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MECHANICAL PROPERTIES OF PLYWOOD FROM BATAI (*PARASERIANTHES FALCATARIA*), *EUCALYPTUS* (*EUCALYPTUS PELLITA*) AND KELEMPAYAN (*NEOLAMARCKIA CADAMBA*) WITH DIFFERENT LAYER AND SPECIES ARRANGEMENT

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Timber from forest plantation can be an alternative to overcome the shortage of raw material for plywood manufacture. However the use of fast growing species may affect the plywood quality. This study investigated the mechanical properties of plywood made from three fast growing species which is batai (*Paraserianthes falcataria*), eucalyptus (*Eucalyptus pellita*) and kelempayan (*Neolamarckia cadamba*). Plywood with five and seven layers veneer were produced with different species arrangement. Bending, bonding shear and panel shear properties of the plywood were determined according to Japanese Agricultural Standard for Plywood. Results showed that the number of layer and veneer thickness affected the board properties. Plywood with seven layers performed better than five layers, showing higher modulus of rupture, modulus of elasticity and bonding shear. Species arrangement affected modulus of rupture, modulus of elasticity, bonding shear and panel shear. Plywood from kelempayan and kelempayan-eucalyptus arrangement performed better than plywood containing batai veneers.

Keywords: Japanese Agricultural Standard for Plywood, forest plantation, raw material, plywood manufacture, fast growing species

INTRODUCTION

Plywood is a kind of wood panel made from sheets of veneer and combined under pressure with an adhesive. It is constructed with veneer grain direction of adjacent layers oriented perpendicular to one another (Youngquist 1999). In the past, Malaysian plywood mills were accustomed to process good quality timber from the forest which are straight, of large diameter and cylindrical form, having straight grain and comparatively free from defects (Wong & Wong 1981). However, the log supply has become critical as the forest resources further diminished. The production of logs decreased from 40.1 million m^3 in 1990 to 15.9 million m^3 in 2012 (DOSM 2013). As an alternative, logs from plantation can be considered to overcome the raw material shortage. However the use of fast growing species may affect the plywood quality. Studies showed that plywood from rubberwood (*Hevea brasiliensis*) and *Acacia mangium* plantations can be produced with some modifications to the process (Wong 1979, Wong et al. 1988). Veneer with high density, mixed with lower density species, can improve the durability and strength of plywood from low density species (Aydin & Colakoglu 2008).

Batai (*Paraserianthes falcataria*) and kelempayan (*Neolamarckia cadamba*) are among species that had been selected for forest programme in Malaysia (MPIC 2017). Before 1996, Batai was planted in Pahang and Sabah in a total area over 13,000 hectares (Hashim et al. 2015), whereas kelempayan was planted in the states of Perak, Pahang, Sarawak and Sabah (Nordahlia et al. 2014). *Eucalyptus* species have shown spectacular growth in many countries (Rodriguez-Solis et al. 2015, Rocha et al. 2016, Zhou et al. 2017, Leksono & Kurinobu 2005). Effect of provenance and genetic variation on the growth of *Eucalyptus pellita* had been reported by Nieto et al. (2016). Numerous species of *Eucalyptus* have been planted in Negeri Sembilan, Pahang, Johor, Sarawak and Sabah (Chew 1980, STA 2015) with early plantation reported by Barnard and Beveridge (1957 in Chew 1980).

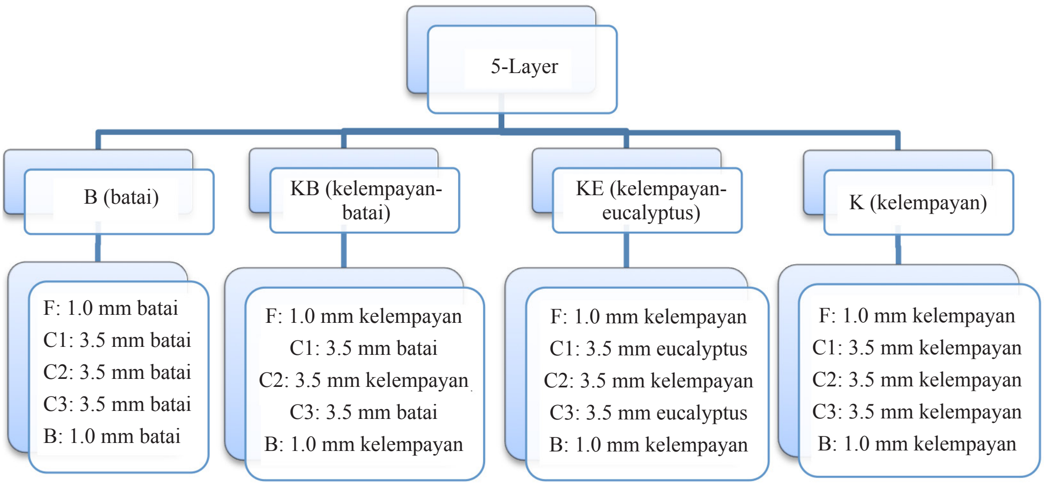
The objective of this study was to investigate the mechanical properties of plywood from batai, kelempayan and eucalyptus plantations with different layer and species arrangement. The information is important to support the use of plantation species for plywood manufacture in Malaysia.

MATERIALS AND METHODS

Batai, eucalyptus and kelempayan logs with diameter 28–45 cm were obtained from a trial plantation plot in Jengka, Forest Department of Pahang, Malaysia. All logs were cut into 1.5 m and 2.7 m in length, and sent to plywood mill for processing and manufacturing. The logs were peeled into veneers with certain thickness. The veneers were dried in dryers to a moisture content of 8–12 %.

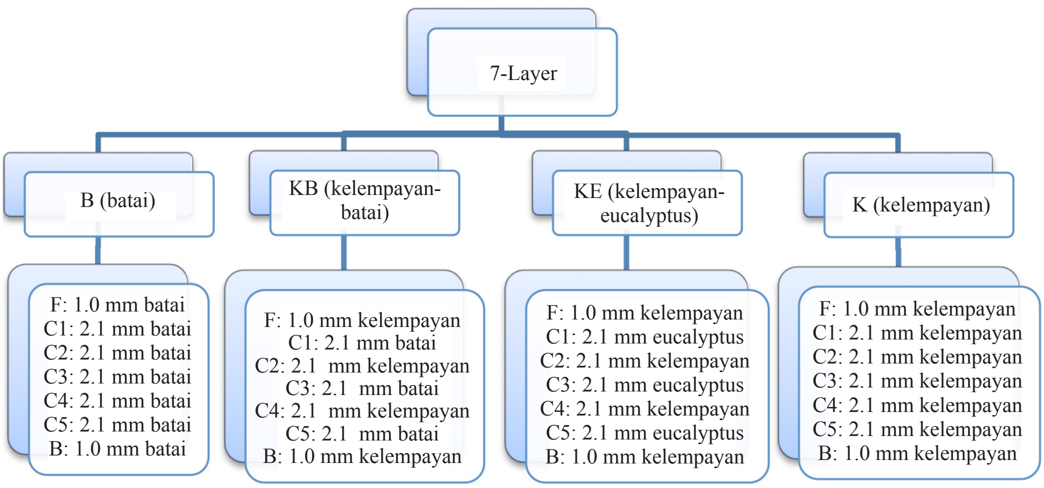
Plywood manufacturing

Five- and 7-layer plywood of at least 183 cm × 92 cm × 1.2 cm size were produced, each with four different arrangements based on veneer size and availability (Figure 1 & 2). Face and back veneers were from batai and kelempayan with thickness of 1.0 mm, whereas eucalyptus, batai and kelempayan were used for the core with veneer thickness 3.5 mm and 2.1 mm for 5- and 7-layer plywood respectively.



F = face veneer, C1 = first core veneer, C2 = second core veneer, C3 = third core veneer and B = back veneer

Figure 1 Species arrangement of 5-layer plywood



F = face veneer, C1 = first core veneer, C2 = second core veneer, C3 = third core veneer, C4 = fourth core veneer, C5 = fifth core veneer and B = back veneer

Figure 2 Species arrangement of 7-layer plywood

The veneers were glued with melamine urea formaldehyde resin through glue spreader machine at spread rate of 38 g 929 cm^{-2}. The resin had viscosity of 2200 cP, pH 6, pot life 2 hours and extension ratio of 1.372. The manually arranged veneers were pre-pressed at 20 kg cm^{-2} pressure for 40 minutes before placing in hot press at temperature 125 °C, and 9 kg cm^{-2} pressure for 8 minutes. The ready boards were trimmed and sanded to 12 mm thickness.

Testing and analysis

Bending (parallel and perpendicular) test, bonding shear as adhesion test and panel shear test were conducted to the boards according to Japanese Agricultural Standard for Plywood (JAS 2014). All test pieces except for panel shear test were conditioned at temperature 20 ± 2 °C and relative humidity 65 ± 5%. Load determination of the test pieces were carried out using 50 kN universal testing machine.

Two sets of rectangular test pieces, 338 mm (length) × 50 mm (width), with length direction parallel and perpendicular to the plywood face grain were prepared for three point bending test. Test span was set at 288 mm and load was applied at not more than 14.7 MPa per minute. For bonding shear, test pieces 25 mm width and length of 80 mm parallel to plywood face grain direction were prepared and nicked to allow the examination of related glue line. The test pieces were immersed in hot water for 3 hours at temperature 60 °C, and then immersed in cold water for cooling down. Bonding shear strength was determined by applying vertical tensile force at parallel direction to the length of the wet test pieces. Test pieces for panel shear test were cut with length of 255 mm in parallel direction to plywood face grain and width of 85 mm. Load was applied to panel edge at speed not more than 2.0 MPa per minute.

Statistical analysis of the results was conducted using SPSS software. Analysis of variance (ANOVA) was used to analyse the effect of plywood layer and veneer species arrangement, whereas Duncan Multiple Range Test (DMRT) was used to determine significant difference of the results.

RESULTS AND DISCUSSION

Table 1 shows mean results of modulus of rupture (MOR), modulus of elasticity (MOE), bonding shear strength and panel shear strength of 5- and 7-layer plywood from batai, kelempayan and eucalyptus. The MOR and MOE values were obtained from the bending test of parallel and perpendicular test pieces.

Highest value of MOR in parallel direction was observed in 7-layer plywood with kelempayan-batai (KB) arrangement (49.47 MPa), and for MOE in 7-layer plywood with kelempayan (K) arrangement (5730 MPa). Meanwhile the highest

Table 1 Mechanical properties of 5- and 7-layer plywood

Layer	Species arrangement	Parallel		Perpendicular		BS (MPa)	PS (MPa)
		MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)		
5	B	20.38	2453	32.38	2878	1.18	5.45
	KB	37.16	4781	34.77	3825	1.29	6.08
	KE	34.63	3993	59.82	6027	1.68	8.69
	K	40.04	4272	49.46	5362	1.40	7.07
7	B	25.35	2733	34.18	3867	1.43	5.68
	KB	49.47	4609	31.12	3959	1.40	6.68
	KE	47.47	5226	59.86	6858	1.83	7.09
	K	48.43	5730	60.14	5408	2.38	6.73
Type 2 bonding shear (JAS 2014)						0.70	

MOR = modulus of rupture, MOE = modulus of elasticity, BS = bonding shear strength and PS = panel shear strength

MOR in perpendicular direction was observed in 7-layer plywood with K arrangement (60.14 MPa) and for MOE in kelempayan-eucalyptus (KE) arrangement (6858 MPa). The highest bonding shear value was observed in 7-layer plywood with K arrangement (2.38 MPa), and for panel shear in 5-layer with KE arrangement (16.00 MPa).

Effects of layer

Modulus of rupture and MOE are important values in strength measurement related to load-bearing ability of plywood (Bal & Bektas 2012). The effect of layer was apparent to bending results. The ANOVA showed that, between layers the MOR and MOE were significantly different at both parallel and perpendicular directions (Table 2). This was supported by the DMRT analysis shown in Figure 3. The MOR and MOE of 7-layer plywood were significantly higher than the 5-layer. Number of layers in plywood has an effect on the mechanical properties of plywood; increasing of veneer layer can increase the bending strength on plywood (Ozen 1981). Plywood usually consists of veneer sheets alternately arranged in parallel and perpendicular directions, and bending strength of plywood is much affected by veneers with main grain parallel to the board length. For parallel bending, the 7-layer plywood had two cores, face and back veneers parallel to the test sample length with total construction thickness of 6.2 mm (2.1 + 2.1 + 1.0 + 1.0 mm), whereas the 5-layer had one core, face and back veneers with construction thickness

Table 2 Summary of ANOVA of mechanical properties of 5- and 7-layer plywood

Source of variation	F-ratio					
	Parallel		Perpendicular		BS	PS
	MOR	MOE	MOR	MOE		
Layer	300.75**	357.96**	12.01**	249.00**	65.40**	0.50ns
Species Arrangement	326.38**	890.84**	306.36**	1957.58**	39.74**	6.38**
Layer * species arrangement	10.57**	109.24**	13.83**	57.13**	18.94**	1.55ns

ns = not significant at p > 0.05, ** = highly significant at p < 0.01, MOR = modulus of rupture, MOE = modulus of elasticity, BS = bonding shear strength and PS = panel shear strength

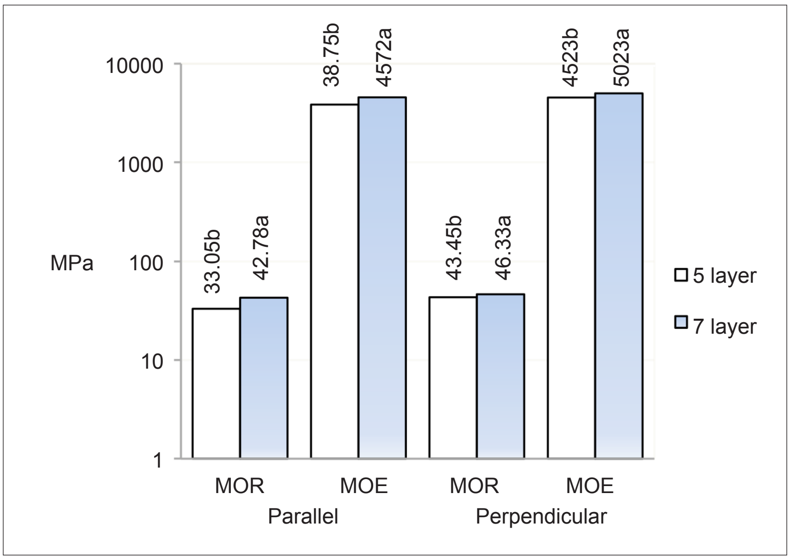


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Figure 3 Duncan Multiple Range Test (DMRT) on bending at parallel and perpendicular directions of 5- and 7-layer plywood of 5.5 mm (3.5 + 1.0 + 1.0 mm). The thickness difference probably gave strength advantage to the 7-layer plywood.

Interestingly, within layers, the plywood had higher MOR and MOE values at perpendicular rather than parallel bending as reported by Kitamura & Wong (1983). This is because, at perpendicular bending, the strength was contributed from veneers parallel to board length, which had higher construction thickness than the parallel bending board. For example, in the 5-layer plywood, the perpendicular test piece had 7.0 mm total thickness of veneers with grain direction parallel to the length of test piece as compared to the parallel test piece with 5.5 mm total thickness. Furthermore, the thin face and back veneers (1.0 mm) used in construction, likely gave low strength to the parallel bending. On the other hand, Bal & Bektas (2014) produced 5-layer plywood with parallel strength higher than perpendicular. The parallel board had veneers parallel to board length with total thickness of 9 mm compared to perpendicular board with thickness of 6 mm.

Plywood is usually produced to have higher bending strength at parallel direction of face grain than perpendicular direction (Biadala et al. 2015, Tsen & Jumaat 2012) in order to meet the design and application requirements (APA 1997, JAS 2014). However, due to high veneer cost, thin veneers have been increasingly used for face and back, thus producing plywood with high strength at perpendicular direction. This type of plywood is usually suitable for general purpose application.

Figure 4 shows the bonding shear value of 7-layer plywood (1.8 MPa) which was significantly higher than the 5-layer (1.4 MPa), indicating good adhesive bonding between surfaces of veneer lay-up. The 5-layer plywood was constructed with thicker core veneers (3.5 mm) than the 7-layer (2.1 mm). Usually, a thicker veneer has tendency to absorb more glue at pre-press which made the glue cure inside the veneer during hot press instead of the glue line. According to Pavlo et al. (2009), veneer bonding is an important process that affects the physical and mechanical characteristic of plywood. Good veneer bonding depends on veneer surface and species, adhesives, press time for pre-press and hot press, and press temperature. Good veneer bonding is also produced from low moisture content veneer (Aydin et al. 2006).

The effect of layers was not significant on the panel shear strength (Figure 4). Generally board strength increased with increasing board density (Irle & Barbu 2010). In this study the board density of 5- and 7-layer plywood was not significantly different (Figure 5), thus the boards had similar panel shear values at about 6.5 MPa. However, the results of MOR, MOE and bonding shear strength were more affected by veneer construction thickness rather than board density.

Effects of species arrangement

The species arrangement had significant effects on MOR, MOE, bonding shear and panel shear properties (Table 2). Statistical differences of the MOR and MOE are shown in Figure 6.

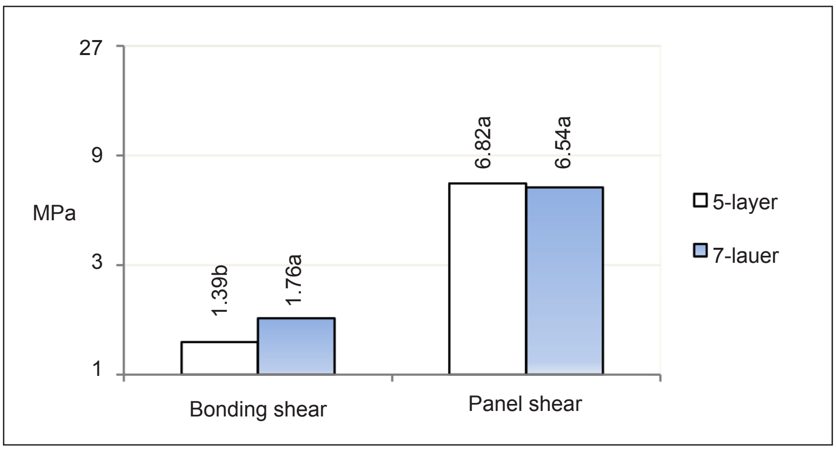

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Figure 4 Duncan Multiple Range Test (DMRT) on bonding shear and panel shear strength of 5- and 7-layer plywood

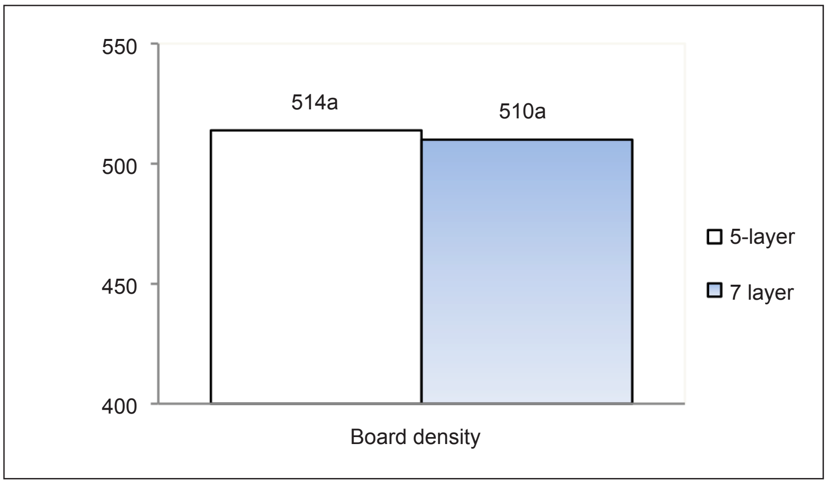

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Figure 5 Duncan Multiple Range Test (DMRT) on density of 5- and 7-layer plywood

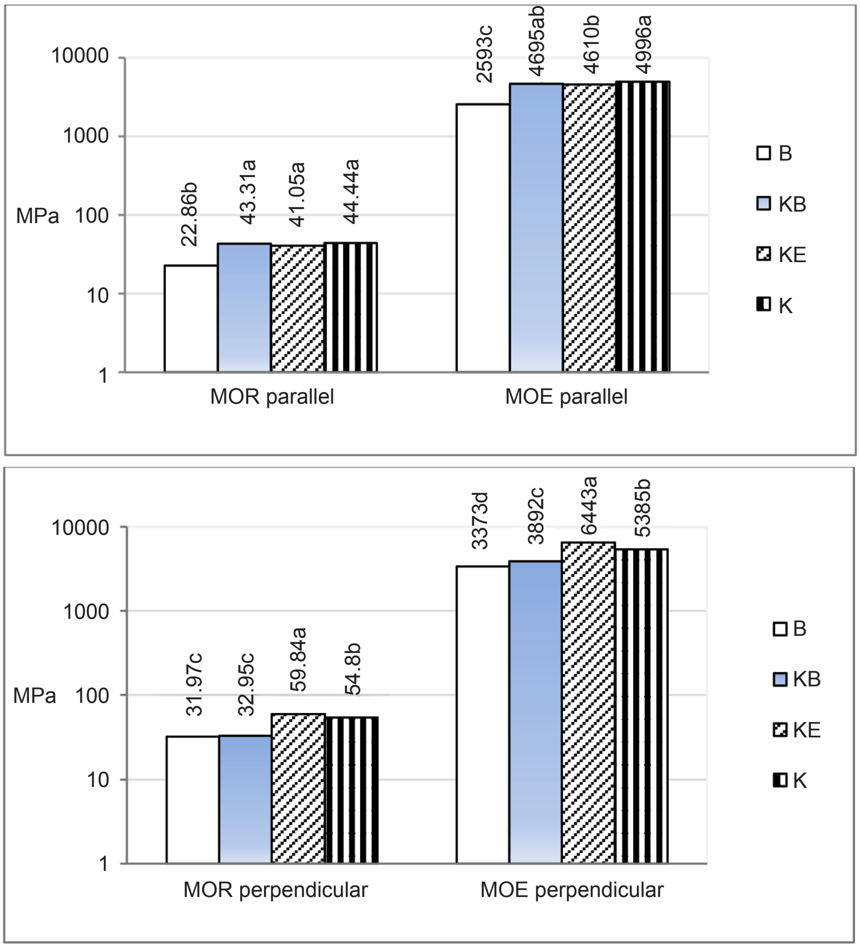

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Figure 6 Duncan Multiple Range Test (DMRT) on bending parallel and perpendicular of plywood with different species arrangement

At parallel bending, plywood from batai (B arrangement) had lower MOR and MOE values than kelempayan (K, KE and KB arrangements). The use of batai and eucalyptus as core veneers perpendicular to board length in kelempayan plywood (KB and KE) reduced the strength, even though not significant for MOR. At perpendicular bending, kelempayan plywood produced high MOR and MOE, and highest when eucalyptus was used as core veneer perpendicular to board length. However, the use of batai as core veneer (KB and B arrangements) significantly reduced the values. Similar to findings shown in Figure 3, the MOR and MOE of perpendicular bending in Figure 6 were higher than parallel bending within the same species arrangements.

Density of wood has proportional effect to its strength in which higher density will produce higher wood strength (Larjavaara & Muller-Landau 2010). In this study the density of batai was expectedly lower than kelempayan and eucalyptus which negatively affected the MOR and MOE of plywood. Batai is light hardwood with density ranging 220–430 kg m^{-3} comparing to kelempayan, 370–465 kg m^{-3} (Nordahlia et al. 2014). The KB and KE arrangements were not significantly different at parallel bending because the strength was highly contributed by kelempayan. Flexural properties of veneer parallel to the grain direction is better than perpendicular (Bal & Bektas 2014). Plywood with KE arrangement had significantly higher property than K arrangement because the KE had a higher density of veneer (eucalyptus) which supported strength.

Meanwhile, significant difference of MOE of perpendicular bending between all species arrangements might be due to different elasticity property of the wood species. Nordahlia et al. (2014) reported elasticity of batai as 6800 MPa and kelempayan as 7700 MPa, whereas Bailleres et al. (2008) reported elasticity of eucalyptus as 13000 MPa.

Plywood with K and KE arrangements had significantly higher bonding shear values than plywood with B and KB arrangements (Figure 7). In bonding shear test, the shear load was applied to core veneer perpendicular to board length, therefore the results were influenced by the core veneers of kelempayan for K arrangement, eucalyptus for KE and batai for B and KB arrangements.

Species that has good absorption with glue and bonding fiber between veneer layers make good strength of bonding shear. However, veneer that absorbs much glue will increase the volume of glue spread or less glue will cure in glue line part. Low results of batai veneers could be associated with its properties. Apart from low density, batai has coarse and even texture with spiral grain that might affect bonding shear (Nordahlia et al. 2014). On the other hand, kelempayan has straight or interlocked grain and the texture is moderately coarse but even (Krisnawati et al. 2011).

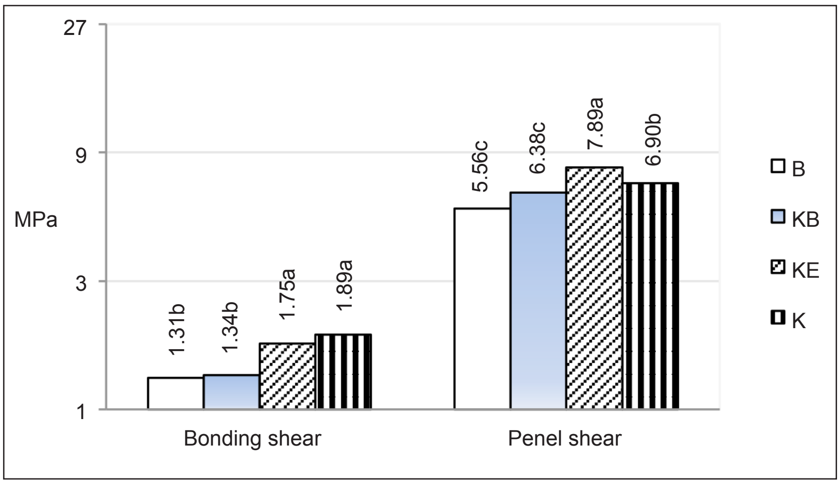

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Figure 7 Duncan Multiple Range Test (DMRT) on bonding and panel shear strength of plywood with different species arrangement

Plywood with KE arrangement had highest panel shear value (Figure 7). Combination of eucalyptus in KE arrangement improved the strength as compared to kelempayan veneer in K arrangement. This was probably due to the higher wood density of eucalyptus, compared to kelempayan. McGavin et al. (2006) recorded eucalyptus density of 529 kg m^{-3} in 8.5-year-old plantation, whereas Bailleres et al. (2008) recorded a density of 588 kg m^{-3} in 15-year-old trees. Figure 8 shows the significant differences of board density between the species arrangements.

CONCLUSIONS

Increased number of veneer layers improved the bending properties of plywood from batai, kelempayan and eucalyptus. Veneer thickness affected the MOR and MOE values of plywood at parallel and perpendicular directions and the bonding quality of plywood. The panel shear strength was more affected by board density rather than the number of layers. Species arrangement affected the mechanical properties and density of plywood in which slight change of veneer species significantly affected the values. All plywood exceeded type 2 bonding quality (shear) requirement for general purpose, specified by JAS (2014), thus showing potential for commercial utilisation.

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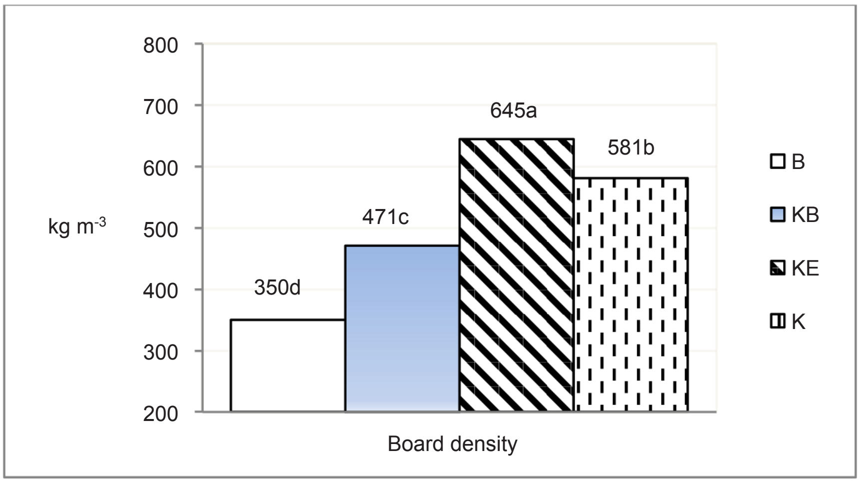

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Figure 8 Duncan Multiple Range Test (DMRT) on density of plywood with different species arrangement

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