Performance of Particleboard Made with *Neolamarckia cadamba*, *Leucaena leucocephala*, and their 50:50 Admixtures

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The performance of a particleboard seems to be related to the chemical constituents of the species and the size distribution the particles. *Neolamarckia cadamba* (NC) and *Leucaena leucocephala* (LL) are fast growing species and good potential resources for particleboard production. This study examined the chemical contents of both species, as well as the mechanical and physical performance of particleboard made with 100% NC, 100% LL, and their 50:50 admixtures. High moisture resistance boards were prepared using melamine urea formaldehyde (MUF) at a content of 10, 12, and 14 %. The 30% extra buffering of LL translated to its lower performance for both mechanical and physical properties. The 50:50 admixtures provided enticing results, as it counteracts the impact of lowered performance of 100% LL. All boards passed the mechanical requirements of the BS EN 312 (2003) standard, but they did not meet the requirement for thickness swelling. The internal bond for cyclic test only failed for 100% LL with 10% resin added. With use of wax, the potential of improvement in swelling properties is possible.

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INTRODUCTION

The need for fast growing species in particleboard production, particularly in Malaysia, prompted this study on two species, *Neolamarckia cadamba* (NC) and *Leucaena leucocephala* (LL). Fast replenishment capability of wood identified the potential of the two species. *Neolamarckia cadamba* is a good forest planation species with commercial return potential in 8 to 10 years (Trianoski *et al.* 2011; Wan-Abdul-Rahman *et al.* 2019). In Malaysia, NC trees have been planted in the State of Pahang and Perak, while the rest was planted in Sabah and Sarawak. *Leucaena L* has a rotation cycle of 2 harvests of wood chips per year due to its capability to coppice. In a previous paper by Wan-Abdul-Rahman *et al.* 2019, the NC:LL particleboard was tested for 50:50 mix for impact of particle size and resin content. The emphasis here is the difference having 100% NVC or LL against the mix. The unscreened material was used as this would be more representative of condition to be used in mill application. Additional properties of buffer capacity and chemical composition of the wood was also looked at. Buffering capacities but has been shown to impact resin behaviour during curing process (Policardi and Thebault 2020).

Higher pH may cause the need to increase the acid quantity to allow same curing time. They also found that melamine urea formaldehyde (MUF) resin to be more effected by the pH. Thus test of the buffering can indicated effects of the hot and water solubles on resin cure behaviour.

Having single species as a complete resource is the dream of a producer to reduce complication during board production. However, a mixed species scenario could be practical, and the combination of two fast growing species NN and LL would help in resource management. Thus, this study determined the mechanical and physical properties of particleboards made from unmixed and a mixture of NN and LL wood with different resin contents.

EXPERIMENTAL

The Educational Forest of Universiti Teknologi MARA Pahang, Jengka, Malaysia, provided the NC and LL wood. The diameter and height for NC and LL were reported previously (Wan-Mohd-Nazri *et al.* 2019). The density and moisture content of samples were tested. Even though the board making utilized the whole tree, the specific gravity (ISO 3131, 1975), chemical composition, and moisture content (TAPPI T 258 om-02, 2006) were done for 3 portions identified as the bottom, middle, and top. The buffer capacity study was done for the combined portions. For chemical analysis, the particles were ground to mesh size 40. Each species was tested for cold water solubility (TAPPI T207 cm-99 1999), hot water solubility (TAPPI T207 cm-99 1999), 1% alkali solubility (TAPPI T212 om-02 2002), alcohol toluene solubility (TAPPI T204 cm-97 1997), ash content (TAPPI T211 om-02 2002), lignin content (TAPPI T222 om-02 2002), and holocellulose content (TAPPI T 203 cm-99 1999) following the TAPPI methods.

To prepare the particleboard, the wood was cut, chipped, air dried, screened to remove fines (< 0.5 mm), and oven dried to below 10% moisture content. The particle size distribution of NC and LL was determined. For buffering capacity, 15 g of oven-dried chips were extracted using 200 mL of deionized water, gently boiled for 2h, and filtered after which the filtrate was cooled to room temperature and titrated with 0.01 N HCl to pH 3.

Particle size distribution was determined by the mechanical screening (sieve analysis) method (EN 15149-1 2010) for 100 g of wood particles.

Whilst the wood properties tested were for portions (top/middle/bottom) of the logs, the particleboard formed was from the combined fraction. The board production parameters were as follows: density, 700 kg/m^3; 12 mm thickness; length, 340 m; and breadth, 340 mm. The board making flowchart is given in Fig. 1.

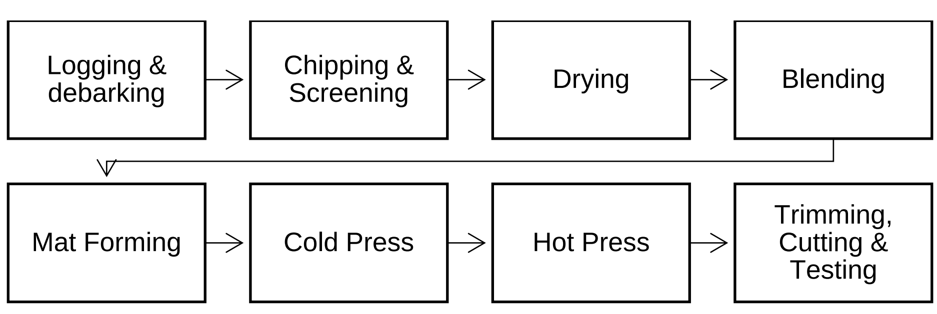

Fig. 1. Flowchart of particleboard formation

Resin was added (10, 12, and 14 %) to unscreened particles; even distribution was ensured by 5 min blending after the last drop of resin was atomized. The resinated particles were formed, cold pressed for 10 min, and hot pressed at 165 °C for 6 min.

Completed boards were conditioned at 20 °C and 65% relative humidity for 24 h. Test specimens were prepared according to relevant EN standards (EN 310, EN312, EN 317, and EN 319) for mechanical and physical properties determination. Because the melamine urea formaldehyde (MUF) resin has a high moisture resistance grade, the additional exposure test for internal bond (IB) was performed as per EN 321 (2002); the cyclic test consisted of a three-cycle accelerated aging treatment. All results were analyzed with IBM SPSS statistical 20 software (Armonk, NY, USA).

RESULTS AND DISCUSSION

Wood Properties

The physical properties of fresh wood depend on its species and on the sampling location such as trunk, sapwood, and heartwood; juvenile and mature wood; or branches and roots (Babinski *et al*. 2014). The wood properties such as specific gravity and moisture content are important when ensuring the suitability for different applications (Wahab *et al*. 2009). The average specific gravity and moisture content for NC and LL are shown in Table 1. The specific gravity for both species increased as the sampling location moved from the top to the bottom of the tree. The highest specific gravity for both species was at the bottom of the tree, with a value 0.45 for NC and 0.76 for LL. According to Lim *et al*. (2005), the density range of NC was from 290 to 465 kg/m^3, and it is classified as light hardwood. LL is medium hardwood (MTIB 2000). The specific gravity was significantly different between species and portions of wood tested (Table 2). The higher moisture content of NC reflected the porosity of the wood.

Table 1. Specific Gravity and Moisture Content of *N. cadamba* and *L. leucocephala*

Species	Tree Portion	Specific Gravity	Moisture Content (%)
Neolamarckia cadamba NC	Top	0.36	93.72
	Middle	0.39	88.52
	Bottom	0.45	71.77
	Average	**0.40**	**84.67**
Leucaena leucocephala LL	Top	0.61	63.22
	Middle	0.67	55.06
	Bottom	0.76	52.11
	Average	**0.68**	**56.80**

Table 2. Summary of ANOVA on Physical Properties

SOV	Df	Specific Gravity	Moisture Content
Species (S)	1	806.45**	47.90**
Tree Portion (TP)	2	64.74**	5.68*
S x TP	3	0.91ns	1.09ns

Note: SOV = source of variance, Df = degree of freedom, ns = not significant, * significant at $p < 0.05$, ** highly significant at $p < 0.01$

The chemical compositions of NC and LL are summarized in Table 3. All values in LL were higher than NC, except for lignin content. For different tree portions, both species showed varying results. Cold water and hot water solubles, alcohol-toluene solubility, and holocellulose content of both species increased as the tree heights decreased. Cold and hot water percentage showed decreasing trends from top to the bottom portion of the tree (Table 3). The highest value of cold water was 6.17% in the top portion of LL, and the lowest was in the bottom portion of NC (2.26%). The average cold water soluble value of LL (5.45%) was higher than NC (2.99%). Likewise, the hot water soluble value of LL (5.98%) was higher than NC (3.62%). NaOH (1%) solubility of NC decreased with tree heights, while LL displayed the opposing trend. The ash content and lignin contents of both species increased from the top to the bottom of the tree. Values of NC differed from earlier work for CW, HW, and lignin (Jamaluddin *et al.* 2018; Wan-Abdul-Rahman *et al.* 2020). Results for LL were very similar to work by Muhammad Zulhilmi (2019) for all properties.

Table 4 shows the analysis of variance (ANOVA) of the effects of species and tree portion and their interactions on chemical properties. The two species were significantly affected for the cold water and hot water but insignificantly dependent on 1% NaOH solubility, alcohol toluene solubility, ash content, lignin content, and holocellulose content. For tree portion, there was no significant effect for 1% NaOH soluble and lignin content. The calculated values of chemical analysis for top, middle, and bottom was taken as average and used as basis of buffer capacity impact consideration.

Table 3. Chemical Compositions of *N. cadamba* and *L. leucocephala* According to Tree Portions

Species	Portion	CW (%)	HW (%)	1% NaOH (%)	Ash (%)	Alcohol (%)	Lignin (%)	Holo (%)
NC	Top	3.75	4.23	12.08	0.52	2.81	22.76	80.64
	Middle	2.95	3.88	12.62	0.62	2.75	22.79	79.30
	Bottom	2.26	2.76	14.43	0.89	2.20	24.87	77.83
	Average	**2.99**	**3.62**	**13.04**	**0.68**	**2.58**	**23.47**	**79.25**
LL	Top	6.17	6.69	14.00	0.65	2.84	20.02	80.76
	Middle	5.38	5.71	13.98	0.75	2.52	23.12	79.14
	Bottom	4.81	5.55	12.93	0.87	2.10	25.03	78.49
	Average	**5.45**	**5.98**	**13.64**	**0.76**	**2.49**	**22.72**	**79.46**

Note: Values are averages of three determinations; CW = cold water soluble; HW = hot water soluble; NaOH = alkali soluble (1% NaOH); AT = alcohol toluene soluble; Holo = holocellulose

Table 4. Summary of ANOVA on Chemical Properties

SOV	Df	CW	HW	1% NaOH	Ash	AT	Lignin	Holo
Species (S)	1	496.01**	76.26**	1.79ns	4.05ns	2.13ns	0.34ns	0.83ns
Portion (P)	2	55.47**	7.71**	0.70ns	19.25**	8.00*	2.60ns	40.15**

Note: SOV = source of variance, Df = degree of freedom, ns = not significant, * significant at $p < 0.05$, ** highly significant at $p < 0.01$; CW = cold water soluble; HW = hot water soluble; NaOH = alkali soluble (1% NaOH); AT = alcohol toluene soluble; Holo = holocellulose

pH Value and Buffer Capacity

Xing *et al*. (2004) noted that the pH and buffering capacity of raw fiber materials is important for understanding the effects of raw material on the curing rate of resin used for panel manufacturing, especially with some less desirable wood materials such as bark, top, and commercial thinning. All portions were mixed with equal proportion prior to extraction. This was done as the particleboard will be using a mixture of all the portions. Upon extraction by boiling, the average pH of LL (5.62) was slightly more acidic than NC (5.99). Interestingly when compared (Fig. 2), the pH drop of NC was sharper at the first mL addition and the drop of pH continued to decrease at a faster rate than LL. Initially, for NC there was a rapid change until 4 mL of acid was added, then a steadily plateau to pH 3 as 7 mL of acid was added. Based on the acid titration result, LL showed a steady change in the pH. Approximately 9 mL of acid was added to change the LL to pH 3.0. The NC solution needed 30% less acid to reach the benchmark of pH 3. The difference in amount of acid needed indicates a potential curing difference for the two species. The particleboard produced in this study utilized MUF, an acid-cured resin.

The difference in behaviour of the NC and LL could be linked to the level of cold and hot water solubles. The NC had an average of 2.99% for cold water and 3.62% for hot water. For LL, the values were 5.45 and 5.98, respectively. At the onset, the LL had a higher concentration of water-soluble material, which could account for the steady reaction toward the HCl. For NC, having a higher pH despite of the lower soluble content indicated the presence of a more alkaline based material, which reacts easily with acid to form salt.

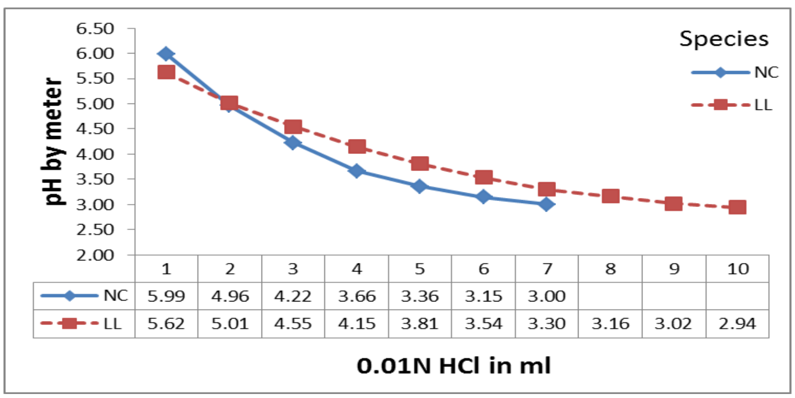

Fig. 2. Buffering capacity of unscreened *N. cadamba* (NC) and *L. leucocephala* (LL) to acid

Particle Size Distribution and Bulk Density

The particle size distribution of both species is given in Fig 3. *Neolamarckia cadamba* had a lower content of smaller particles than LL. The particle of NC was normally distributed, with 1.4 mm making up the highest percentage. *Leucaena leucocephala* particle distribution was skewed toward smaller sizes, where the highest value was for particle size of 0.5 mm. The sieve size percentage showed that the overall NC size ratio was 47:53, for the 1.4 mm and lower against the above 1.4 mm sieve size, respectively. The LL overall size showed an approximate ratio of 86:14 respectively for the same range. The particle size distribution plays an important role in bulk density, compressibility, durability, and flow-ability of densified products. Densified materials provide important information about quality and performance (Tumuluru *et al*. 2011; Guo *et al*. 2012; Zhang and Guo 2014).

The bulk density of NC and LL was 118.5 and 145.4 g/cm^3, respectively. They were significantly different at $p \leq 0.05$. Protasio (2012) studied the effects of compaction ratio and bulk density on three different *Eucalyptus* species and found a direct correlation between these variables and the bending properties and inverse correlation with the thickness swelling of the resulting particleboard panels.

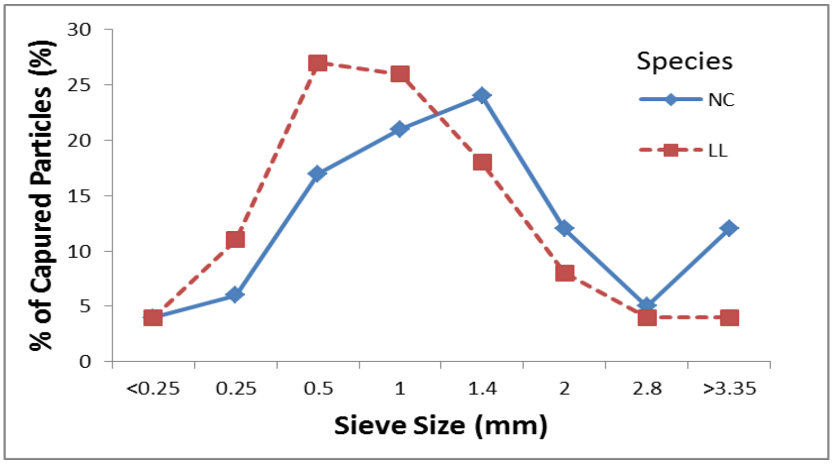

Fig. 3. Particle size distributions of *N. cadamba* and *L. leucocephala*

Particleboard Properties

Table 5 summarizes the physical and mechanical properties of MUF bonded particleboard made from NC, LL, and their mixed particles at three resins content. The performance of all boards met the BS EN 312 (2003) requirement for all tests except for thickness swelling (TS). The NC board with 14% resin content showed the best performance. In general, LL performance was lower than NC and the 50:50 mixed particles.

Table 5. Physical and Mechanical Properties *N. cadamba* and *L. leucocephala* Particleboards with Different Resin Contents

No.	Species	RC (%)	MOE (MPa)	MOR (MPa)	IB (MPa)	IB-CT (MPa)	TS (%)	WA (%)
1	NC 100	10	3159 (411)	23.98 (4.85)	0.71 (0.23)	0.18 (0.03)	23.24 (9.89)	88.85 (13.19)
2	NC 100	12	3202 (585)	26.25 (7.62)	0.88 (0.34)	0.36 (0.30)	19.56 (3.65)	74.10 (14.09)
3	NC 100	14	3542 (585)	27.59 (5.40)	0.87 (0.33)	0.45 (0.15)	15.36 (2.04)	71.10 (15.65)
4	NC:LL 50:50	10	3060 (483)	23.28 (5.15)	0.70 (0.40)	0.15 (0.03)	24.63 (5.71)	84.32 (13.13)
5	NC:LL 50:50	12	3147 (633)	23.57 (6.03)	0.79 (0.41)	0.23 (0.01)	22.90 (2.43)	75.85 (14.57)
6	NC:LL 50:50	14	3522 (441)	26.56 (4.16)	0.82 (0.37)	0.41 (0.01)	19.38 (1.89)	72.29 (12.88)
7	LL 100	10	2699 (507)	20.76 (4.20)	0.69 (0.19)	0.10 (0.03)	27.59 (2.10)	83.84 (8.81)
8	LL 100	12	2726 (494)	22.50 (4.41)	0.70 (0.35)	0.23 (0.03)	22.89 (1.64)	78.02 (13.83)
9	LL 100	14	3004 (398)	23.55 (3.39)	0.78 (0.39)	0.31 (0.09)	20.05 (1.87)	74.80 (12.83)
Minimum requirement EN 312 (2003)			2050	15	0.45	0.15	14	-
			EN 310 (2003)	EN 310 (2003)	EN 319 (2003)	EN 321 (2002)	EN 317 (2003)	-

(Standard deviation), NC = *Neolamarckia cadamba*; LL = *Leucaena leucocephala*; RC = resin content; MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond; IB-CT = internal bond for cyclic test; TS = thickness swelling; and WA = water absorption

Table 6 shows the ANOVA of the effects of species mix, resin content, and their interaction with particleboard properties. The species mix significantly affected the particleboard properties except for IB. For resin content, all test parameters were significantly affected. The interaction of species mix and resin content were significant only for TS and water absorption (WA).

Table 6. Summary of ANOVA on Particleboard Properties

SOV	Df	MOE (MPa)	MOR (MPa)	IB (MPa)	IB CT (MPa)	TS (%)	WA (%)
Species Mix (SM)	2	14.96**	15.73**	2.48ns	5.61**	6.68**	15.03**
Resin Content (RC)	2	15.28**	11.76**	6.6**	28.47**	105.26**	44.18**
SM x RC	4	1.19ns	0.42ns	0.38ns	0.30ns	8.01**	3.78**

Note: SOV = source of variance, Df = degree of freedom, ns = not significant, * significant at $p < 0.05$, ** highly significant at $p < 0.01$; MOE = modulus of elasticity; MOR = modulus of rupture; IB = internal bond; IB-CT = internal bond for cyclic test; TS = thickness swelling; and WA = water absorption

Effects of Species and Mixing

In particleboard production, specific gravity is a crucial property that impacts the compaction ratio, which influences the mechanical and physical properties of the board. Lower specific gravity allows board compaction with less spring back, which yields a stable, high density final product with good bond strength (Haygreen and Bawyer 2003). When making particleboard from mixed species, the combination of particles having different specific gravity may have positive impact. The effects of individual and species mixing on particleboard properties are compared in Fig. 4. Particleboard made from 100% NC gave higher modulus of elasticity (MOE) and modulus of rupture (MOR) values than 50:50 mixed species and 100% LL particleboards. Babatunde *et al*. (2008) showed the same trends where boards made from LL, a high specific gravity wood species have lower mean values and strength when compared with boards made from *Gmelina arborea*, a low specific gravity wood species. The particle size distribution of LL with more fines would also translate to lower bending flexibility. The significant reduction of MOE and MOR when 100% LL was used confirms this.

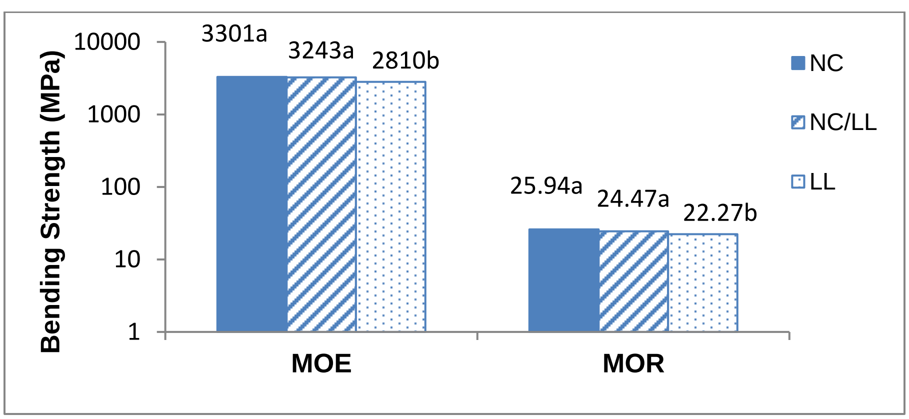

Fig. 4. MOE and MOR of the particleboards. Entries NC, NC/LL, and LL denote mixing ratio; and letters a, and b indicate values in cluster to be significantly different at $p \leq 0.05$.

Figure 5 shows the effects of species mix on IB and IB CT. Particleboard made from NC gave the highest value of IB and IB CT, while particleboard made from LL gave the lowest value. According to Imtiaz *et al*. (2014), the high specific gravity of raw material also results in a more porous mat structure than that for wood panels, which results in a lower surface area for resin bonding. Poor resin penetration along with low surface area reduces the bonding strength (Nemli 2003; Tabarsa *et al*. 2011). Chow *et al*. (1986) stated that the decreased of strength properties in IB-CT due to accelerated aging test in hardwood composite panels may be attributed to thickness swelling and the deterioration of the glue bond, as a result of springback that results in lower density of board. The IB reduction of NC, NC+LL, and LL were 60%, 67%, and 71%, respectively. This is an inverse relationship to the specific gravity of the particles use. Another potential factor that could lower the IB reading for LL is the fact that it has higher buffering. The buffering slows down curing, especially when using MUF as a binder (Policardi and Thebault 2020). The significant IB reduction once the LL had been added indicates the need to modify the resin cures time prior to bonding.

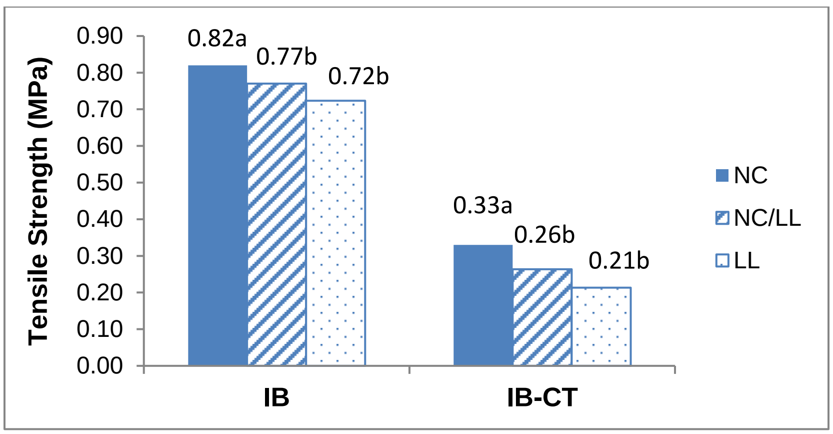

Fig. 5. IB and IB-CT of the particleboards with species mix: Entries NC, NC/LL, and LL denote mixing ratio; and letters a, and b indicate values in cluster to be significantly different at $p \leq 0.05$.

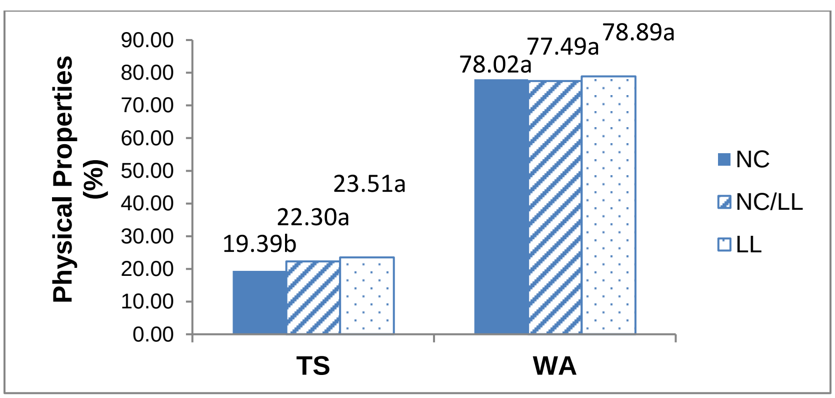

Fig. 6. TS and WA of the particleboards with different species mix. Entries NC, NC:LL, and LL denote mixing ratio; and letters a, and b indicate values in cluster to be significantly different at $p \leq 0.05$.

The TS and WA behaviors of test combinations are shown in Fig. 6. Particleboard made from NC gave the lowest TS value (significant at $p \leq 0.05$) compared with mixed species and LL, reflecting its compactness. The WA showed no significant difference for all combinations, though in actual value the NC performed better. The lower density wood provides a high density compaction rate and, therefore, a higher contact surface between the particles than high density wood (Elbadawi *et al.* 2015). Uncompacted particleboard develops more irregular voids in between the particle during the formation, thus enhancing the water absorption and thickness swelling of boards (Sotannde and Oluwadare 2012).

Effects of Resin Content

The resin content impact for the neat and combined particleboard does not differ much from previous reports, where for each combination of the MOR and MOE had a proportional relationship to the resin content (Ratkhe *et al*. 2012; Salari *et al*. 2013). Thus, as per theory the 14% resin content performed the best compared to 12% and 10% for MOE and MOR (Fig. 7). With increasing resin content, the coverage of particles increased, leading to better surface interaction, reflected by the MOR and IB (Fig. 8).

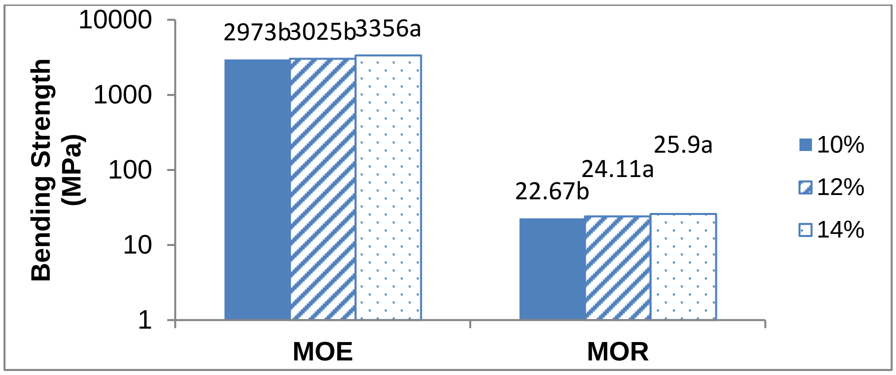

Fig. 7. MOE and MOR of the particleboards made with different resin content: Entries 10, 12, and 14 represent resin content; different letters a, b, and c indicates values in a cluster to be significantly different at p≤0.05.

Figure 8 indicates that the IB for the resin dosage for 10% was significantly lower than the other two dosages. Dosages at 12 and 14% were not significantly different. For standard board usage, 12% resin gave sufficient IB, and cost saving could be achieved. When subjected to cyclic test, which represents a high moisture environment, the IB-CT showed that the 2% extra dosage would give significant difference in performance. Overall, the IB and IB-CT showed a significant proportional relationship to resin percentage.

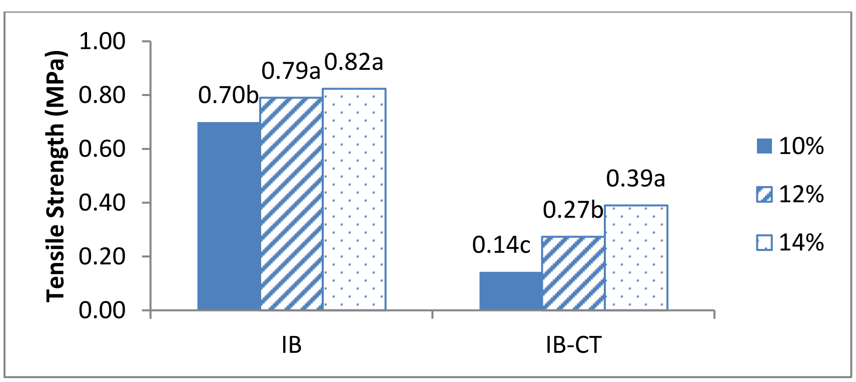

Fig. 8. IB and IB-CT of the particleboards made with different resin content: Entries 10, 12, and 14 represent resin content; and different letters a, b, and c indicate values in cluster to be significantly different at p≤0.05.

The impact of resin content on thickness is significant, as can be seen in the lowering of swelling by 27% compared to the 16% increment in resin used. The water absorption did not display the same reduction (only 15%) for the 14% dosage (Fig. 9). The lowering of swelling shows that the bonding resulting from the resin was strong enough to resist the bulking effect, which resulted from absorbed water orientation. The 10% resin dose resulted in the lowest performance. The absorption for 12 and 14% were not significantly different. The swelling was different and was reflected in the IB-CT reading differential shown in Fig. 8. The reduction in swelling was even at 13% as the resin increased. Having a higher dosage should reduce the thickness swelling further. Melamine urea formaldehyde is a high moisture resistant resin; it resists hydrolysis to a good extent. The issue of high absorption cannot be resolved by resin alone. Low reduction of water intake of only 4% moving from 12 to 14 % indicates that the porosity in the particleboard will still allow absorption of water close to 70% even if the resin content is increased. The addition of wax is likely to improve the absorption level, as the hydrophobic nature of wax would repel water.

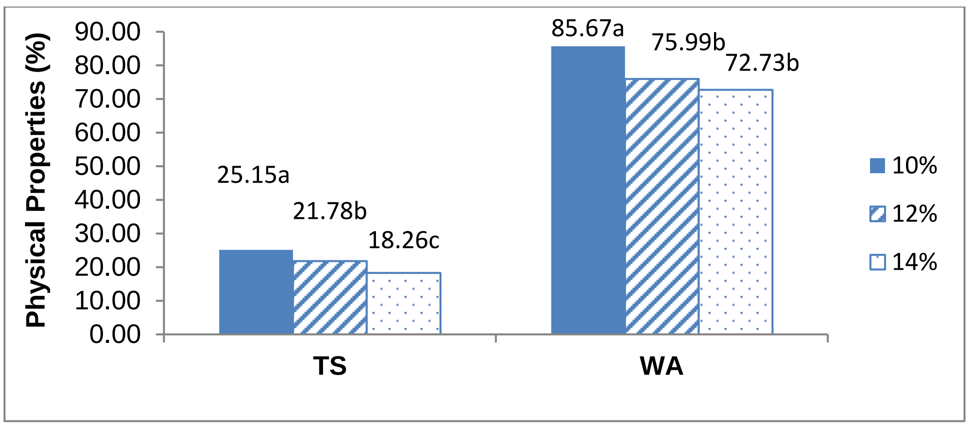

Fig. 9. TS and WA of the particleboards made with different resin content: Entries 10, 12, and 14 represent resin content; and letters a, b and c indicate values in cluster to be significantly different at $p \leq 0.05$.

CONCLUSIONS

1. All boards made with the exception of 100% LL met the EN312 minimum requirement for mechanical strength. The potential of the *N. cadamba* and *L. leucocephala* mixture in particleboard manufacturing was shown by evaluating the mechanical properties of the board. However more work is needed for improvement of the thickness swelling (TS) values.
2. When comparing the different species, *N. cadamba* with 14% resin content gave best overall performance.
3. Combination optimization of these species could be further explored; this would allow planned planting volume of *N. cadamba* and *L. leucocephala*, if it is to be a viable continuous resource for the industry.

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