EFFECTS OF PRESSING TEMPERATURE AND PRESSING TIME ONTO THE PROPERTIES OF BINDERLESS PARTICLEBOARD MADE FROM RATTAN FURNITURE WASTE

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ABSTRACT

High awareness on the importance of building green structures by utilizing waste materials has given intense ideas on converting wastes to the value-added board. Thus, this study aims to convert rattan furniture wastes into binderless particleboards (BPB) using the hot-pressing process at different pressing temperatures of 170 °C, 180 °C, and 190 °C and pressing time of 4, 5, and 6 min. These self-bonded particleboards underwent mechanical and dimensional stability tests according to the Japanese Industrial Standards (JIS A5908). Most of the BPB produced met the minimum strength requirements, although they did not meet the standard requirement for dimensional stability of boards; yet, these board products were still comparable with commercial particleboards in terms of strength. The mechanism of self-bonding that occurred during manufacturing process was the chemical bonding of rattan components and physical consolidation amongst rattan fibers. The disorderly orientation of rattan fibers and some of the ruptured fibers occurred in the BPB produced had affected the board strength. It can be concluded that rattan furniture waste worked well as an alternative material in producing particleboards for structural usage.

Keywords: Binderless, Furniture, Strength, Stability, Natural Fiber.

INTRODUCTION

Particleboard is a panel material manufactured by pressing particles of wood or other lignocellulosic materials with or without the addition of adhesive under heat consolidation. Currently, 90% of particleboards are using urea-formaldehyde (UF), a synthetic resin that provides strong and durable bonds among fibers. However, the air pollution created from the toxic of formaldehyde emission has gained attention regarding health effects such as cancer (Seller, 2001; Boon et al., 2013; Saadaoui et al., 2013). Moreover, the shortage of quality wood from the natural forest in the world is nerve-racking (Mancera et al., 2008). Regulations and pressures from environmental policies on cutting down trees due to these problems have caused the increase in cost involved in manufacturing the particleboards (Hashim et al., 2011). Afterward, the search for alternative resources has been focused where non-wood or agricultural material has received noteworthy attention due to their renewability and accessibility.

Rattan furniture has large market world-wide, through exporting this furniture type to countries such as Europe, America and Australia, that contribute more than RM3.3 million in 2016 (Malaysian Furniture Council, 2015). Moreover, this medium industry participates in developing the poverty reduction in certain Asia tropical region. It resulted from the good properties of rattan cane such as lightweight, strong, versatile, durable and diverse that can be used as potential alternative raw materials in replacing wood (Muniandy et al. 2012). However, the inefficiency on disposing of waste can lead to social and environmental problems (Charoenvai, 2013). Most of the furniture industries have same issue on the high amount of wastes produced during the furniture manufacturing process, including the rattan furniture industry. These wastes have become a burden to the environment through open burning and illegal dumping (Ariffin *et al.* 2001). It was estimated that 30% of a single bar of rattan cane lost during the process of producing the furniture came from cutting, debarking, coring, and skinning process, which costs about 10% of an average price of rattan (Olorunnisola *et al.* 2005). Thus, the idea of producing BPB using rattan furniture waste seems possible as it not only eliminates the hazardous concept of using resin but also reduces the overall production costs.

The previous studies showed that some researchers manufactured BPB using a variety of raw materials (Okuda & Sato, 2004; Xu *et al.* 2006; Hashim et al., 2011; Charoenvai, 2013; Nonaka et al., 2013; Fahmy & Mobarak, 2013; Hidayat et al., 2014). They were using the hot-pressing process, steam treatments, and extrusion. The easiest way of manufacturing BPBs is by the hot-pressing process, where it consolidates the fiber mat into particleboard at certain density and thickness. One of the important parameters of the hot-pressing process is pressing temperature (Boon et al., 2013; Zhang et al., 2015). Hence, the objective of this study was to develop BPB using rattan furniture waste by the hot-pressing manufacturing process via various hot-pressing conditions which are pressing temperature and time. The BPB produced were expected to meet the minimum requirements of board standard for real-life practical application.

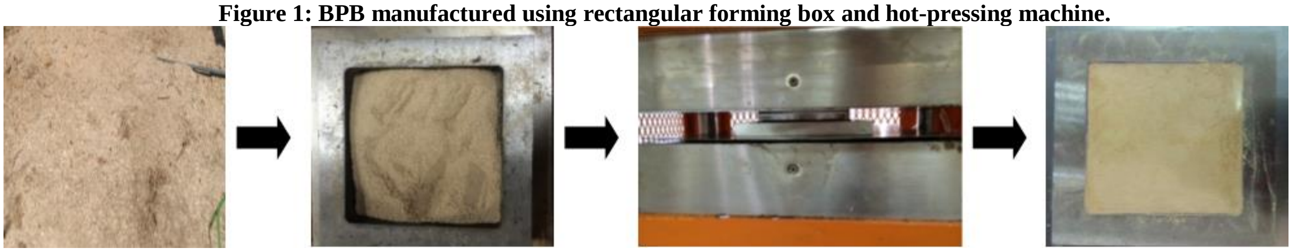
MATERIALS AND METHODS

Rattan furniture wastes were collected from a furniture company located in Pusing, Perak. The wastes in the powder form were manually sieved to separate the unnecessary materials such as dust, rubbish, and sands. After that, these wastes were blended and electronically sieved into powder size of approximate 50μm, and were dried in the oven at 40 °C for 48 hours.

BOARDS MANUFACTURING

BPB was manufactured by the hot-pressing process with targeted densities of 1.0 g/cm^3 through pressing temperature settings of 170°C, 180°C, and 190°C and pressing time durations of 4, 5, and 6 min, respectively. The rattan furniture waste fibers of 50μm with the moisture content of 10% were manually hand-formed into the homogeneous single-layer mat using a rectangular forming box with the size of 11cm x 11cm. The mat was put between aluminum plates in a single opening hydraulic hot-pressing machine and pressed at the pressing pressure of 150kPa, where the hot-pressing process illustrates as in Figure 1. The boards were then cut into test samples according to JIS, which were conditioned at relative humidity 65±5% and temperature of 20±2 °C.

Figure 1: BPB manufactured using rectangular forming box and hot-pressing machine.



BPBs were tested for strength and dimensional stability properties, according to boards' standard JIS A5908, Type-13 (JIS A5908, 2003). The tests for strength in terms of modulus of rupture (MOR) and internal bonding (IB) were done using Shimadzu precision universal testing machine autograph. Three test samples for each condition with the size of 11cm x 5cm were prepared for static 3-point bending test at loading speed of 10 mm/min, and the MOR values of test samples were calculated using equation as below.

Modulus of Rupture, $MOR\ (MPa) = 3PL / 2bt^2$ (1)

Where: P = maximum load (N), L = length of span (mm), b = width of test sample (mm), t = thickness of test sample (mm)

At the same time, three test samples of 5cm x 5cm were used for the IB strength test under a tension loading speed of 2mm/min. The maximum load obtained were recorded, and the the IB values of test samples were calculated using equation as follow.

Internal bonding, $IB\ (MPa) = P' / 2bL$ (2)

Where: P' = maximum load (N) at the time of failing force, b = width of test sample (mm), L = length of test sample (mm)

As for dimensional stability tests in terms of thickness swelling (TS), the 5cm x 5cm test samples were measured (t_1) before immersed horizontally in water at room temperature about 3 cm below the water surface for 24 hours. After that, the samples were taken out of the water and left on tissue paper to remove excess water on the surface of test samples for approximately 10 minutes. Then, the test samples were measured (t_2) again to calculate TS of the BPB, using equation below.

Thickness swelling, $TS\ (\%) = (t_2 - t_1) / t_1$ (3)

Where: t_1 = thickness before immersion in water (mm), t_2 = thickness after immersion in water (mm)

The morphological analysis also has been done to the BPB using the scanning electron microscope operating at 70kV, where the samples were sputter-coated with Au and mounted on Al holders using double-sided electrically conductive carbon adhesion tape to prevent electrical charging during SEM examination. These testing results are significant to ensure the BPB produced meets boards' standard requirements that are relevant to be used in furniture industry.

RESULTS AND DISCUSSIONS

EVALUATION ON PHYSICAL PROPERTIES OF BOARDS

BPB produced are slightly dark brown in color and generated a peculiar smell, which indicates the modification of chemical components inside the fibers during the hot-pressing process (Fahmy & Mobarak, 2013; Hidayat et al., 2014; Carmen et al., 2015). BPB has smooth surfaces with glossy sections resulted from the fineness of fiber particles used and strong bonding generated between fibers (Hashim et al., 2010; Panyakaew & Fotios, 2011; Marashdeh, 2011). The densities of BPB were in the range of 0.75-0.95 g/cm^3, as shown in Table 1 below.

Table 1: Thickness and densities of BPB after hot-pressing processes

Pressing Parameters [Temperature (^{o}C), time (min)]	Thickness (cm)	Densities (g/cm^3)
170, 4	3.97 ± 0.02	0.75 ± 0.01
170, 5	4.00 ± 0.02	0.77 ± 0.01
170, 6	3.99 ± 0.02	0.80 ± 0.01
180, 4	3.98 ± 0.02	0.90 ± 0.01
180, 5	3.99 ± 0.02	0.93 ± 0.01
180, 6	4.01 ± 0.02	0.95± 0.01
190, 4	4.00 ± 0.02	0.88 ± 0.01
190, 5	4.02 ± 0.02	0.90 ± 0.01
190, 6	3.99 ± 0.02	0.91 ± 0.01

EVALUATION ON STRENGTH PROPERTIES OF BOARDS

Figure 2 represents MOR values for BPB manufactured with pressing temperatures of 170 °C, 180 °C, and 190°C and pressing time of 4, 5, and 6 min, respectively. It clearly shows that the MOR values increased with the increasing of pressing temperature. BPB pressed at 180 °C and 5 min had the highest MOR value of 28.5 MPa. Conversely, all BPB pressed at 190 °C decreased MOR approximately 14% lower compared to BPB pressed at 180 °C and 5 min. This is due to the burned fibers inside the board resulted from high temperature (190 °C) and it is noted that the MOR values depend on fiber strength and geometry, not the bonding strength among fibers (Carmen et al., 2015). Previous studies found that the melting point of rattan furniture waste was 177.8 °C, (Maisarah et al., 2015), thus the BPB pressed at 170 °C had the lowest MOR values as not enough heat was supplied to allow the lignin flow to the fiber surface. Sufficient heat is required for fiber plasticizing and degradation of chemical components which helped bonds the fibers together as sufficient heat is supplied (Widyorini et al., 2005; Okuda et al., 2006; Xie & Liu, 2012), yet high temperature can burn and destroy the fiber properties (Nonaka et al. 2013). On the other hand, the variation in pressing time showed no significant in MOR values of the BPB produced (Boon et al., 2013; Hidayat et al., 2014; Pesenti et al., 2017).

Figure 2: Modulus of Rupture (MOR) for BPBs produced at different hot-pressing temperature and pressing time

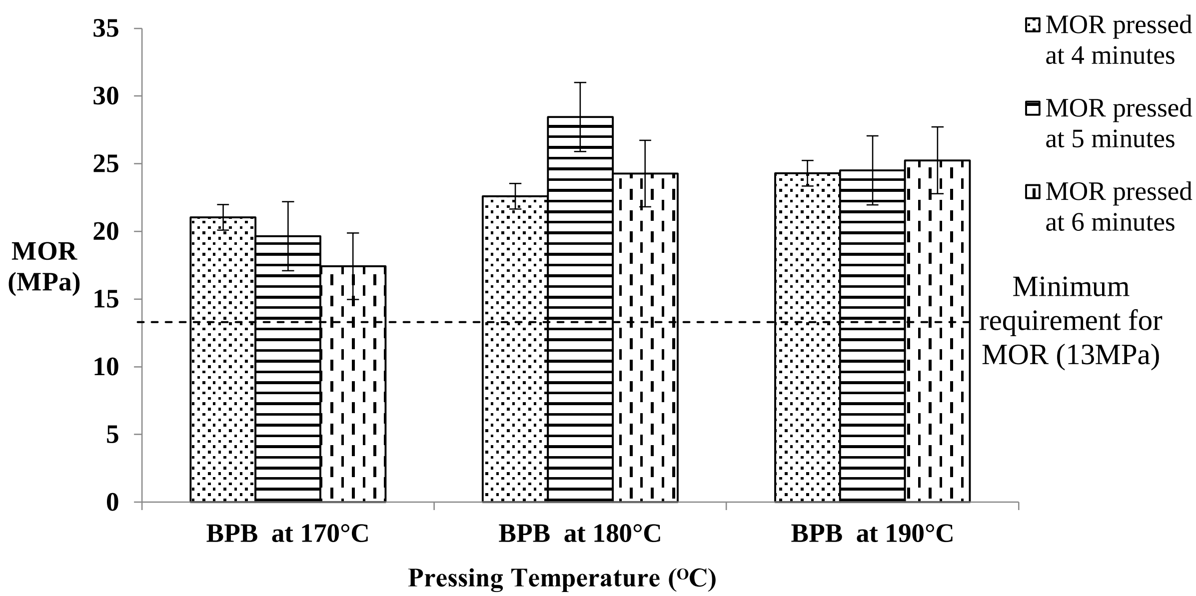
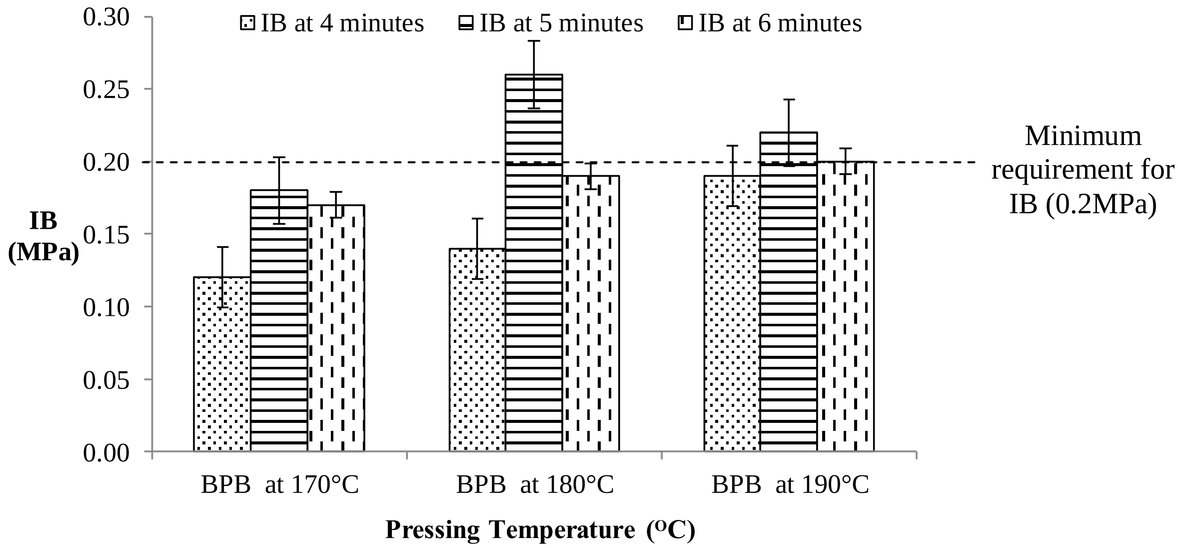


Figure 3 illustrates the IB strength values of BPB, which increased with the increasing in pressing temperature from 170 °C to 180 °C and slightly reduced when the pressing temperature was 190 °C. The longer pressing time from 4 min to 5 min improved the IB strength values (Panyakaew & Fotios, 2011; Xie & Liu, 2012), and gave enough time for heat transfer from surface to core layer of BPB which allowed lignin to fully plasticized and flow wells (Okuda et al., 2006; Mancera et al., 2008). Previous studies (Hashim et al., 2011; Pintiaux et al., 2015) stated that longer pressing time was not adequate and still difficult to create a strong bond between fibers compared to boards produced using synthetic adhesive. The IB strengths were lightly reduced at pressing time of 6 min due to excessive drying and burned fibers.

The minimum requirements of MOR and IB strength values according to JIS A5908, Type-13 (JIS A5908, 2003) are 13.0MPa and 0.2MPa, respectively. All BPB met the minimum requirements of MOR values as stated by JIS standard. These MOR values were much higher compared to BPB made from oil palm trunk (Hashim et al. 2011), kenaf (Xu et al. 2006) and coconut husk (van Dam et al., 2004), which were 5.73MPa, 10.4MPa, and 14.4MPa, respectively. Only BPB pressed at 180 °C and 190 °C at 5 min meet the minimum requirement of IB strength values according to the JIS standard. However, these IB strength values were relatively high considering as no binder was used for manufacturing the BPB. The kenaf particleboard using 4% paraformaldehyde had IB strength values of 0.11MPa (Sellers et al., 1993).

Figure 3: Internal bond strength (IB) for BPBs produced at different hot-pressing temperature and time

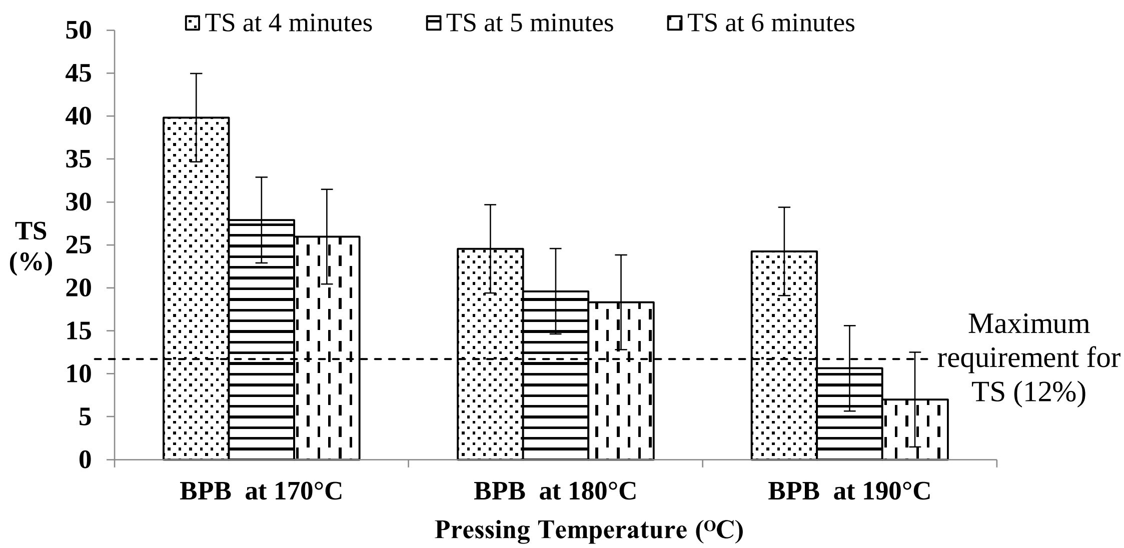


EVALUATION ON DIMENSIONAL STABILITY OF BOARDS

In Figure 4, BPB from the different pressing temperatures at the various pressing times show the values of thickness swelling (TS) after 24 hr of immersion in water at room temperature. The TS of BPB decreased with the increase of pressing temperature in the range of 5.0% to 80%. TS was reduced by 38.3% by increasing the pressing temperature from 170 °C to 180 °C. None of the BPB managed to meet TS requirement based on JIS standard except for BPB produced at 190 °C/5 min and 190 °C/6 min, which were 10.63% and 6.99%, respectively. These two values were low, which indicated the reduction of hygroscopicity due to degradation of hemicellulose at high pressing temperature. Similar studies have been conducted previously (Okuda & Sato, 2004; Boon et al., 2013; Fahmy & Mobarak, 2013). The high values of TS of boards made from natural fibers were reported by other scholars due to the hydrophilic nature of these natural fibers and their internal structure (Sulaiman et al., 2009; Quintana et al, 2009; Pesenti et al., 2017).

Figure 4 clearly shows that increase in pressing time that was inversely proportional to the TS and values. This was agreed by the research conducted by Okamoto and friends (1994), who stated that dimensional stability of MDF improved with the increasingly pressing time and pressure. The TS was reduced by 29.9% by increasing the pressing time from 4 min to 5 min for BPB pressed at 170 °C. These dimensional stability values can be improved by applying pretreatment to the raw materials before the hot-pressing process (Zhang et al., 2015; Pintiaux et al., 2015).

Figure 4: Percentage of thickness swelling (TS) of BPB produced with different pressing temperature and pressing time



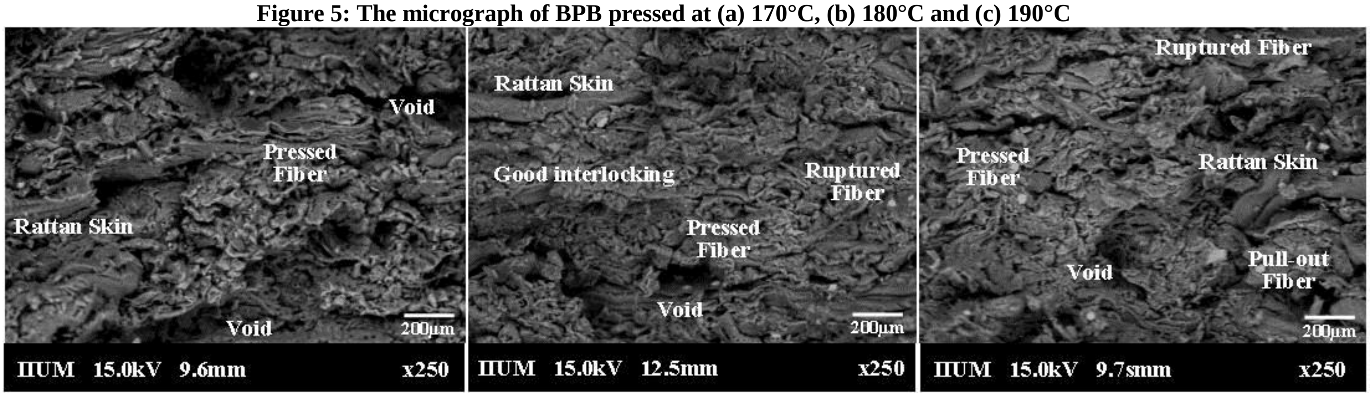
EVALUATION ON THE MORPHOLOGY OF BOARDS

Morphological analysis was carried out in order to study the microstructure of the BPB after hot-pressing process at pressing temperature of 170°C, 180°C and 190°C with fixed pressing time of 5 minutes and particle size of 50µm. The micrographs obtained are illustrated in Figures 5(a), (b), and (c) under magnification of 250x. Most of the parenchyma cell walls were found to be fully compressed and degraded. Strong physical consiladation amongst compressed cell wall fibers occasioned in good mechanical properties of board produced. There were few parts of rattan that can be detected from the micrographs such as rattan skin, ruptured rattan fibers, and the pullout of rattan fibers as the wastes were a mixture of all parts of rattan used for manufacturing furniture. It caused disorderly orientation of rattan fibers, which these parts distorted and disturbed interaction of fibers that led to hollow space and created less adhesion among particles, apparently reduced the board properties (Nonaka et al., 2013; Pesenti et al., 2017). The chemical interaction and interlocking between fibers were significantly important for BPB as no adhesive was used in producing these boards.

The BPB pressed at 170 °C in Figure 5(a) had more voids compared to the other two types of BPB resulted from the low temperature that was not sufficient enough applied to hydrolyze lignin and other chemical components inside rattan furniture waste particles (Xie & Liu, 2012; Zhang et al., 2015). It was believed that the occurrence of voids contributed to lower mechanical and physical properties obtained by BPB. In Figure 5(b), there were few voids arose with most of the fully compressed fibers. The micrograph also illustrates good interlocking between fibers, similarly shown by previous researchers (Hashim et al., 2011; Boon et al., 2013). By applying enough heat and pressure, the hydrogen bonding system and water molecules inside particles broke down and provided pseudo-plastic flow behavior which contributed to good mechanical properties of BPB (Widyorini et al. 2005; Okuda et al., 2006; Mancera et al., 2008; Pintiaux et al., 2015).

The figures also proved that the mechanisms of self-bonding inside rattan fibers during the hot-pressing process resulted from chemical bonding through heat and physical consolidation from pressure applied onto the BPB (Okuda et al., 2006; Fahmy & Mobarak, 2013; Zhang et al., 2015; Hashim et al., 2016). The micrograph in Figure 5(c) shows that the degraded parenchyma with many voids occurred amongst fibers. The temperature used for these BPB was high that caused the microstructure of BPB produced distorted and led to hollow space and created less adhesion among particles (Hashim et al., 2011). Besides, there were tiny bubbles known as blisters with small crack occurred on BPB surfaces, resulted from high moisture trapped inside the rattan waste particles. All these contributed to low mechanical properties.

Figure 5: The micrograph of BPB pressed at (a) 170°C, (b) 180°C and (c) 190°C



CONCLUSION

The study discovered that rattan furniture waste suits the criteria as an alternative material for producing binderless particleboards (BPB). The use of these wastes reduces the production cost as well as solves the waste management issues. Testing revealed that pressing temperature played important roles in manufacturing BPB, which by increasing the pressing temperature gave high strengths and good dimensional stability of BPB produced. However, not all BPB produced met the standard requirement of JIS A-5908, Type-13. Results showed that optimum parameters for BPB manufacturing are pressing temperature of 180 °C and pressing time of 5 min, giving the properties of MOR 28.5 MPa, IB 0.26 MPa and TS 6.99%, respectively. The microstructure taken from SEM proved that BPB pressed at these parameters had good bonding and interlocking between fibers.

Further tests should be conducted in a larger scale to improve the properties and qualities of BPB for practical application; for instance, interior parts of buildings or furniture. In addition to that, it should be focused on the improvement of dimensional stability of BPB by reducing the moisture absorption of fiber to the surrounding environment. The understanding on mechanism of self-bonded boards can be applied on other natural fibers, either woody or non-woody materials; where this helped to lessen the waste volume produced in furniture industry, as we moving towards greener world.

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REFERENCES

Ariffin, W.T.W., Husain, H., and Salleh, A.H. (2001). Transfer of Technology Model: Rattan Furniture Making Unit. *International Network for Bamboo and Rattan (INBAR) & Forest Research Institute Malaysia (FRIM)*, pp. 1-44.

Boon, J. G., Hashim, R. Sulainam, O. Hiziroglu, S., Sugimoto, T. Sato, M. (2013). Influence of processing parameters on some properties of oil palm trunk binderless particleboard. *European Journal Wood Product*, 71(5), 583-589.

Charoenvai, S. (2013). New insulating material: Binderless particleboard from durian peel. *Advanced in Civil Engineering and Building Materials*, CRC Press, 119–123.

Cristescu, C., Sandberg, D., Ekevad, M., Karlsson, O. (2015). Influence of pressing parameters on mechanical and physical properties of self-bonded laminated beech boards. *Wood Material Science & Engineering*, 10(2), 205-214.

Fahmy, T. Y. A. & Mobarak, F. (2013). Advanced binderless board-like green nanocomposites from undebarked cotton stalks and mechanism of self-bonding. *Cellulose*, 20(3), 1453-1457.

Hashim, R., Saari, N., Sulaiman, O., Sugimoto, T., Hiziroglu, S., Sato, M., & Tanaka, R. (2010). Effect of particle geometry on the properties of binderless particleboard manufactured from oil palm trunk. *Materials and Design*, 31(9), 4251–4257.

Hashim, R., Said, N., Lamaming, J., Baskaran, M., Sulaiman, O., Sato, M., Sugimoto, T. (2011). Influence of press temperature on the properties of binderless particleboard made from oil palm trunk. *Materials and Design*, 32(5), 2520–2525.

Hashim, R., Wan Nadhari, W. N. A., Sulaiman, O. (2016). Green Binderless Board from Oil Palm Biomass. *Green Binderless Board from Oil Palm Biomass. Renewable Energy and Sustainable Technologies for Building and Environmental Applications, in Springer International Publishing Switzerland*, 11, 175-186.

Hidayat, H., Keijsers, E. R. P., Prijanto, U., van Dam, J. E. G., Heeres, H. J. (2014). Preparation and properties of binderless boards from *Jatropha curcas L*. seed cake. *Industrial Crop and Products*, 52, 245-254.

JIS - A 5908. 2003. *Particleboards, Japanese Standards Association*, Tokyo, Japan.

Maisarah, T., Zuraida, A., Roszalia, A., Luqman, M. A. (2015). characterization of rattan waste for binderless particleboard (BPB) production. *Advanced Materials Research*, 1115, 317-320.

Mancera, C., Ferrando, F., Salvadó, J. (2008). Cynara cardunculus as raw material for the production of binderless fiberboards: optimization of pretreatment and pressing conditions. Journal of Wood Chemistry and Technology, 28(3), 207-226.

Malaysian Furniture News 5th Issue. (2017). Retrieved August 13, 2017, from http://www.mfc.my/images/stories/pdf/MFC_5thIssue.pdf
Marashdeh, M. W., Hashim, R., Tajuddin, A. A., Bauk, S., Sulaiman, O. (2011). Effect of particle size on the characterization of binderless particleboard made from *Rhizophora spp*. mangrove wood for use as phantom material. *BioResources,* 6(4), 4028–4044.
Muniandy, K., Ismail, H., Othman, N. (2012). Biodegradation, morphological and FTIR study of rattan powder-filled natural rubber composites as a funtion of filler loading and a silane coupling agent. *BioResources,* 7(1), 957–971.
Nonaka, S., Umemura, K., Kawai, S. (2013). Characterization of bagasse binderless particleboard manufactured in high-temperature range. *Journal of Wood Science,* 59(1), 50-56.
Okamoto, H., Sano, S., Kawai, S., Okamoto, T., Sasaki, H. (1994). Production of dimensionally stable medium density fiberboard by use of high-pressure steam pressing. *Mokuzai Gakkaishi*, 40, 380-389.
Okuda, N. & Sato, M. (2004). Manufacture and mechanical properties of binderless boards from kenaf core. *Journal of Wood Science,* 50(1), 53–61.
Okuda, N., Hori, K., Sato, M. (2006). Chemical changes of kenaf core binderless boards during hot pressing (I): influence of the pressing temperature condition. *Journal of Wood Science,* 52(3), 244–248.
Olorunnisola, A.O., Pitman, A., Mansfield-William, H. (2005). Strength properties and potential uses of rattan-cement composites. *Journal of Bamboo and Rattan*, 4(4), 343-352.
Panyakaew, S. & Fotios, S. 2011. new thermal insulation boards made from coconut husk and bagasse. *Energy and Buildings,* 43, 1732-1739.
Pesenti, H., Torres, M., Oliveira, P., Gacitua, W., Leoni, M. (2017). Exploring Ulex europaeus to produce nontoxic binderless fibreboard. *BioResources*, 12(2), 2660-2672.
Pintiaux, T., Viet, D., Vandenbossche, V., Rigal, L., Rouilly, A. (2015). Binderless materials obtained by thermo-compressive processing of lignocellulosic fibers: A comprehensive review. *BioResources,* 10(1), 1915-1963.
Quintana, G., Velasquez, J., Betancourt, S., Ganan, P. (2009). Binderless fiberboard from steam exploded banana bunch. Industrial Crops and Products, 29(1), 60-66.
Saadaoui, N., Rouilly, A., Fares, K., Rigal, L. (2013). Characterization of date palm lignocellulosic by-products and self-bonded composite materials obtained thereof. Materials Design, 50, 302-308.
Sellers, T. Jr., Miller, G. D., & Fuller, M. J. (1993) Kenaf core as a board raw material. Forest Prod J 43:69-71
Sulaiman, O., Salim, N., Hashim, R., Yusof, L.H.M., Razak, W., Yunus, N.W.M., et al. (2009). Evaluation on the suitability of some adhesives for laminated veneer lumber from oil palm trunk. Mater Des; 30:3572-80.
van Dam, J.E.G., Oever, M.J.A.V.D, Keijsers, E.R.P, (2004) Production process for high density high performance binderless boards from whole coconut husk, Industrial Crops and Products 20, 97-101.
Widyorini, R., Higashihara, T., Xu, J., Watanabe, T., & Kawai, S. (2005). Self-bonding characteristics of binderless kenaf core composites, Wood Sci Technol, 39:651-662.
Xie, L., Liu, J., DU, A., (2012) Effect of Hot-pressing factors on binderless fibreboard properties, International Conference on Biobase Material Science and Engineering, 978-1-4673-2383-3
Xu, J., Widroyini, R., Yamauchi, H. (2006). Development of binderless fibreboard from kenaf core. Journal of Wood Science, 52(3): 236-243.
Zhang, D., Zhang, A., Xue, L. (2015) A review of preparation of binderless fiberboards and its self-bonding mechanism. Wood Science Technology, 49, 661-679.