE as shown in Table 1.[8]

Through parametric and nonparametric procedures with the condition as mentioned above and considering the safety factor of bending in 10 years loading of 2.1,[8,13] the strength characteristic and allowable strength is presented in Table 4. With the sufficiently small values of the relative difference between NPE and NTL, the value of NPE as shown in Table 4 is the allowable stress for bending.[8] The allowable stress of any species or group species could also be established through parametric procedures with the small difference value between parametric point estimate (PPE) and NPE or NTL.

The reference resistance for LRFD of the timber was calculated based on the format conversion and reliability normalization factor as mentioned in ASTM D 5457.[9] Format conversion used the ASD load duration adjustment factor of 1.15, LRFD time effect factor of 0.80, and specified LRFD factor for bending of 0.85.[8] The calculation based on reliability normalization factor was conducted using an assumption that the distribution was a Weibull distribution, although the goodness of fit of the Weibull distribution for some species or group of species were lower than 100% as shown in Table 2. In the reliability normalization factor procedure, sample size and coefficient of variations are the decisive factors.

The reference resistance of a species or group of species established through format conversion seemed higher than the one through reliability normalization as shown in Table 5. When the coefficient of variation of the strength of a species is relatively high, the reference resistance based on the reliability normalization would be much lower than the one from format conversion due the reverse position of the coefficient of variation in the reliability normalization equation. Such phenomena indicate that the application of LRFD based on the reliability normalization factor for tropical timbers needs more study.

With reference to Tables 1, 4, and 5, the application of allowable stress and reference resistance for species and/or group of species will mean very safe but inefficient use of the timber due to the use of the fifth percentile of the distributions and/or statistical nonparametric values as the predicted values.

Table 5. Reference resistance of the bending strength (MPa) of timber for load and resistance factor design (LRFD) based on ASTM D 5457

Specimens	Format conversion				Reliability normalization
	Parametric		Nonparametric		
	5% PE Weibull	5% PE log-normal	5% PE	5% TL	
Timber from natural forest	32.05	36.04	33.25	32.05	26.71
Borneo timber	46.81	47.65	49.48	45.97	41.95
Shorea sp.	24.92	25.04	25.15	24.08	16.83
Kapur	34.82	32.18	37.47	36.88	20.70
Planted hardwood	25.76	27.10	27.20	26.37	18.98
Acacia mangium	19.71	23.70	21.77	19.96	16.60
Falcata	21.64	23.60	21.41	20.80	17.19
Rubber wood	37.74	37.36	38.76	38.35	33.51
Maesopsis eminii	36.88	36.30	37.74	36.65	29.99
Hardwood	29.26	31.80	29.51	29.16	23.41
Softwood	23.70	23.95	23.60	22.73	17.36
Pinus merkusii	25.76	25.65	26.37	25.76	22.18
Agathis	17.17	22.61	17.80	16.81	14.27
Tropical timber (total)	27.58	28.42	27.71	27.33	20.93

Table 6. The coefficient of determination of the relationship between MOE and MOR

Specimens	Number of samples	Coefficient of determination (R^2)
Timber from natural forest	566	0.56
Borneo timber	314	0.53
Shorea sp.	192	0.64
Kapur	60	0.71
Planted hardwood	300	0.57
Acacia mangium	120	0.71
Falcata	60	0.63
Rubber wood	60	0.61
Maesopsis eminii	60	0.64
Planted softwood	228	0.36
Pinus merkusii	168	0.60
Agathis	60	0.68

Application grading regardless of species conception for the tropical timber

Some difficulties appeared when visual grading the tropical timber due to the variety of timber species and their embedded characteristics. Shorea sp. consists of 194 species of which 163 species are found in Melanesia.[15] It was also reported that from 400 pieces of mixed tropical timber, namely "Borneo," 23 species were found with a wide range of density and strength of the timber.[5] Visual grading for predicting the strength through evaluation of imperfections, being expressed as the "strength ratio" of clear straight-grain, small specimens of a species, is difficult to apply to the tropical species in such conditions.

The MOE is by far the best predictor of MOR.[2] Some studies of single species reported a relatively strong relationship between MOE and MOR of the timber.[2-5] Table 6 shows the relationship between MOE flat wise and strength of the timber of some species and groups of species. The coefficient of determination (R^2) of the relationship between MOE and MOR of the known single species was in the range of 0.60 to 0.71, but it was lower for the mixed species. When all of the specimens were taken into account,

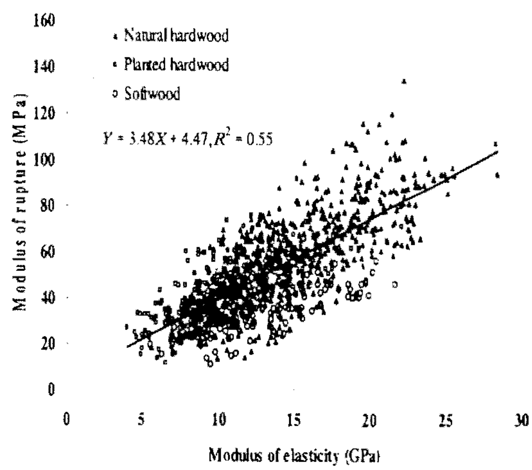

Fig. 3. Relationship of MOE and MOR for group of species of tropical timbers

the R^2 value was 0.55 as shown in Fig. 3. The R^2 value of softwood represented by *Pinus merkusii* and agathis was 0.36. Although the value was quite small, it was better than combining the data of *Pinus merkusii* with falcata of which

Table 7. Equations for predicted MOR based on MOE of the timber species

Specimens or group of specimens	Regression line
Borneo	MOR = 10.67 + 3.11 MOE
Shorea sp.	MOR = 4.41 + 3.11 MOE
Kapur	MOR = 7.64 + 3.11 MOE
Acacia mangium	MOR = 11.86 + 3.11 MOE
Falcata	MOR = 2.86 + 3.11 MOE
Rubber wood	MOR = 7.54 + 3.11 MOE
Maesopsis eminii	MOR = 4.76 + 3.11 MOE
Pinus merkusii	MOR = − 9.69 + 3.11 MOE
Agathis	MOR = 3.87 + 3.11 MOE

the mean value of the strength was similar to those of *Acacia mangium*, rubber wood, and *Maesopsis eminii* from the hardwood. The R^2 value of the relationship between MOE and MOR of such a combination was less than 0.30.

Because the R^2 value of MOE and MOR of all timber specimens in this experiment was 0.55, MOE is a good predictor of MOR, although the application of using MOE as a single variable would cause the over/underestimation of MOR, at least for one species as expressed by the high value of allowable stress F calculated and a very small significant value. The hypothesis that at least there is a species providing a MOR value significantly different from others could be accepted. The fact that there is at least one species providing significantly different MOR endorsed that the identification of the timber species will improve the prediction of MOR through MOE from 74.2% (R^2 = 0.55) to the range of 77.5% (R^2 = 0.60) to 84.3% (R^2 = 0.71).

The prediction equation of MOR based on MOE was obtained through the regression dummy analysis with matrix variables for species and/or group of species. It was found that species and group of species and/or MOE gave a significant effect on MOR with the high calculated value of F and very small significant value. The hypothesis that at least one species and/or MOE provide significant effect on the MOR is accepted. The regression line of the species and group of species is shown in Table 7 and Fig. 4. Using MOE as the strength predictor regardless of species will overestimate MOR for softwood, especially *Pinus merkusii*, as shown in Fig. 4.

Although the timber from natural forest is still dominant in the timber construction industries in some tropical areas, promotion of the utilization of planted timber, especially fast growing species, has been disseminated for some decades. Because the selection cutting policy has been applied since the early 1980s, the availability of some selected species for timber construction has decreased. In many cases, rough visual grading and small clear specimen test results have been applied for predicting the strength of the timber. For the unknown species from natural forest, it is classified as a second class timber although it covers a wide range of strength.[5] The utilization of timber from fast growing trees is not yet popular due to the opinions on such timber as being of low grade for construction. With such background, the application of mechanical timber stress

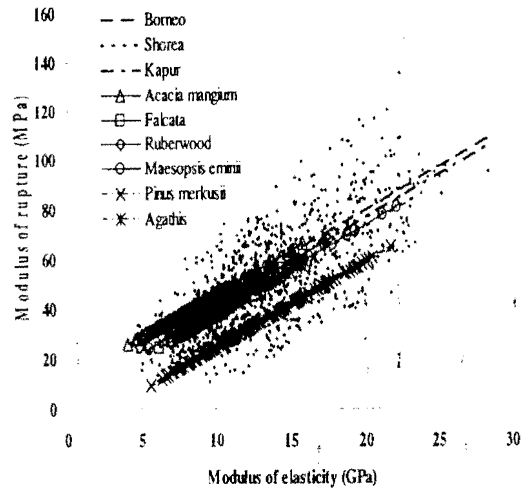

Fig. 4. Regression line of MOE and MOR for species and group of species of tropical timbers

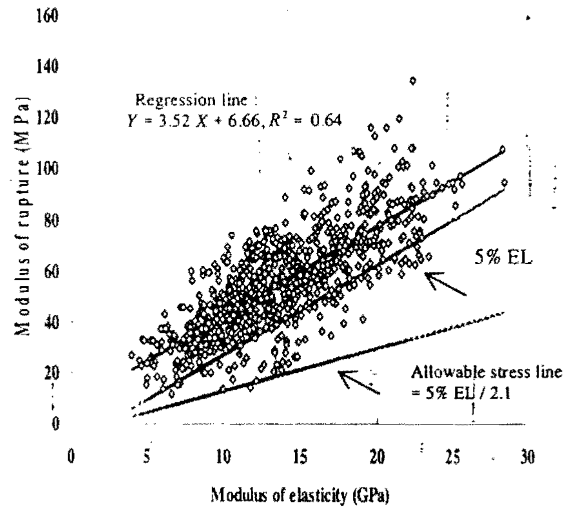

Fig. 5. Regression line, 5% exclusion limit, and allowable stress line of tropical hardwood

grading to tropical planted timber based on MOE with regard to and/or regardless of species is very important.

Establishment of timber strength classes

Although the regression line of agathis is close to hardwood as shown in Fig. 4 and Table 7, there is a tendency for MOE to predict lower values of MOR than those of hardwood. With consideration that *Pinus merkusii* and agathis would be overestimated, the timber strength classes regardless of species was established only for hardwood with the regression line and the 5% exclusion limit as shown in Fig. 5. Exclusion of the values of softwood from the equation as shown in Fig. 3 improved the relationship of MOE and MOR to 0.64 as shown in Fig. 5. The strength classes of timber were derived based on 5% Exclusion limit ($R_{0.05}$) of ASD and LRFD as shown in Table 8. The reference resistance was estimated through format conversion with a load