Effective Utilization of Fast-Growing *Acacia mangium* Willd. Timber As a Structural Material

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Abstract

This study aims to evaluate the full-scale strength performance of *Acacia mangium* Willd. timber and establish characteristic values, as well as the timber strength classes, by the application of mechanical grading. A total of 120 actual size specimens were selected from two areas and the modulus of elasticity and modulus of rupture were tested. The results showed that *A. mangium* timber could be a substitute structural material for light timber construction. Effective utilization of *A. mangium* timber could be obtained when the timber is mechanically graded. The result promotes the effective utilization of *A. mangium* timber, which has a high annual growth rate, from managed forests, thus reducing the destruction of natural tropical forests.

Key words: strength characteristic, *A. mangium* timber, allowable stress, structural materials

Introduction

Although many alternative building materials had been developed, timber still plays an important role in building construction. The reason why timber has remained a primary construction material for thousands of years is simply that no competitive material has all the advantages of timber. A material may equal it in rigidity but lack its insulating qualities. Another may rival it in strength but fail on the point of workability. A third may rank with it in workability but fail to measure up in ruggedness (Anonymous 1956). Timber is also manufactured from renewable resources. A comparative study of timber and synthetic alternatives, as materials for single-storey houses, as well as buildings, showed that timber is an environmentally superior building material. The analysis was conducted on the basis of energy involved in production, e.g. carbon released and carbon stored, life cycle analysis, and environmental chemical analysis (Towsend *et.al*. 2004) Owing to its superiority as a building material, the use of timber in building construction is increasing with increased demand of housing and buildings.

For many years, people in tropical areas utilize high-quality timber for their housing and building requirements. The need for foreign revenue, to support economic development, accelerated the exploitation of tropical forests, thus reducing their potential as a timber resource. The situation also widened the gap between supply and demand for tropical timber from natural forests.

One strategy for solving such problems was the development of the Industrial Forest Estate (Hutan Tanaman Industri/HTI), with the planting of fast-growing species. One indigenous fast-growing species is *Acacia mangium* Willd. *A. mangium* was originally found in eastern Indonesia, but it could grow well in other places, even in marginal lands. It was widely planted in Indonesia almost two decades ago to supply the raw material for pulp, paper and MDF industries. In 2003, *A. mangium* plantations covered 0.8 million hectares, and are predicted to reach 1 million hectares in 2010. The reported annual growth of *A. mangium* is 20 ~ 50 m^3/ha, with harvesting in 8 years (Djojosubroto 2003). Prioritizing the utilization of *A. mangium* for structural materials is crucial owing to the decrease in supply from natural forests, which has seriously affected people's ability to purchase timber for construction.

Data on physical and mechanical properties is necessary when timber is used in building construction. Through testing on small clear specimens, *A. mangium* timber from Australia showed a modulus of rupture (MOR) of 106 MPa, modulus of elasticity (MOE) of 11.6 GPa and compression parallel to grain of 60 MPa (Lemmens *et.al*. 1995). In addition, 10-year-old *A. mangium* timber from Selangor, Malaysia, showed an average MOR of 94.1 MPa and MOE of 7.3 GPa (Razali and Wong 1994). A small clear specimen of 7-year-old *A. mangium* from Sabah, Malaysia, showed an average MOR of 75.9 Mpa and MOE of 10.1 GPa, while a 21 × 40 × 750 mm example showed a MOR of 66.4 MPa and MOE of 6.4 MPa (Sasaki *et.al*. 1994). The moisture content of the tested timber from those areas was around 11% and the average density of those from Selangor was 0.56 g/cm^3 and the average specific gravity of those from Sabah was 0.54 g/cm^3. The data show that larger specimens have a lower strength and rigidity than smaller specimens. It might be due to inherent defects in large specimens. The size of large specimens mentioned above is not the usual size for structural timbers; therefore, to evaluate structural performance, testing on timber of actual size should be conducted.

This study was conducted to evaluate the full-scale strength and rigidity of *A. mangium* timber as structural material, which was limited for non-structural usage. The aim was to establish the characteristics of the timber based on parametric and non-parametric evaluative procedures, as well as analyzing an effective method for predicting the strength of the timber in structural usage.

Materials and Methods

The tested timbers were collected from two different areas: Indramayu and Banten in West Java, Indonesia. After cutting, logs were transported and sawn to obtain 60 × 120 × 3000 mm (T×R×L) plain timber. Timbers were piled and dried in a kiln to air-dry conditions. Moisture content of the timbers was measured periodically from the sample specimens during the drying period.

Sixty samples were randomly selected from each area, resulting in 120 samples. All of the defective characteristics were evaluated, i.e. knots, fiber angle and checks were measured, and pinholes and discolorations identified. The classification of defects, their numbers and sizes were measured, based on the standard specifications for timber as building material (Anonymous 1987). The static modulus of elasticity in flat-wise orientation (MOEf) was measured by center-point loading with a simple grading machine, which can magnify the deflection about 40 times. Flexural strength and rigidity was tested in edge-wise orientation using a universal-testing machine in third-point loading, based on ASTM D 198-84 (Anonymous 2000). The density of specimens was measured in air-dry conditions. Following the procedure in ASTM D 2915-98 (Anonymous 2000) the application of adjustment factors for moisture content and loading system, as well as reduction factors, was carried out. Statistical analysis, e.g. ANOVA, linear regression, and parametric analysis, was applied for analyzing test results.

Result and Discussion

Rigidity and Strength of *A. mangium* Timber

The test results in Table 1 showed that MOR, from the weakest to the strongest, fell in the ratios of about 1/9 to 1/8, while the lowest to the highest MOEf and edge-wise MOE (MOEe) were in the ratios of about 1/4 to 1/3. The MOR of actual size *A. mangium* appeared to be lower than those of smaller sizes, as mentioned above. The strength of actual size timber is mainly affected by defects inherent in a piece of timber, as actual size timber has a higher probability for containing defects than small size timber. It is understandable for actual size timber because wood fibers may be cut producing sloping grain and distortions around knots. The presence of knots, fiber angles and other defects in actual size timbers could be the reason for the lower MOR of tested timber. The macrostructure of knots, fiber angle etc. has been cited as the explanation of why tensile strength along the grain may drop from more than 100 MPa for clear wood to less than 10 MPa for structural timber of low quality (Hoffmeyer 1995).

Table 1. Performance of *A. mangium* timber

Timber properties	Minimum	Maximum	Average	Standard deviation	Coefficient of variation
Indramayu (10-year-old)					
Moisture content (%)	14.9	19.5	16.5	1.5	0.1
Density (g/cm^3)	0.41	0.60	0.47	0.1	0.1
MOE flat-wise (GPa)	4.1	14.3	8.5	2.8	0.3
MOE edge-wise (GPa)	6.6	20.8	11.6	3.3	0.3
MOR (MPa)	15.3	92.0	43.6	15.7	0.4
Banten (12-year-old)					
Moisture content (%)	15.2	19.4	16.9	1.8	0.1
Density (g/cm^3)	0.45	0.67	0.56	0.1	0.1
MOE flat-wise (GPa)	5.3	15.8	9.3	2.3	0.2
MOE edge-wise (GPa)	5.7	19.1	10.1	2.8	0.3
MOR (MPa)	11.6	75.7	41.6	15.8	0.4
For both locations					
Moisture content (%)	14.9	19.5	16.7	1.6	0.1
Density (g/cm^3)	0.41	0.67	0.53	0.1	0.1
MOE flat-wise (GPa)	4.1	15.8	8.9	2.6	0.3
MOE edge-wise (GPa)	5.7	20.8	10.9	3.20	0.29
MOR (MPa)	11.6	92.0	42.2	15.9	0.37

Note: MOE = modulus of elasticity; MOR = modulus of rupture.

Table 2. Severity of defects, expressed as visual grades, for *A. mangium* timber

Visual grades	Number of defects	
	Banten (12-year-old)	Indramayu (10-year-old)
Grade A	6	12
Grade B	29	37
Grade C	25	11

Besides lower strength and rigidity, *A. mangium* timber of actual size showed a higher variation than small clear specimens. The inherent defects and high proportion of juvenile wood are the reasons of these phenomena. As a fast-growing species, *A. mangium* timber has a high proportion of juvenile wood. It has been reported in hard woods that there is an insignificant difference between the first 5 ~ 20 growth rings and those in the outer part of the stem (Hoffmeyer 1995). For softwood, the ratio of MOR for juvenile and mature wood was reported to be 0.5 ~ 0.9, but only limited research has been done for hardwood. Juvenile wood has a greater influence in reducing the mechanical properties of higher grade than lower grade structural timber (Green *et.al*. 1999). This must be taken into account when considering *A. mangium* timber as a structural material, which was limited for non-structural usage.

At similar size, the MOEf and MOR of *A. mangium* timber were higher than another fast-growing tropical species, such as *Gmelina arborea, Eucalyptus deglupta*, and *Paraserianthes falcataria* (Sasaki *et.al*. 1994; Firmanti *et.al*. 2005). The density of *A. mangium* timber was higher than other tested fast-growing species but the presence of defects, such as knots, was almost similar. The strength and rigidity of *A. mangium* timber were lower than Borneo (a trading name for mixed tropical timber), Shorea (*Shorea sp*.) and Kapur (*Dryobalanops aromatica*) woods which are commonly used in building construction (Firmanti *et.al*. 2005). The lower MOEf and MOR of *A. mangium* timber, compared to other timbers typically used in construction, are affected by the lower density and relatively high percentage of defects. With the minimum MOR of 11.6 MPa and MOEf of 4.1 GPa as shown Table 1, *A. mangium*, with restricted usage, is a potential substitute for timber from natural forests. The lowest strength class in European Norms (EN)-338 for softwood, using the 5% percentile (i.e. not the lowest timber strength), is 16 MPa for MOR and 4.7 GPa for MOEf (Gloss 1995a).

To investigate the difference in strength and rigidity characteristic of timber from the two locations, a mean comparison, using one-way analysis of variance (ANOVA), was performed. *F*-tests at 95% confidence interval for MOEf, MOEe and MOR of *A. mangium* timber from Indramayu and Banten were 0.81, 0.16 and 1.20, respectively. The *F* table at 0.05 probability, numerator degree of freedom for location 1 and denominator degree of freedom of 59 samples is 4.004 (Lawless 1982). The lower value of the *F*-test compared to the *F* table signifies that there was no significant difference in the strength and rigidity performance between *A. mangium timber* from Indramayu and Banten.

The insignificant difference between the rigidity and strength of timbers from Banten and Indramayu could be explained by the production characteristics of the timber. Although timbers from Banten were higher in density, they contained more defects than those from Indramayu. The timber defects were reflected by visual grading. The Indonesian timber grading code classifies the visual grade of structural timber into three categories grade: A, B and C, based on the size and position of knots, fiber angle and the length of checks etc. The Banten area contained greater amounts of low-grade timber than Indramayu, as shown in Table 2. The defects might have a direct association with the lack of pruning in the cultivation system, as many branches were kept on the trees and more knots were found in sawn timbers from Banten. The sum of these effects, i.e. timber of higher density but with more defects, resulted in a similar outcome, as regards rigidity and strength, to timber with a lower density but fewer defects. The effect of these defects on timber strength and rigidity was also identified from results for the two evaluated locations. A higher MOR was found in timber from Indramayu, with a relatively low density, than timber from Banten, in which the density was higher, as shown in Table1.

The MOR of straight-grained timber declined with the higher fiber angle: from 100% MOR in straight-grained timber to 89, 81 and 55% for 1/15, 1/10 and 1/5 fiber angles, respectively (Green *et.al*. 1999). As shown in Table 2, visual grades of timber from Banten are predominantly in grade C, which has a limit for fiber angel of 1/5, and grade B with a limit of 1/7. The fiber angle limit for grade A is 1/10. It is clear that a higher fiber angle resulted in a lower grade of the timber.

Another dominant defect was knots. *A. mangium* trees were planted for the pulp and paper industries, where pruning was unnecessary, with most timber having knots in all parts. Knot size is a parameter for classifying the visual grades of structural timber. The allowed knot size for grade A is smaller than B and C. Since the timber from Banten is lower grade than timber of Indramayu, these defect conditions affected the similarity in strength and rigidity of timber from both locations, although the density of timber from Banten was higher than that of Indramayu.

Strength Characteristics for Using *A. mangium* Timber in Structures

Data on the strength of timber is needed when using timber as a structural material. As a natural material, timber strength is established in a piece of timber as an accumulative effect of density and the defects mentioned previously. For a certain timber species, allowable stress is usually derived from its characteristic value, which is defined as the population mean, median or tolerance limit value, estimated from test data after it has been adjusted to standardized conditions of temperature, moisture content and characteristic size (Anonymous 2000). Non-parametric and parametric procedures are usually used in the derivation of characteristic value or allowable strength of timber. As statistical analysis has shown that location was insignificant as regards rigidity and strength, the characteristic values for *A. mangium* timber was established using 120 samples.

Using a non-parametric procedure, the mean values of MOEf, MOEe and MOR of tested *A. mangium* fell within the 75 and 95% confidence intervals, as shown in Table 3. When the width of the confidence interval, calculated as $ts / \bar{X}\sqrt{n} \leq \lambda$, the allowable value for the modulus of elasticity is the sample mean, as shown in Table 1. In this equation, *s* is standard deviation, $\bar{X}$ is samples mean, *n* is number of samples and λ is the width of confidence interval. Usually, λ is predetermined in the range 0.01 ~ 0.10 (Anonymous 2000). For *A. mangium*, the allowable values of MOEf and MOEe are 8.9 and 10.9 GPa, respectively.

For the MOR, the allowable strength could be established through non-parametric or parametric procedures. Non-parametric point estimate (NPE) and non-parametric lower estimate (NTL), as well as the parametric procedures of normal distribution, log-normal distribution and Weibull distribution are shown in Fig. 2. The estimated population parameter at 95% confidence interval of non-parametric and parametric procedures provided different characteristic values for MOR, as shown in Table 4.

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Table 3. Population mean and 75 and 95% confidence interval for flexural strength performance of timber.

Properties	Mean	Confidence interval		Width of confidence interval	
		75%	95%	75%	95%
MOE flatwise (GPa)	8.9	8.5 ~ 9.2	8.7 ~ 9.4	0.03	0.05
MOE edgewise (GPa)	10.9	10.3 ~ 11.2	10.5 ~ 11.5	0.03	0.05
MOR (MPa)	42.2	40.6 ~ 43.9	39.4 ~ 45.1	0.04	0.07

Table 4. Estimates of population parameter for *A. mangium*

Parameter	MOE flat-wise (GPa)	MOE edgewise (GPa)	MOR (MPa)
Normal			
μ	8.9	10.9	42.2
σ	2.6	3.2	15.9
5% lower tolerance limit	4.4	5.1	14.5
Lognormal			
λ	2.2	3.2	3.7
ξ	0.3.	0.3	0.4
5% lower tolerance limit	5.1	6.3	19.6
2P-Weibull distribution			
η	9.8	11.8	47.3
m	4.2	5.6	3.1
5% lower tolerance limit	4.9	6.4	16.3
Non-parametric			
5% point estimate	5.1	6.5	16.6
5% tolerance limit	4.6	6.2	15.2

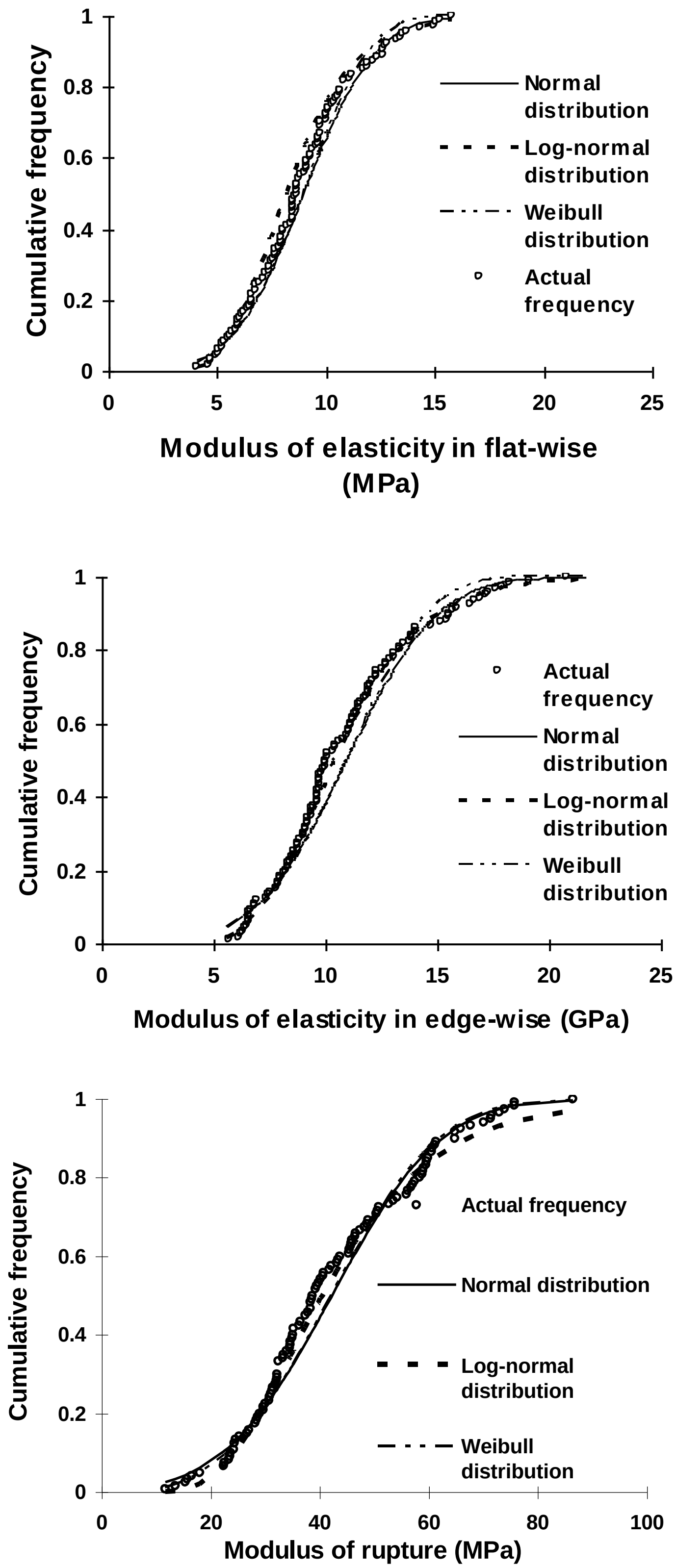

Fig. 2. Parametric distributions of modulus of elasticity and modulus of rupture for *A. mangium* timber

In general, the strength characteristic value in allowable stress design is the fifth exclusion limit (R_{005}) of the population distribution. The strength characteristic values of MOR based on NPE, NTL, 5% tolerance limit of normal distribution, log-normal distribution, and Weibull distributions were 18.2, 15.2, 14.7, 19.6 and 22.4 MPa, respectively. Based on the sample mean values and standard deviations, and the relatively small difference in NPE and NTL, 120 samples were sufficient for establishing the allowable stress using a non-parametric procedure. The value of (NPE-NTL) / NPE, expressed as δ, was 0.084. Resting within the range 0.01 ~ 0.10, the value of NPE and NTL could be utilized as the allowable stress value. The parametric tolerance limit (PTL) is calculated as follows (Anonymous 2000):

$$\mathrm{PTL} = \bar{X} - Ks$$

where $\bar{X}$ is the mean value; *s* is standard deviation. *K* depends upon the sample size, the percentile 100–*p* and confidence $1-\Upsilon$ In this paper, the number of samples was 120, the 100–*p* was 95%, and $1-\Upsilon$ was 0.95. With reference to Table 5 and Fig. 2, the goodness-of-fit of the tested values presented by the plots, and the normal, log-normal, and Weibull distributions were 65, 90 and 36%, respectively.

A goodness-of-fit test for parametric distribution to the data distribution is necessary to get a confidence value for allowable strength. For parametric procedures, the improper selection of population distribution would produce inappropriate strength characteristic values (Hunt and Bryant 1996) Fig. 3 shows that, although the frequency of the testing result was not well fit to the Weibull distribution, the 5% exclusion limit for Weibull distribution was similar to those of normal distribution and non-parametric values in the lower end. Distribution of wood properties, especially related to strength, and characteristic value in the lower end is typically fitted to lognormal distribution (Hunt and Bryant 1996), but in ASTM 5457-97 the assumption for both is a Weibull distribution (Anonymous 2000).

Application of Timber-strength grading for the Effective Utilization of *A. mangium* Timber

The non-parametric procedure shows the allowable strength of *A. mangium* as 15.2 MPa; with the parametric procedure it is 16.34 MPa. The MOR of tested *A. mangium* was in the range 11.6 ~ 92.0 MPa, with a mean value of 42.2 MPa. Since the use of structural timber is based on its characteristic strength value, i.e. the strength determined by the lower percentile of the population, the high strength of the majority of the population cannot be effectively utilized unless each timber is graded separately (Anonymous 1990).

With reference to Table 2, most of the timbers were classified as Grade B or C. The results of grading showed that knots were found in most samples (88%) and fiber angle in 26 pieces (44%) and a small percentage of other defects. Based on visual grading, as mentioned in the timber design code, among 120 sawn timbers, 18 pieces were in Grade A, 66 in Grade B and 36 was in Grade C. The strength ratio for Grade A, B and C is 0.80, 0.63 and 0.50, respectively. Following Indonesian standards (Anonymous 1987), the visual grade of timber, having density as the basic criterion, allowable stress of *A. mangium* was calculated in the range 4.34 ~ 12.17 MPa.

Comparing the allowable stress, based on the calculation of non-parametric procedures as mentioned above, the allowable MOR of tested *A. mangium*, based on the Indonesian timber design code, is very small, too conservative and wasteful, resulting in a dissipation of wood strength. Such a classification does not work effectively in timber strength classification because the determination of defects was only based on size, and the location of knots has never been taken into account. The predictive accuracy of visual grading therefore has its limitation. Since the grading decision depends on the judgment of the grader it can never be totally objective (Gloss 1995b).

As mentioned above, if the use of structural timbers is based on the strength of the lower percentile of the population, the high strength of the majority of the population cannot be utilized effectively, given an assumed strength based on the density being too conservative. Simple static equipment for measuring deflection was applied to timber. In this experiment, using a simple linear-regression analysis, the coefficient of determination (R^2) of the relationship between MOEf and MOR was 0.61, as shown in Fig. 3. Coefficients of determination of the relationship between MOEf and MOR have been reported in some studies as 0.72, 0.53, 0.55 and 0.56 (Steffen *et.al.* 1997).

Modulus of elasticity alone gives a better prediction than density, annual ring width and knot data combined. Due to the fact that timber also contains data on the clear wood properties along with defects, such as knots, fiber angle etc., combining the MOE with other data therefore has only a small effect on predicted performance. The coefficient of determination of the relationship between MOE and bending strength of 58 × 120 mm Norway spruce timber was reported to be 0.49, but with the addition of knot data it was 0.59 (Johansson 1995).

The coefficient of determination (R^2) or the coefficient correlation (R) gives an indication of the relationship between independent and dependent variables (Gomez and Gomez 1984). High R^2 could be obtained from the data that fall in the upper and lower ends of normal distributions. Fig. 3 shows MOEf and MOR data scattered so evenly that the MOEf could be used to predict MOR. An evaluation for the modulus of elasticity as a predictor of bending strength was conducted using ANOVA, as shown in Table 6. With calculated *F* significantly higher than the *F* table, it confirmed that MOEf could be used as a predictor of MOR.

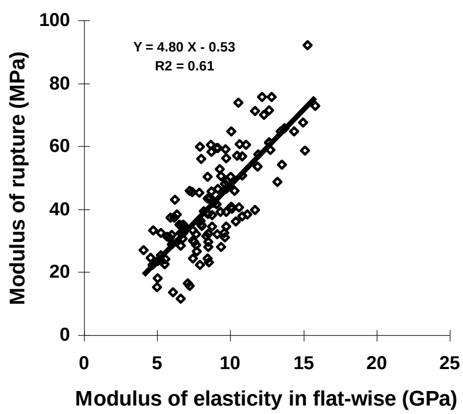

Fig. 3. Relationship between MOEf and MOR of *A. mangium* timber.

The results of this research provide evidence that, in the utilization of *A. mangium* as a structural material, applied mechanical grading, using MOEf as a predictor, is the most effective technique compared to conventional methods of allowable stress by species or visual grading.

One important fact in the use of timber as a structural material is timber strength class. Since the MOE is used as the principal predictor of strength, timber strength classes in some countries are based on the MOE. The timber strength class for *A. mangium* has been determined through multiple regression analysis of some tropical timber species. Table 7 shows the *A. mangium* timber strength classes. The bending strength characteristic of *A. mangium* timber (allowable stress) in Table 7 is similar to the allowable bending stress, at similar MOE values, for deciduous species in EN 338 (Gloss 1995a). Kretschmann and Green (1999) determined a lower allowable stress of bending, at similar MOE values, for machine-graded timber than those for *A. mangium*, but the difference was insignificant, regardless of species, as shown in Table 7. In comparison to the Japanese timber strength classification, the strength and rigidity of *A. mangium* is relatively consistent with the strength and rigidity classification of Karamatsu (*Larix leptolepis*), Hinoki (*Chamaelyparis obtuse* S. and Z.) and Hiba (*Thujopsis dolabrata* S. and Z. var. hondai) woods (Anonymous 2002).

The result that *A. mangium* timber could be used as a substitute material in light-timber structures, such as detached houses, promotes the effective utilization of fast-growing species, which are planted in well-planned plantations. With a high annual growth, *A. mangium timber* could be harvested in 6 ~ 10 years. In Indonesia, the predicted area of 6.5 million ha of *A. mangium* timber can fulfil the timber needs in existing industries (Djojosubroto 2003). Considering the fact that natural tropical forests have been seriously degraded, over the long-term, the use of *A. mangium* timber for housing and other light structures will reduce the destruction of exotic natural tropical forests for a more sustainable humanosphere.

Table 5. Goodness-of-fit of parametric distributions for frequency of test result plots

Properties	Fitness of parametric distributions (%)		
	Normal	Lognormal	2P-Weibull
MOE flat-wise	100	100	71
MOE-edgewise	54	100	69
MOR	65	90	36

Table 6. ANOVA of regression between MOE flat-wise and MOR

Parameter	Sum of square	Degree of freedom	Mean square	$F_{calculated}$	F_{table}
Regression	17892.48	1	17 892.48	183.27	3.92*
Residual	11520.25	118	97.63		6.85**
Total	29412.73	119			

Table 7. Timber strength class of *A. mangium* and strength class for timber, regardless of species, based on MOE

Grade	MOE (GPa)	Allowable Stress of *A. mangium* (MPa)	Allowable Stress Regardless of Species (Mpa)
E 150	15.0	25.2	20.3
E 135	13.5	22.7	17.9
E 120	12.0	20.3	15.5
E 115	10.5	17.8	13.0
E 90	9.0	15.4	10.6
E 75	7.5	13.0	8.2
E 60	6.0	10.5	5.7

Conclusions

As a fast growing species, *A. mangium* is a prospective material for timber structures in Indonesia. It can be a substitute for tropical hardwood, the supply of which is decreasing year by year. Since the strength and rigidity of a piece of timber are affected by density and inherent defects, there was an insignificant difference between the strength and rigidity of *A. mangium* timber from the two areas studied.

Without application of visual or mechanical grading, the use of timber is based on its characteristic strength value, i.e. the lower 5-percentile of the population. Under such conditions, the high strength of the majority of pieces can not be utilized effectively. Based on non-parametric analysis, the allowable MOR for *A. mangium* was calculated as 16.60 MPa, MOEf as 8.93 GPa and MOEe as 10.87 GPa. The result of parametric analysis showed a high degree of fitness to a log-normal distribution. The parametric tolerance limit of MOR was 19.60 MPa.

Through the regression analysis and ANOVA, it was found that MOEf was a good predictor for bending strength due to high correlation coefficient and the *F*-values. Effective utilization of fast-growing *A. mangium* timber, which was planted for pulp and paper usage as a structural building material, can be obtained through the implementation of mechanical stress grading, using flat-wise MOE as a predictor. The timber strength class had also been established to promote the effective utilization of *A. mangium* as a structural material. Such strength classes conform to the European norm, American and Japanese mechanically graded solid timber strength classes.

The result of this study will promote the effective utilization of fast-growing species, planted in well-designed plantations. In the long-term, the application of *A. mangium* timber for housing and other light structures will reduce the destruction of exotic natural tropical forests for a more sustainable humanosphere.

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