J. Bamboo and Rattan, Vol.8, Nos. 1&2, pp. 1-11 (2009)

Effects of face to core particle size ratios on properties of particleboard manufactured from Ethiopian highland bamboo - *Yushania alpina*

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Abstract: A study was conducted to evaluate the effects of face to core proportion of particles on the mechanical and physical properties of oriented particleboard produced from Ethiopian highland bamboo (*Yushania alpina*). Three-layered oriented particleboards were manufactured from 4 face to core particle proportions at 750 kg/m^3 target density. Urea formaldehyde resin (10%) was used as a binder. Strength and dimensional stability performances of all boards were assessed based on ISO standards. The results showed that the Modulus of rupture (MOR) and Modulus of elasticity (MOE) increased by 23 to 34 per cent and 9 to 20 per cent respectively, with an increase of fine particles at face layer from 20 per cent to 25 per cent and 30 per cent. A further increase of the ratio beyond 30 percent at face layer could not improve MOR and MOE. Decreasing core layer ratios below 50 per cent resulted in the improvement of internal bond (IB) strength. Higher surface screw withdrawal resistances were obtained for boards made with 25 per cent and 30 per cent fine particles at face layers. On the other hand, edge screw withdrawal resistance showed an increasing trend with increase of IB strength. Increase in fine particles proportion from 20 per cent to 25 per cent and to 30 per cent reduced thickness swelling by 11 and 21 per cent, respectively. However, further increase to 40 per cent increased the thickness swelling significantly. According to the results, bamboo boards made with the ratio of face to core particle being 30:40:30 have highly improved properties than others. Generally, *Y. alpina* culms are suitable raw material for the production of high performance regular purpose particleboards.

Keywords: Face to core proportion, strength properties, internal bond, screw withdrawal and thickness swelling.

INTRODUCTION

Ethiopia has more than a million hectare of bamboo resources. However, these resources have not been used for industrial applications such as particleboard, fibreboard, ply bamboo boards and laminated bamboo lumber boards. On the other

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hand, local wood processing factories face shortages of raw material supply for their products. Currently there is an acute shortage of wood products in the country. Most of construction enterprises and furniture processing factories are heavily depending on imported wood-based products. The abundant resources of bamboo in the country can be used as an alternative raw material for domestic wood-based panel boards and paper industries to substitute imported products (Kelemwork, 2005). In order to utilize this resource, there is lack of information on major technological properties and processing methods those affect bamboo end uses for industrial application.

Previous studies reported that mechanical properties and dimensional stability of three-layered particleboards are influenced by various processing parameters. Face to core proportion is one crucial factor that affects these properties. Thicker boards have steeper density gradients (*i.e.*, very high face density and very low core density) due to longer time required for surface temperature and moisture to penetrate into the core layer of the boards (Zhang *et al.*, 1998). The difference in the compactness of the board would certainly give marked variation in a panel. Bowyer *et al.* (2003) reported that multilayer boards are technically superior for many applications because layering increases the bending strength and stiffness of the boards by altering the relative properties of the face and the core without increasing overall board density.

In recent years, oriented particleboards made by aligning the particles in desirable direction has been used in various structural applications. The mechanical and electrostatic methods of orientation which are recently used in manufacturing of particle-based structural composite can increase the use of low quality raw material to produce high quality engineered composite boards ((Kawai, 1996). Considerable amount of work has been reported on the use of softwood for three-layered boards. For instance bending strength of highly-oriented particleboard was found to be two times higher than that of random particleboard (MCNatt *et al.*, 1992; Shupe *et al.*, 2001). In the case of oriented bamboo particleboards, limited research has been reported and there is lack of information on the effects of face to core particle size ratio.

Changing particles proportion on the face layer of the board markedly affect the stress-strain relationship in the mat during hot pressing and consequently resulting in changes in the vertical density profile distribution, and ultimately having a considerable impact on bending strength and stiffness of the boards (Giemer *et al.*, 1975). As Brumbaugh (1960) and Kelly (1977) reported, particle geometry has a definite relationship with packing efficiency and thus influences the density of the composite. The void volume fractions and the mat density are closely related to the heat and mass transfer properties. Zombori *et al.* (2001) also reported that small and more uniform-sized particles in three-layered boards have small voids. Increasing the percentages of fine particles in the face layer could decrease the voids. The relation is attributed to retardation of the moisture movement and heat transfer from face to core region of the board.

The objective of this experiment was to evaluate the effects of face to core particle size ratio on the mechanical properties and dimensional stability. Three-layered oriented bamboo particleboards were manufactured using four different face and core particle size proportions. Urea-formaldehyde resin was used for bonding the bamboo particles.

MATERIALS AND METHODS

Sample collection

Three-year-old *Yushania alpina* culms used in this study were harvested from Ambo, one of the major bamboo growing areas in Ethiopia. The age of bamboo culms was assessed by the colour of the sheath. After harvesting, the mean density of culms was measured from fresh samples. The experiment was conducted in the Forest Research Institute Malaysia (FRIM) in 2004.

Sample preparation and board manufacturing

Flaked particles were screened on a circular vibrating screener. Fine particles of 1-2mm were chosen for face layer, and coarse particles of larger than 2 mm were chosen for core ayer. The accepted particles were then dried to 5 per cent moisture content in an oven at 60^{0}C. Based on the oven-dry weight of the particles, 4 types of three-layer oriented particle boards were manufactured from 4 face to core particle proportions (20: 60: 20, 25: 50: 25, 30: 40: 30, and 40: 20:40) at 750 kg/m^3 target density. Sample boards were manufactured using 1-2 mm (fine particles) on the face layer and coarse >2 mm in the core layer. Face particles were aligned to the longitudinal axis of the board and the core particles aligned perpendicular to face.

Urea formaldehyde resin (10%), based on the oven-dry weight of the particles, was used as binder. Ammonium chloride solution (3%) based on the solid content of resin and liquid wax emulsion (1%) based on the oven-dry weight of the particles, were used as hardener and water repellent respectively. After blending, boards were hand-formed using a square aluminum box of 400 x 400 mm size for aligning the furnish. The box had a frame consisting slots of 10 mm wide divided by thin aluminum plates between the slots which were located about 25-40 mm above the top of the mat. The furnish was passed between the slots manually. The space between the aluminum slots ensures to fall in the same direction into the forming mat underneath. The distance between the bottom of the aluminum slot and the top of the mat was closely controlled by putting additional aluminum frame at the side of the frame so that the orientations of the particles were the same. The forming box was prepressed at 3.5 MPa for about 3 min in mat forming press. The consolidated mat was finally pressed in hot press with 4 MPa at 170 ± 2^{0}C for 6 min to obtain a board of 15 mm thickness. All the specimens were conditioned at 20 ± 2^{0}C room temperature with 65 ± 5 per cent r.h. for 5 days until the test specimen weight became constant.

Properties measured for board evaluation

The mechanical properties and dimensional stability of three-layered oriented bamboo particleboards were evaluated in accordance with the International Standards Organization (ISO, 2003a) for wood-based panel products. The modulus of elasticity (MOE) and modulus of rupture (MOR) were determined in accordance with ISO/DIS 16978 (ISO, 2003b) by applying a load to the centre of a test piece supported at two points over a span of 300 mm. Tensile strength perpendicular to the surface or the internal bond (IB) strength was determined in accordance with ISO/DIS 16984 (ISO, 2003c). Screw withdrawal test was conducted based on British Standard (BS 5669: part 1:1989).

The increment in thickness swelling (TS) of specimens after 24 h of soaking in water was determined in accordance with ISO/DIS 16983 (ISO, 2003d) as percentage of the original thickness and weight. Vertical density profile of the board was measured by using MALDPX 200 and X-ray density profile meter. All the specimens were conditioned at 20 ± 2°C room temperature with 65± 5 per cent r.h. for 5 days until the test specimen weight becomes constant.

Experimental design and analyses

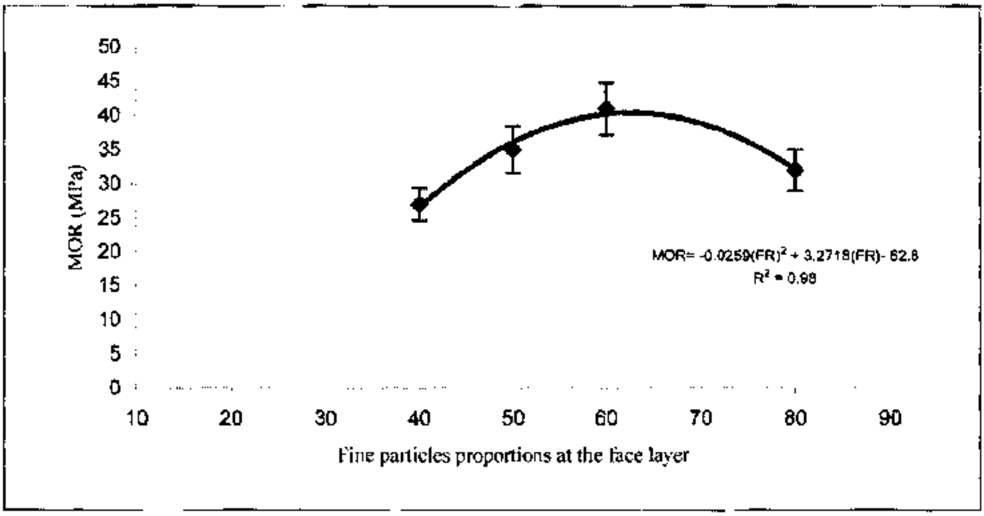
Completely randomized design (CRD) was used to conduct this experiment. Analysis of variance (ANOVA) was used to determine significant effects of face to core particle size proportion on the board properties. Least significant difference (LSD) method was used for mean comparison at $P \leq 0.05$.

RESULTS AND DISCUSSION

Strength properties

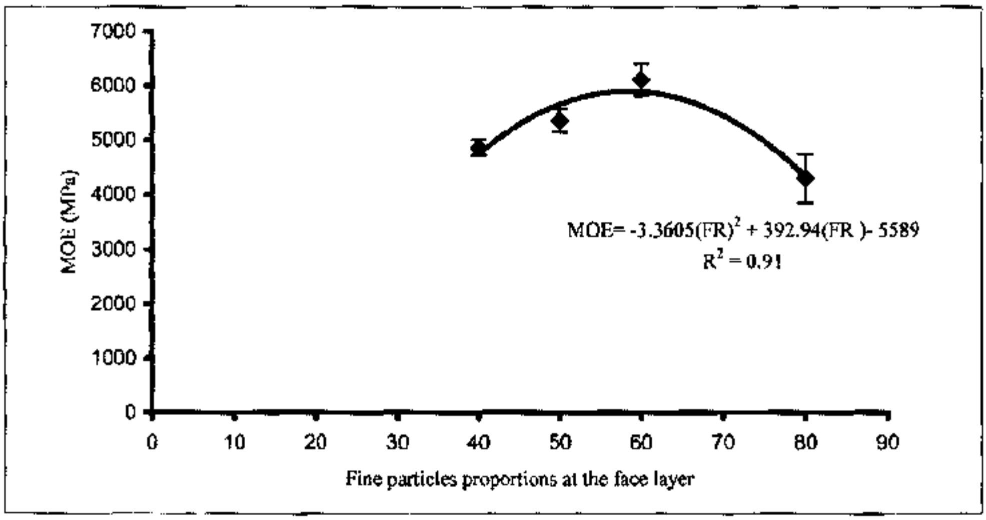
The effects of fine to coarse particle size layer structure on bending and stiffness properties of three-layered bamboo particleboard are given in Figures 1 and 2. The MOR increased with an increasing of fine particles at face layer up to 60 per cent and decreases beyond that (Fig.1).

When fine particles ratio at the face layer increased from 20 per cent (on both faces) to 25 per cent, the MOR was increased by 23 per cent. A further increase of 5 per cent increased the MOR by 34 per cent. However, an increase of fine particles at the face layer beyond 30 per cent did not improve the MOR. The MOR values obtained in this experiment were compared with conventional three-layered oriented *Y. alpina* boards made from 100 per cent fine particles (Kelemwork *et al.*, 2005). The result showed that 25 per cent and 30 per cent fine particle face layer boards made in this experiment had 9 per cent and 22 per cent higher values respectively, than conventional boards.



Note: bars indicate standard deviations
FR=fine particles ratio

Figure 1. Effects of fine particle proportions at the face layer on modulus of rupture (MOR).



Note: bars indicate standard deviations
FR=fine particles ratio

Figure 2. Effect of fine particle proportions at the face layer on modulus of elasticity (MOE).

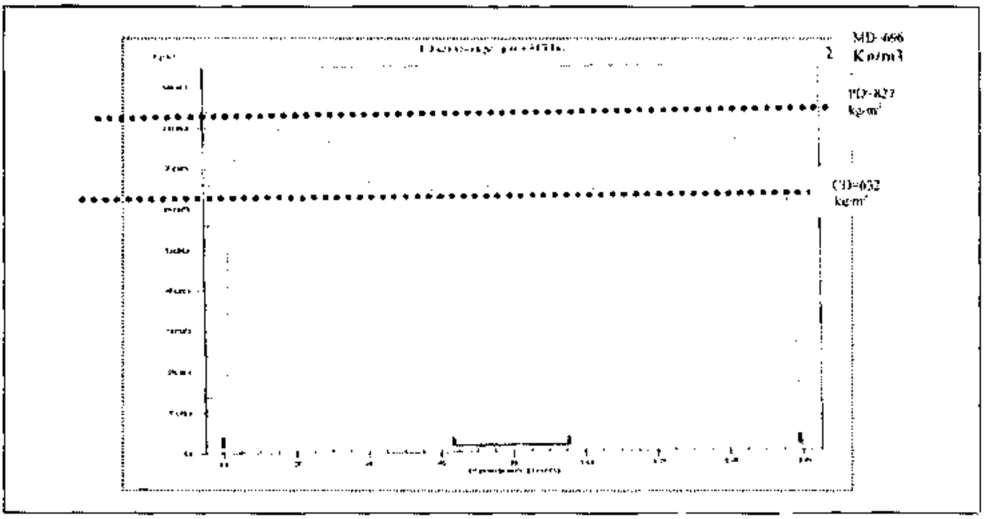
As indicated in Figure 2 similar trend was observed for MOE, when the face ratio of fine particles increased from 20 per cent to 25 per cent and to 30 per cent, the MOE increased by 9 per cent and 20 per cent, respectively. Boards made from fine particles sizes at 25 per cent face layer had 3 per cent lower MOE values compared to conventional three-layered oriented boards made from 100 per cent fine particles. However, at 30 per cent, the MOE increased by 14 per cent than that of oriented conventional boards made from 100 per cent fine particles.

The improvement of MOR and MOE values in three-layered particleboards could be related to the amount and size of fine and coarse particle used for face and core layers. As Brumbaugh (1960) and Kelly (1977) reported, particle geometry has a definite relationship with packing efficiency and thus influences the density of the composite. The void volume fractions and the mat density are closely related to the heat and mass transfer properties. Zombori *et al.*, (2001) also reported that small and more uniform-sized particles in three-layered boards have small voids. Increasing the percentages of fine particles in the face layer could decrease the voids. The relation is attributed to retardation of the moisture movement and heat transfer from face to core region of the board. Excessive moisture content on the face layer of boards enhanced plasticization of the bamboo particles, besides retarding the occurrence of precure, giving rise to tight and hard faces near the surfaces. When sufficient heat finally reached the core, most of bamboo particles would have been compressed and set near the faces, leaving no excessive particles in the core for further compression. As a result, a wide, low-density zone is formed in the core region. Earlier researchers like Giemer *et al.* (1975) and Wong (1999) reported that three-layered boards that had high surface density were able to bear higher load before failing during static bending. The low-density core might have contributed to increase deformation during static bending as the result (tensile) failure formed from the top to bottom surface. Regression equations of three-layered boards shown in Figures 1 and 2 may be used to predict the MOR and MOE of three-layered boards containing percentage of fine particles in the face layer from 20 per cent to 40 per cent.

Face to core particle proportions had significant effects on density profile formation of the boards. Figure 3 shows the density profile formation of three-layered oriented bamboo particleboard produced from 30:60:30 fine to core particles proportion. Generally, the density profile of all types of board has U-shape (*i.e.*, high face density and low core density) density profile. The rate of the moisture and heat transfer from the face to core and the water to migrate from the core surface of the board are strongly dependent upon the amount of face layer particles proportion. As face/core ratio increases, improved strength and dimensional stability are expected.

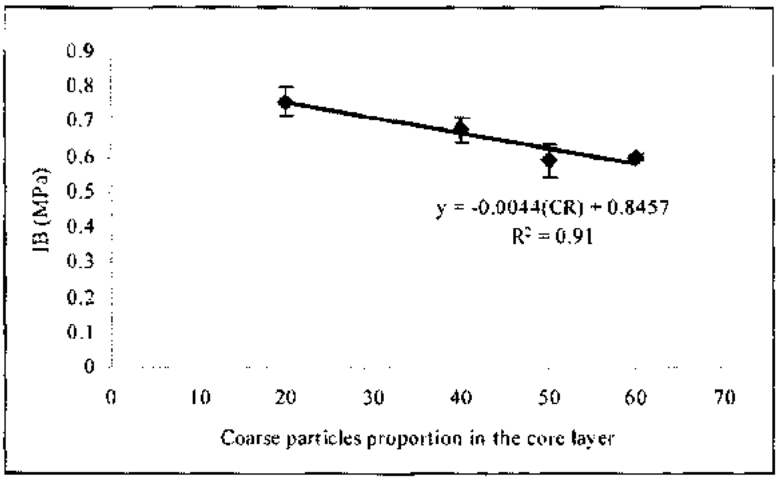
Internal bond

Fine to coarse particle sizes ratio had significant effects ($P \leq 0.01$) on the IB strength. As shown in Figure 4, the IB values were markedly affected by changing the fine to coarse ratios of the particles. Decreasing core layer ratio below 50 per cent resulted in the improvement of IB strength. Increasing coarse particles ratio in the core layer might have affected the complete polymerization of resin. During hot pressing, coarse particles in the core layer were compacted by high pressure.



MD : mean density, PD : peak density, CD : core density

Figure 3. Typical density profile of three-layered oriented bamboo particleboards.



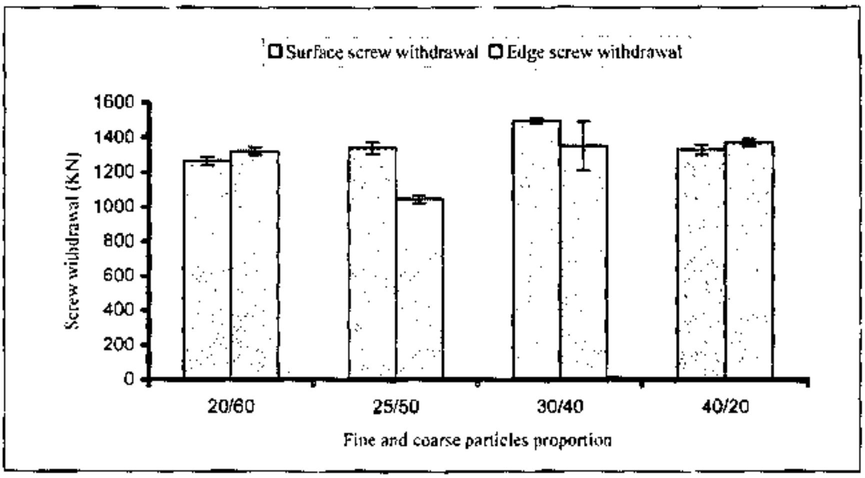
Note: bars indicate standard deviations, CR : coarse particles ratio

Figure 4. Effect of coarse particles ratios in the core layer on internal bond srength.

The regression analysis between IB and coarse particles ratio in the core layer indicates highly significant relation between the two. Based on an equation, it is possible to predict the IB where the values decrease, if the proportion of the coarse particles in the core increases from 20 per cent to 60 per cent. The IB strength of boards made from 100 per cent fine particles was much superior to boards made from mixed particles in this experiment (Kelemwork *et al.*, 2005).

Surface and edge screw withdrawal resistance

The surface and edge screw withdrawal tests were carried out to evaluate the holding strength of screws in three-layered boards. As shown in Figure 5, surface screw withdrawal resistance was affected by face to core proportion of the particles. Higher surface screw withdrawal resistances (1337 and 1495 KN, respectively) were obtained for boards made with 25 per cent and 30 per cent fine particles at face layers (Fig. 5). The lowest value of surface screw withdrawal resistance (1263 KN) was observed for boards made with 20 per cent fine particles at face layers. The results showed that surface screw withdrawal resistances of three-layered boards were improved by changing the amount of fine particles on board surfaces. Higher plasticization of fine particles during hot pressing might have increased the screw holding abilities in this region.



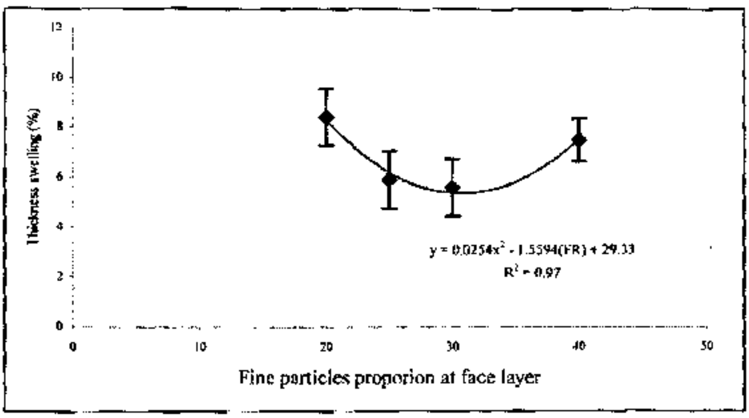
Note: bars indicate standard deviations
SWS : surface screw withdrawal, SWE : edge screw withdrawal

Figure 5. Effect of fine to coarse particle ratios on screw withdrawal.

On the other hand, edge screw withdrawal resistance showed an increasing trend with increases of IB strength. Comparison of boards made from different coarse particle ratios in the core layer showed that boards with low IB strength (0.588 MPa) exhibited the lowest screw withdrawal resistance than other board types. This implies that edge screw withdrawal resistance may be influenced by the IB strength. Lin and Eckelman (1995) reported the same observation where the screw holding ability of wood composites are closely related to the IB of the boards and the length and diameter of the screws. Wong (1999) also reported plane (surface) screw withdrawal resistance is predominantly dependent on mean density. All the screw withdrawal resistance obtained in his study comply the British Standard (BS 5669: part 1:1989).

Thickness swelling

The 24 h water-soaking tests revealed that fine to coarse particle ratios significantly affected the rate of thickness swelling (TS). As indicated in Figure 6, an increase in fine particles proportion from 20 per cent to 25 per cent and to 30 per cent reduced thickness swelling by 11 and 21 per cent, respectively. However, further increase to 40 per cent increased the thickness swelling significantly. Due to the release of residual compressive stress imparted to the board during hot pressing, variations in TS across the board thickness are unavoidable. The release of this stresses usually creates springback (irreversible TS) and as a result, adhesive bonds between the particles deteriorate. The extent of the springback depends on the amount of fine to coarse ratio distribution. This may happen due to variation of density profile through the panel thickness. Wang and Winistorfer (2003) reported about non-uniform stress development and relaxation through the thickness of the mat during pressing due to complex interaction of heat, pressure and temperature. Xu (2000) also reported that as more compression set was induced in high-density surface areas due to hot pressing, the subsequent release of compressive stress due to water uptake resulted in high swelling in this region. The mean values of mechanical and physical properties of three-layered oriented bamboo particleboard are presented in Table 1.



Note: bars indicate standard deviations, FR : fine particle ratio

Figure 6. Effect of fine particles proportion at face layer on thickness swelling.

CONCLUSION

Boards made from 30 per cent proportion of fine particles at the surface layer has hard, smooth and dense surface preferred for various uses. As the fine particles ratios at the face layer increased from 20 per cent (on both faces) to 25 per cent and 30 per cent, the MOR and MOE improved. Decreasing core layer ratios below 50 per cent

Table 1. Mean comparisons of mechanical properties and dimensional stability of three layered oriented *Y. alpina* particleboards

Fine: coarse : fine proportion	MOR (MPa)	MOE (MPa)	IB (MPa)	SWS (KN)	SWE (KN)	TS (%)	WA (%)
20: 60 : 20	27c	4864c	0.600c	1263c	1322a	7.5a	33a
25 : 50 : 25	35b	5357b	0.588c	1339b	1046b	6.5b	35a
30 : 40 :30	41a	6114a	0.685b	1495a	1350a	5.8c	35a
40 : 20 :40	32b	4302d	0.752a	1328b	1367a	7.5a	33a
ISO standard*	15	2100	0..300	-	-	15	-

ISO standard* : ISO (2003) standards for high performance regular purpose particleboard
Note: Means having different letters in the same columns are significantly different at $P<0.05$.

resulted in the improvement of IB strength. Higher surface screw withdrawal resistances were obtained for boards made with 25 per cent and 30 per cent fine particles at face layer. An increase in fine particles proportion from 20 per cent to 25 per cent and to 30 per cent highly improved thickness swelling. Based on the results obtained in this experiment it is possible to conclude that oriented three-layered bamboo particleboard manufactured at 25 per cent and 30 per cent face particle proportion can be used for high performance structural and furniture application.

ACKNOWLEDGEMENTS

The authors acknowledge the help rendered by the Wood Composite and Testing Laboratories of the Forest Research Institute Malaysia (FIRM) during board manufacturing and testing. The first author also wishes to thank the Ethiopian Agricultural Research Organization (EARO) for the financial grant and study leave.

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