Binderless Bark Particleboard Made from Gelam (*Melaleuca viridiflora* Sol. ex Gaertn.) Bark Waste: The Effect of the Pressing Temperature on Its Mechanical and Physical Properties

Eva Oktoberyani Christy,[a,b,*] Soemarno,[c] Sumardi Hadi Sumarlan,[d] and Agoes Soehardjono [e]

This study investigated the effects of the pressing temperature on the mechanical and physical properties of binderless bark particleboard made from Gelam bark waste and the improvement of those properties. In addition, the thermal insulation properties of the particleboard were determined. Four different temperatures (140 °C, 160 °C, 180 °C, and 200 °C) were used to make single-layer binderless bark particleboard with a target density of less than or equal to 0.59 g/cm^3. Results revealed that the pressing temperature affected the mechanical properties (modulus of rupture, modulus of elasticity, and tensile strength perpendicular to panel surface), which increased as the temperature increased, and the physical properties (thickness swelling and water absorption), which decreased as the temperature increased. Based on the Tukey test, increasing the temperature from 180 to 200 °C did not significantly affect the mechanical or physical properties, except for the tensile strength perpendicular to panel surface. None of the mechanical properties met SNI standard 03-2105-2006 (2006); however, the 12% maximum thickness swelling requirement was met for binderless bark particleboard hot-pressed at 200 °C. Binderless bark particleboard hot-pressed at 200 °C had high water resistance, regardless of its low strength, and a thermal conductivity value of 0.14 W/m·K.

Keywords: Mechanical properties; Dimensional stability; Thermal conductivity; Self-bonding; Lignocellulosic material

*Contact information: a: Postgraduate Program, Faculty of Agriculture, Brawijaya University, Malang 65145 Indonesia; b: Department of forestry, Faculty of Agriculture, Palangka Raya University, Palangka Raya, Central Kalimantan 74874 Indonesia; c: Department of Soil Science, Faculty of Agriculture, Brawijaya University, Malang 65145 Indonesia; d: Department of Agricultural Engineering, Faculty of Agricultural Technology, Brawijaya University, Malang 65145 Indonesia; e: Department of Civil Engineering, Faculty of Engineering, Brawijaya University, Malang 65145 Indonesia; *Corresponding author: eochristy28@gmail.com*

INTRODUCTION

Lignocellulosic materials from agricultural waste products, forestry residues, and other non-wood products can be used as alternative raw materials for the production of composite panels, *e.g.*, particleboards and fiberboards. A similar trend is also apparent in the use of adhesive-free panel technology. These tendencies are driven by the scarcity of wood resources and the formaldehyde emissions associated with the production of particleboards (Wang *et al.* 2018). Formaldehyde emissions from formaldehyde-based adhesives are quite detrimental to human health, as they may lead to illness, *e.g.*, leukemia

(Golden 2011; Zhang and Lin 2016). Numerous studies have addressed this global problem. These studies encourage the production of binderless boards from waste generated in the production of rattan furniture (Ahmad *et al.* 2019), also from agricultural waste such as unripe coconut husks (Araújo Junior *et al*. 2018), wheat straw residues (Domínguez-Robles *et al.* 2020), rice husk (Ferrandez-Garcia *et al*. 2017), sunflower bark and flax shives (Mahieu *et al*. 2019), banana trunk waste (Nadhari *et al.* 2019), and almond residues (Ferrandez-Villena *et al.* 2019). There are also binderless boards made from other natural resources, *i.e.*, Totora (*Schoenoplectus californicus* (C.A. Mey) Soják) stems (Hidalgo-Cordero *et al.* 2020) and *Arundo donax* L. rhizomes (Ferrandez-Villena *et al.* 2020).

Wood bark is a lignocellulosic-based forestry residue waste product that could be considered for the production of binderless particleboards (Romaní *et al.* 2020). Chen and Yan (2018) pointed out that bark is the outermost layer of a tree trunk. The primary chemical composition of tree bark is quite similar to wood, *i.e.*, it consists of cellulose, hemicellulose, and lignins; however, tree bark is also rich in extractives such as tannins, suberins, rosins, *etc*. Chen and Yan (2018) also stated that tannins and lignins have adhesive properties. With regard to these two components, Chow (1972, 1975) argued that a high-density bark board can be made without synthetic resin, since both extractives and lignins, which are phenolic materials, can function as an adhesive and therefore may contribute to the self-bonding process of bark particles. Nitu *et al*. (2017) pointed out that the chemical composition of a lignocellulosic material is an important consideration and determines its suitability in the making of binderless composites.

In the case of manufacturing panels from tree bark without synthetic adhesives, the authors learned that high-temperature pressing is more favorable because a temperature higher than 180 °C will improve the physical and mechanical properties of the board. At that temperature (greater than 180 °C), thermal reactions, *i.e.*, polymerization and partial degradation of the chemical components of the bark, will occur. The polymerization of the phenolic extractives and possibly lignins will produce a strong bond between the bark particles (Chow 1972, 1975). In addition, it should be noted that oven-dried samples comprised of wood and bark begin to soften at 180 °C (Chow and Pickles 1971). In regard to the parameters of binderless particleboard production *via* the hot-pressing process, Gupta *et al.* (2011) argued that the pressing temperature is one of the most important parameters in producing particleboards without synthetic resin (bark board), since the binding of wood bark particles without synthetic adhesive is believed to occur due to a thermal effect. Gupta *et al.* (2011) found that all the properties of the bark board made from beetle-infested lodgepole pine (*Pinus contorta*) bark drastically increased as the pressing temperature increased, from 170 to 230 °C. In the production of adhesive-free boards using other materials, Boon *et al.* (2013) maintained that the role of the pressing temperature in terms of improving the mechanical properties of binderless particleboards made from palm oil trunk is more important than any other parameters.

Gelam bark waste (GBW) is a lignocellulosic material, and Xiao *et al.* (2014) mentioned that the bark from the *Melaleuca* tree is rich in lignins. It is an abundant waste material, which is generated by peeling the bark off a Gelam log with a diameter of less than 10 cm. The Gelam tree has multi-layered bark, and it is one of the *Melaleuca* species grown in Central Kalimantan. According to Sakasegawa *et al.* (2003), this tree is locally referred to as Gelam in Indonesia. Supriyati *et al.* (2015) mentioned that the *Melaleuca* species naturally and abundantly grows in Indonesian territory, especially in the peat

swamp forests of Central and South Kalimantan, and along the southern coast of Sumatera. Usually, bark waste is simply burned, used as land filling, or thrown into the river, which obviously creates an environmental problem. Given the chemical content of GBW, the authors believe that it is suitable to proposing the use of GBW to produce a low-density binderless bark particleboard (BBP) *via* the hot-pressing process with the pressing temperature as a variable parameter. To the best of the authors' knowledge, there is only limited information on the making of binderless bark particleboards from Gelam bark waste. A previous study by Sato (2008) explored the possibility of producing high-density bark binderless boards from *Melaleuca* bark with the hot-pressing temperature at 180 °C. However, there is no information about the effect of the pressing temperature on low-density binderless bark particleboard properties made from Gelam bark using a high-pressing temperature at 180 °C and 200 °C in the production of its. Therefore, this recent study investigates the effect of the pressing temperature on the mechanical and physical properties of BBP made from GBW. The mechanical and physical properties evaluated included the modulus of rupture (MoR), modulus of elasticity (MoE), tensile strength perpendicular to panel surface (TSPtPS), density, moisture content (MC), thickness swelling after 24 h of soaking (TS24h), and water absorption after 24 h of soaking (WA24h). Also, the chemical properties of the raw materials were determined by conventional chemical analysis. Furthermore, Fourier-transform infrared spectroscopy was used to observe any changes in the FTIR spectra between the raw material and the BBP, which were pressed at different temperatures. Observation *via* scanning electron microscopy equipped with energy-dispersive X-ray analysis was also performed to study the microstructure and quality of the bonding was formed in the BBP. Besides, according to Lakreb *et al*. (2018) there has been growing interest in using bark particleboard as a thermal insulation material in recent years. As in studies by Pásztory *et al*. (2017) and Pásztory *et al*. (2019), the resulting bark particleboard has a low density, resulting in good thermal insulation properties. Regarding BBP, which also made with the low-density target. So that thermal insulation properties also need to be determined in view of its use as an insulating material.

EXPERIMENTAL

Raw Materials

Gelam (*Melaleuca viridiflora* Sol. ex Gaertn.) bark waste used in this study was obtained from Central Kalimantan, specifically from a local Gelam wood seller in the village of Garung, Jabiren Raya, in the Pulang Pisau Regency (location coordinates 114°12'29.99"E and 2°38'14.96"S). The GBW was obtained by stripping Gelam wood logs with a diameter of less than 10 cm and an approximate thickness of 3.5 mm. Both parts of the bark, *i.e.*, inner and outer, were used in the study. The bark was manually cut using a machete to a length of approximately 1 cm to 4 cm (Fig. 1a), then air-dried for approximately three weeks until the moisture content decreased to the range 13% to 15%. Afterward, these small pieces were mashed using a wood crusher, and the particles that passed through the 10 mesh sized filters were used to make the BBP (Fig. 1b). Finally, the particles were air-dried until the moisture content decreased to 5% to 7%. The irregular shapes of the bark particles, which occurs in both the outer and inner barks, can be seen in Fig. 1c.

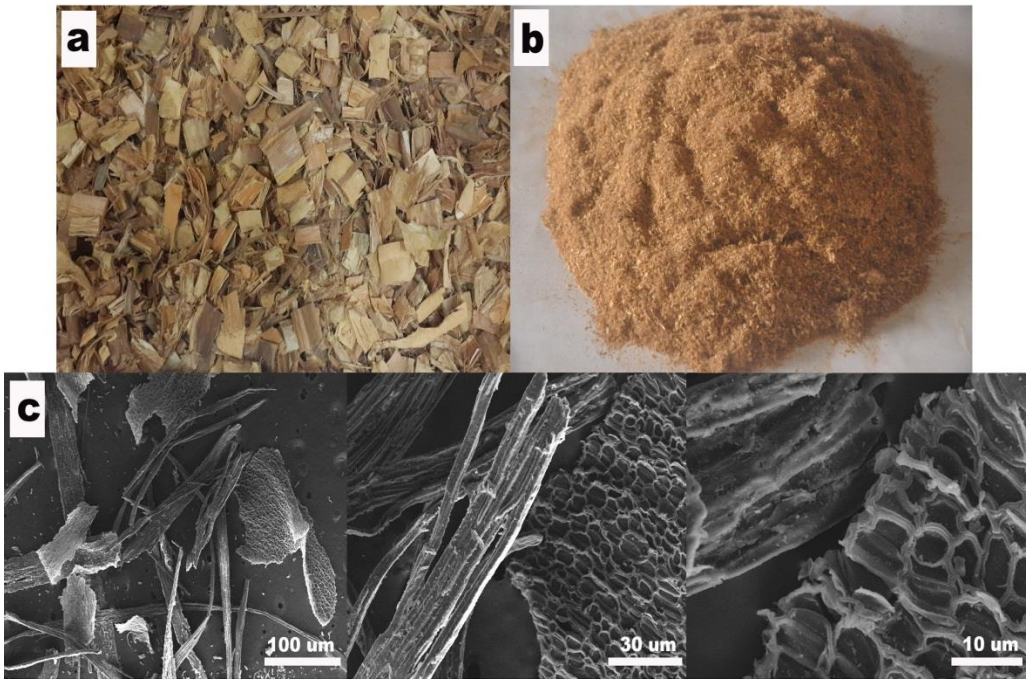

Fig. 1. Photograph of the barks: (a) small cut bark; (b) bark particles; and (c) SEM micrographs of the bark particles at different magnifications.

Chemical Analysis of the Raw Materials

The chemical content of the GBW was analyzed according to the following standards: SNI standard 8401:2017 (2017)/Identical with TAPPI standard T204cm-07 (Alcohol-benzene and dichloromethane Extractives), SNI standard 01-1305-1989 (1989) (Solubility in hot water), SNI standard 14-1838-1990 (1990) (Solubility in 1% NaOH), Wise methods (Wise 1946) (Holocellulose), ASTM standard D1103-60 (1977) (α cellulose), SNI standard 0492-2008 (2008) (Klason Lignin), and SNI ISO standard 776:2010 (2010) (Ash). All chemical analyses were repeated three times.

Manufacturing and Testing

There are four types of BBP based on the pressing temperature used during manufacturing, *i.e.*, the boards pressed at 140, 160, 180, and 200 °C (five replicates for each temperature treatment), for a total of 20 single-layer boards measuring 300 mm x 300 mm x 10 mm with a target density of less than or equal to 0.59 g/cm^3. To make the boards, 540 g of bark particles were first manually molded into a mat shape by placing and trampling it on a rectangular wooden forming box, whose base was covered with an aluminum sheet. A thickness bar was placed on top of the aluminum sheet, in the form of a wood frame measuring 300 mm long and 10 mm thick. The dimensions of the wooden forming box were 300 mm x 300 mm with a height of 100 mm. After the mat was molded, its upper surface was covered with another aluminum sheet (as shown in Fig. 2). Then the mat was cold-pressed for 5 min, followed by hot pressing at four different temperatures (for each temperature sample set) with a pressure of 30 kg/cm^2 for 20 min using a hydraulic hot press (Carver Laboratory Press, Carver Inc., Wabash, IN). To avoid blowing and blistering as well as ensuring the continuity of pressing the board with a hot-pressing machine, without turning off the tool, the board was immediately removed from the hot-pressing machine and transferred into a clamp to be cooled for 24 h, after which the clamp

was removed. Then, the board was conditioned for two weeks *via* air-drying at a temperature of 25 °C to 30 °C with a relative humidity of 60% to 65%. Finally, the board was ready to be cut into a test sample.

Fig. 2. The manual formation of a mat

Five replicate test samples for each physical and mechanical properties test were prepared for each pressing temperature. All tests were carried out according to SNI standard 03-2105-2006 (2006). The physical properties tests included determining the density, moisture content (MC), thickness swelling after 24 h of soaking (TS24h), and water absorption after 24 h of soaking (WA24h) of the boards. The SNI standard 03-2105-2006 (2006) does not set standards for the water absorption of particleboard. However, the water absorption needs to be tested to determine how resistant the boards were to water, particularly for exterior use.

For the density and MC tests, samples measuring 100 mm x 100 mm were prepared. For these two tests, the same samples were used, because the density test did not damage the samples. The density test was carried out under air-dry conditions. First, the sample was weighed, then its volume was calculated by measuring the average length and width of the boards from two different measurement points; the thickness of the boards was determined by measuring the average thickness from four measurement points. The density of the boards was obtained by dividing its weight by its volume. Meanwhile, the MC was calculated by subtracting the initial weight of the board from the final weight of the board after it was dried in an oven at 103 °C ± 2 °C until it reached a constant weight.

The TS24h and WA24h values of the boards were determined using test samples measuring 50 mm x 50 mm. The tests were carried out by submerging the samples horizontally underwater at a temperature of 25 °C ± 1 °C for 24 h. Before submerging the samples, the authors made a note of the initial weight and thickness of the samples. After soaking, the weight and thickness of the samples were remeasured. The measurement method for determining the thickness of the samples, before and after soaking, was taken at the same location, *i.e.*, all four corners that were located 10 mm from its actual corners (at the point of intersection of the length and width measurement).

When testing the mechanical properties of the boards, *i.e.*, its modulus of rupture (MoR) and modulus of elasticity (MoE), samples were prepared that measured 200 mm x 50 mm, and the test was conducted using an Iber Test universal testing machine (Model MIB20AM, Madrid, Spain) under dry conditions. The test samples were placed horizontally on the two supports (the length of the support span was 150 mm), and the load was applied at the center of the samples with a loading speed of 10 mm/minute. The deflection was recorded, and the load application was continued until it reached its maximum load. In principle, the MoR refers to the ability of the adhesive-free particleboards to withstand a centrally applied load in a dry state. The tensile strength perpendicular to panel surface (TSPtPS) test, which is also known as the internal bonding

strength (IB) test, is intended to measure the strength of adhesive-free particleboard in terms of sustaining an upright tensile load on its surface. The testing was carried out on a test sample that measured 50 mm x 50 mm. First, the length and width of the sample were measured and recorded. Then the sample was glued to two iron blocks and left to dry for 24 h. Afterward, the sample was pulled vertically with a loading speed of 2 mm/min.

Three pieces of BBPs that were pressed at 200 °C were selected for the thermal conductivity tests (λ) at room temperature using a Kemtherm QTM-D3 thermal conductivity meter equipped with QTM PD3 probe (Kyoto Electronics Manufacturing Ltd, Kyoto, Japan). The basic principles of testing used the transient hot-wire method. Samples measuring 145 mm x 55 mm were prepared for the test. The probe was connected to the measuring device (the cable is connected to a 220-volt power supply), and the device was then heated for 30 min. The value of the heater current was 1 A^2, which was based on the conductivity of the sample being tested. The value of the constant was adjusted to the value on the probe constant table; the probe was then placed on top of the sample. After a count down from 60 to 0 s, the thermal conductivity value would be shown on the digital display.

The data collected from testing the mechanical and physical properties were statistically analyzed using a single-factor analysis of variance (ANOVA) in Microsoft Excel for Windows, followed by Tukey's (HSD) post hoc test with α equal to 0.05.

Fourier Transform Infrared Spectroscopy (FTIR)

The samples used in the analysis were the raw materials as well as the boards that were hot pressed at four different pressing temperatures (these samples were previously used in the bending strength tests). The FTIR analysis was carried out with a Shimadzu IR Prestige-21 Infrared spectrophotometer (Shimadzu Corporation, Kyoto, Japan). The test samples were prepared in the form of KBr-pellets, and then the IR spectra were taken within the range of 4000 to 500 cm^{-1} and recorded with 40 scans at a resolution equal to 4.0 cm^{-1}.

Scanning Electron Microscopy (SEM)

For this analysis, the BBP samples were cut into parallel-sections and cross-sections. Then, a microstructure observation was performed using a Carl-Zeiss (Evo MA 10, Cambridge, United Kingdom) scanning electron microscope (SEM), equipped with a Bruker (Quantax, Bruker Nano GmbH, Berlin, Germany) energy dispersive X-ray spectroscopy (EDX) detector, which was operated using an accelerated voltage of 20 kV. Before observation, the samples were coated with gold-palladium for 60s using an Emitech sputter coater (SC7620, Quorum Technologies Ltd, Lewes, United Kingdom). The SEM micrographs were taken at 60 x, 300 x, and 1000 x magnifications for each surface and cross-section. The EDX analysis for the cross-sections was taken at 300 x magnifications.

RESULTS AND DISCUSSION

All BBPs, *i.e.*, the samples made at different pressing temperatures, were made without delamination. The board pressed at a temperature of 200 °C had a smooth surface. Moreover, all the boards pressed at different pressing temperatures showed varying surface colors, ranging from light brown to dark brown with respect to the lowest temperature to the highest (as shown in Fig. 3). The material also emitted a distinctive odor. Similar results were also noticeable in the binderless boards made using the following raw materials:

bagasse (Panyakaew and Fotios 2011), palm oil trunk (Boon *et al.* 2013), unripe coconut husk (Araújo Junior *et al.* 2018), wheat straw (Wang *et al.* 2019), soybean straw (Song *et al.* 2020), jute stick (Nitu *et al.* 2020), and densified wood (Shi *et al.* 2020); this could be the result of the modification of the chemical components that occurs during the heat treatment (Panyakaew and Fotios 2011; Wang *et al.* 2019). The presence of hemicellulose degradation and extractive movement may be the cause of the darkening of the color (Shi *et al*. 2020). Furthermore, Pintiaux *et al*. (2015) mentioned that the color change in the specimen was a sign of degradation, as reported by Araújo Junior *et al.* (2018) biomass components, namely hemicellulose, decompose at temperatures of 170 °C or higher, while cellulose decomposes at 200 °C or higher. Meanwhile, lignin decomposes more slowly in the range of 200 to 500 °C.

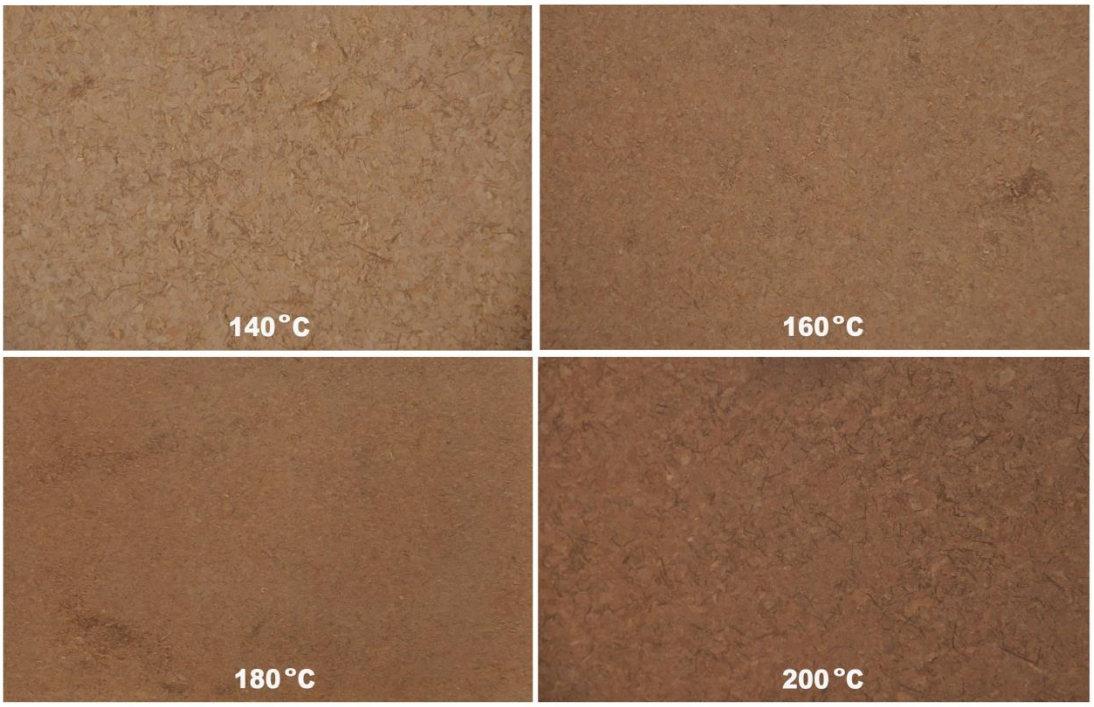

Fig. 3. Appearance of the BBP surface at various pressing temperature

Chemical Properties of the Raw Material

The results of the GBW chemical analyses are shown in Tables 1 and 2. As can be seen in Table 1, the average holocellulose value for GBW was 78.8%, which is higher than the holocellulose values of woods from Borneo (Pettersen 1984). The GBW holocellulose value was also relatively higher than the holocellulose value found in a study by Ozgenc *et al.* (2017). The high holocellulose content of the bark is probably the result of the bark being peeled from the trunk using a commercial log-peeling machine. Tree bark stripped with commercial log-peeling machines often contains a large amount of actual wood, with less lignins and extractives and more cellulose than only bark (Geng *et al.* 2006). This explanation seems plausible because it is quite likely that wood could have been ripped away along with the bark when the bark was stripped from the trunk; this is also true for the Gelam bark stripped in the traditional way using a machete. Another explanation for this is the fact that holocellulose still contains lignin residues (Santana and Okino 2007). As shown in Table 1, the holocellulose content is corrected by lignin residues (Harun and

Labosky 2007) and showed a lower value than GBW. Meanwhile, the average alpha-cellulose value of GBW was lower than the alpha-cellulose value of the woods from Borneo. The ash content of GBW (1.23%) is not high compared to the ash content of shagbark hickory (7.8%) but was higher than that of *Melaleuca* sp. wood (1.04%).

Table 1. The Main Components and the Ash Content of GBW Compared with Data from Literature Reviews on Wood and Other Tree Barks

Wood Species	The main components and the ash content (%)			
	Holocellulose	Alpha cellulose	Klason lignin	Ash
GBW[1]	78.8 (0.14)[a]	37.58 (0.40)	47.7 (0.30)[a]	1.23 (0.03)[b]
Melaleuca sp. Wood[2]	-	-	31.11[a]	1.04
Woods from Borneo[3]	62 to 74	42 to 55	26 to 35	0.1 to 1.6
Shagbark Hickory[4]	45.3 (44.0)[c]	-	38.0[d]	7.8
White Pine[4]	40.3 (38.9)[c]	-	50.0[d]	1.0
Alder[5]	51.96	-	45.78[e] (33.55)[f]	-
Chestnut[5]	51.48	-	25.23[e] (14.55)[f]	-
Beech[5]	63.52	-	32.87[e] (24.25)[f]	-

Note:
1 This work; bark from wood with a diameter less than 10 cm, values in parenthesis are standard deviation
2 Supriyati (2015): *Melaleuca* sp. wood with a diameter less than 10 cm (sample collected near bark)
3 Pettersen (1984): Wood
4 Harun and Labosky (2007): Bark
5 Ozgenc *et al.* (2017): Bark
a Based on materials free from alcohol-benzene extractives
b Based on original bark/unextracted bark
c Corrected holocellulose
d After extraction with ethanol-benzene followed by treatment with 1% NaOH and then treated with 72% H_2SO_4
e Klason lignin content after the alcohol-benzene dissolution
f Klason lignin content after the alcohol-benzene and NaOH 1% dissolution

The Klason lignin content of GBW (47.7%) is lower than the Klason lignin content of white pine bark but higher than the Klason lignin content of shagbark hickory (Harun and Labosky 2007). In addition, the Klason lignin content of GBW is higher than the Klason lignin contents of alder, chestnut, and beech bark, after an alcohol-benzene only dissolution and an alcohol-benzene and NaOH 1% dissolution (Ozgenc *et al.* 2017). The Klason lignin content of GBW is also higher than the Klason lignin content of *Melaleuca* sp. wood. From these results, the authors concluded that the Klason lignin content of GBW was high. However, Santana and Okino (2007) claimed that the method for determining lignin content has some flaws, which may give the impression of a higher lignin content than the actual figure (most common) or reduce it (rare). In the case of tree bark, Dou *et al.* (2018) argued that Klason lignins possibly also include other components other than lignins, even though the samples have been extracted in succession with several different solvents using commonly used methods. These components include condensed and hydrolysable tannins, and suberins that give the impression of a higher lignin content instead of the actual value (Harkin and Rowe 1971; Harun and Labosky 2007; Rowell *et al.* 2012). For the results of misleading from standard lignin analysis, Harkin and Rowe (1971) mark the word "lignin" which consists of a mixture of true lignin and suberized phlobaphene ranging from 40 to 50% for hardwood bark.

Table 2. Extractive Contents/solubility of GBW Compared with Data from Literature Reviews on Wood and Other Tree Barks

Wood Species	Extractives/solubility (%)			
	Alcohol-benzene extractives	Solubility in Hot water	Dichloromethane extractives	Solubility in 1% NaOH
GBW[1]	7.78 (0.43)	4.07 (0.13)[a]	7.03 (0.02)	32.65 (0.25)
Melaleuca sp. Wood[2]	4.28	4.01	-	15.94
Woods from Borneo[3]	1 to 14	2 to 13	-	-
Shagbark Hickory[4]	11.0	-	-	-
White Pine[4]	5.7	-	-	-
Alder[5]	9.23	-	-	37.63
Chestnut[5]	15.20	-	-	46.13
Beech[5]	5.50	-	-	26.93

Note:
[1] This work; bark from wood with a diameter less than 10 cm, values in parenthesis are standard deviation
[2] Supriyati (2015): *Melaleuca* sp. wood with a diameter less than 10 cm (sample collected near bark)
[3] Pettersen (1984): Wood
[4] Harun and Labosky (2007): Bark
[5] Ozgenc *et al.* (2017): Bark
[a] Solubility in hot water performed after the sample underwent alcohol-benzene extraction treatment

A comparison of the extractive contents/solubility of GBW is given in Table 2. The alcohol-benzene extractives (7.78%) and 1% NaOH (32.65%) solutions of GBW were higher than the alcohol-benzene extractives, and the solubility values of *Melaleuca* sp. wood, its solubility value in hot water did not differ by much. When compared to the alcohol-benzene extractives (1% to 14%) and the solubility in hot water (2% to 13%) of the woods from Borneo, the solubility value of GBW was still within range. The dichloromethane extractives (7.03%) of GBW were slightly lower than the alcohol-benzene extractives. In contrast, when compared to bark from other wood species, the alcohol-benzene extractives of GBW were higher than white pine (5.7%) and beech (5.50%), but lower than shagbark hickory (11.0%), alder (9.23%), and chestnut (15.2%). Likewise, the solubility value of GBW in 1% NaOH was lower than alder (37.6%) and chestnut (46.1%). However, the Klason lignin, extractives, and ash contents of GBW were higher than the *Melaleuca* sp. Wood values. As stated by Sakai (2000), in general, wood bark contains more extractives than the wood sampled from the same tree. Still, the results of the chemical analysis label GBW as a lignocellulosic material, and its primary contents are holocelluloses and lignins.

The conventional chemical analysis of GBW in Table 1 revealed there was an overestimation of holocellulose and Klason lignin content, which may be due to contamination. This can happen since Klason lignin was determined on the bark extracted only with alcohol-benzene without being followed by extraction with hot water and 1% NaOH. So, possibly phenolic compounds (such as tannins, phenolic acids) and suberin remain in the bark samples. Those compounds potentially function as a contaminant in Klason lignin. Since phenolic components dissolve in sulfuric acid, causing the lignin content in tree barks increase (Ozgenc *et al*. 2017). It also is mentioned by Gonultas and Ucar (2013) and Gonultas and Candan (2018) that phenolic compounds, such as tannins,

could be condensed and remain with lignin in acidic conditions, which contributes to the overestimation of lignin content. Concerning suberin, as evidenced by Krogell *et al*. (2012), TMAH-Pyr-GCMS analysis has shown that suberin detected in Klason lignin residues from hexane and acetone-water pre-extracted Norway spruce bark. Previous work by Ozgenc *et al*. (2017) has indicated that lignin determined by Klason analysis in bark samples previously extracted with alcohol-benzene alone tends to be overestimated compared to lignin determined in bark samples that were extracted successively with alcohol-benzene and 1% NaOH. Likewise, for holocellulose determination, when a polymeric compound such as suberin is likely to remain in the bark sample after alcohol-benzene extraction, it would interfere with this holocellulose analysis method. Suberin tends to limit the access of delignification reagents to lignin in the bark (Rowell *et al*. 2012). Therefore, it is not feasible to obtain relatively pure holocellulose because it will likely contain a considerable amount of lignin. To overcome waxlike material, Harun and Labosky (2007) proposed that the alcohol-benzene extracted bark should be followed by treatment with 1% anhydrous EtOH/KOH to remove waxlike materials. This means that the conventional analytical procedures used for wood are failing or inadequate for bark. However, relating with the high yield of holocellulose obtained in this study, it does not dismiss the possibility that, as previously stated, the presence of wood which is also peeled off when peeling the bark, also contributes to a higher holocellulose content. Besides, the bark contains quite a lot of fibers, although they are shorter than wood fibers.

However, indications of a high "lignin" and extractives content can be an essential ingredient in the production of BBP because, as phenolic materials, they can function as a natural adhesive. This refers to previous studies (Chow 1972, 1975; Gupta *et al.* 2011) that examined the effects of the pressing temperature on the properties of boards made without adhesive, wherein the possible polymerization and softening of these chemical components contribute to the self-bonding of bark particles at high-pressing temperatures.

Chow (1972) and Chow (1975) made bark boards from the bark of Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) without synthetic adhesive, using the hot-pressing method with a pressing temperature ranging from 200 to 300 °C and found that within this temperature range, the polymerization of extractives and lignins plays a role in the self-bonding of the bark particles. Furthermore, the studies by Chow (1972) and Chow (1975) also show that when boards are pressed at high temperatures (200 to 300 °C) under an appropriate time-temperature schedule, they will yield mechanical and physical properties that are similar to bark boards made using 4.5% phenol-formaldehyde. Additionally, when boards are pressed at high temperatures, a certain amount of moisture is released, which is probably the result of condensation and dehydration of the chemical components of the bark. This method of board making, based on a study by Chow and Pickles (1971), found that oven-dried Douglas-fir and red alder bark begin to soften at a temperature of 180 °C, while some minor additional softening occurring at 280 °C, *i.e.*, when moisture condensation is released. When a material a moisture content of greater than 10%, softening begins to occur at 160 °C. Afterward, it is postulated that the thermal softening of moistened bark that occurs at a temperature below 200 °C is primarily associated with plasticization, which only occurs in the amorphous region. Meanwhile, at temperatures higher than 180 °C, the thermal reaction of the bark is associated with the polymerization and partial degradation of various components of the bark, where the polymerization expects to be more advantageous for the dimensional stability, water resistance, and strength properties of the bark boards. Following the same pathway, Gupta *et al.* (2011)

found that bark boards manufactured from beetle-infested lodgepole pine bark without synthetic resins could be bonded through polymerization of the extractives and lignins, and softening at higher temperatures (greater than 200 °C). Another study by Hashim *et al.* (2011) showed that a low pressing temperature (180 °C) is not sufficient for the plasticization of palm oil bark particles to occur when making particleboards without adhesive, considering that the glass transition values of lignins, cellulose, and hemicellulose in a dry state are 200, 220, and 170 °C, respectively. Gao *et al.* (2011) described the process of manufacturing homogeneous binderless bark panels from refined black spruce bark with pressing temperatures in the range of 200 to 260 °C as well as from the ground bark particles with a pressing temperature of 260 °C. Gao *et al.* (2011) found that a higher pressing temperature is more favorable for *in-situ* transformation, degradation, crosslinking, polymerization, and bark thermosetting process, *i.e.*, more bark mass will be degraded.

In the current study, the authors decided to make a board using a pressing temperature no higher than 200 °C for 20 min, because when the authors attempted to make a board at a temperature higher than 200 °C for 20 min, the process resulted in a partially scorched surface of the board.

FTIR

To get an overview of any changes in the chemical structure between the raw material and BBP pressed at different temperatures, FTIR analysis was carried out. The collected infrared spectra are shown in Fig. 4. After overlaying the spectra, changes only occurred at five absorption points, *i.e.*, 3338, 1718, 1508, 1234, and 1041 cm^{-1}. The absorption region at the 3400 cm^{-1} is the absorption of the hydroxyl group (OH). There was a decrease in the absorption intensity of the hydroxyl group as the temperature was increased, which presumably was caused by the loss of OH due to the hot-pressing process. This process is closely related to the high hydrophobicity of the hot-pressed board (Araújo Junior *et al.* 2018). The absorption at the 1718 cm^{-1}, which was detected in the BBP, may be produced by the acetyl polysaccharides group. Jumhuri *et al.* (2014) stated that the absorption region at the 1736 cm^{-1} not only indicates the presence of carboxylate groups, but also indicates the presence of C=O groups (acetyl polysaccharide group), which likely originated from hemicellulose. The rising temperature leads to a degradation of hemicellulose, which is marked by a decline in the absorption intensity as the temperature rises. The absorption at approximately 1505 to 1512 cm^{-1} originates from the aromatic unit of lignins (C=C) (Widyorini *et al.* 2016), the absorption at 1508 and 1510 cm^{-1} are associated with lignins (Ozgenc *et al*. 2017), and absorption at the 1500 cm^{-1} is characteristic of lignin absorption of binderless fiberboard made from wheat straws (Wang *et al.* 2018). In addition, the absorption at approximately 1200 cm^{-1} originates from a lignin derivative (Okuda *et al.* 2006). There is a change in the absorption peak at approximately 1508 and 1200 cm^{-1}, along with the increase in pressing temperature. The higher the pressing temperature, the lower the absorption intensity at the 1508 cm^{-1}, which indicated that lignin degradation occurred. The absorption at the 1041 cm^{-1} originates from the bonding of C-O-C hemiacetal polysaccharides (Liao *et al.* 2016), and the present study also showed a change in that group due to the increase in pressing temperature. The C-O-C bond on the BBP is believed to originate from cellulose and hemicellulose. The decrease in absorption intensity at the 1041 cm^{-1}, along with the rising pressing temperature, points to hemicellulose degradation.

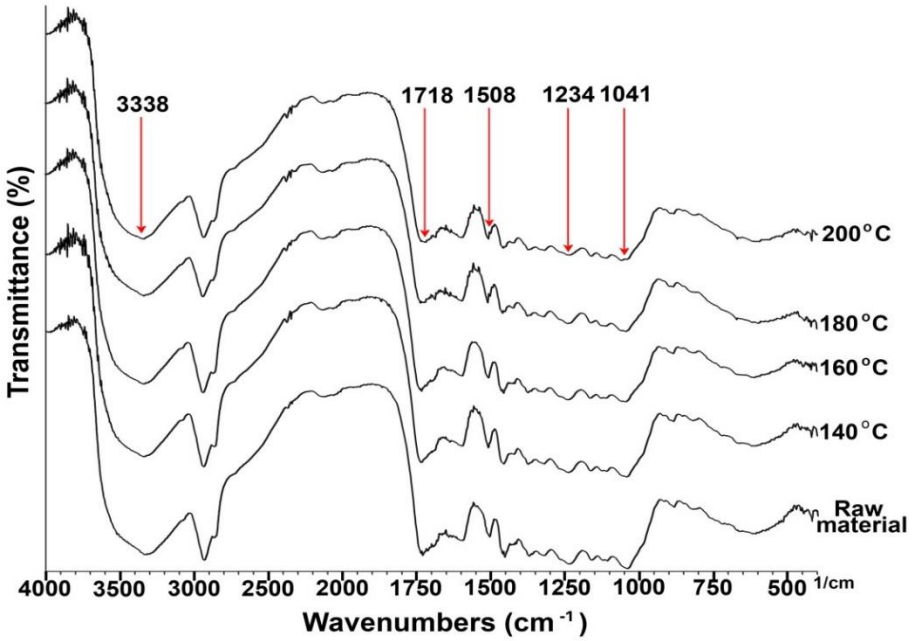

Fig. 4. The FTIR spectra of the GBW and BBP at different pressing temperatures

SEM-EDX

The SEM micrographs of the surfaces of the BBPs manufactured with four different temperature treatments are shown in Fig. 5. The BBPs pressed at temperatures of 140 and 160 °C, still have many loosely interlocked particles, which results in a rough surface (as shown in Figs. 5a and 5b). The compressed particles are from the phloem and rhytidome, which are fibers from the phloem tissues/secondary phloem and periderm that are part of the rhytidome (Chiang and Wang 1984). The boards that were pressed at a temperature of 180 °C had a somewhat smooth surface (Fig. 5c) and had slightly tighter interlocking particles than the boards treated at 160 °C, which indicated that softening had begun to occur. The boards treated at a temperature of 200 °C (Fig. 5d) show more compact and tightly interlocked particles, which produces a smooth surface and indicated the possibility of the occurrence of extractive polymerization and possibly lignins at a temperature that causes softening (Chow 1972). At a temperature of 200 °C, it is visible that the lignins were already flowing and partially coating the bark particles surface on the board surface. This phenomenon was similar to the results observed by Araújo Junior *et al.* (2018), who analyzed the SEM micrograph of binderless fiberboards made from unripe coconut husk pressed at a temperature 220 °C. Araújo Junior *et al.* (2018) argued that the smooth surface of the panel was the result of the presence of lignins on the outside of the fibers, which increased under the high-pressing temperature, causing the lignins to flow as a layer of ink. The results of the SEM micrographs of the cross-sections of the four BBPs that were treated at four different pressing temperatures are shown in Fig. 6. They were consistent with the SEM micrographs of the surfaces of BBPs, wherein a higher pressing temperature led to a denser packing of the boards. In Figs. 6a and 6b, there are more voids and gaps, which indicated poor bonding between the particles. However, the BBPs that were pressed at a temperature of 180 and 200 °C (Figs. 6c and 6d) showed almost no void spaces and tended to have a smoother texture. There appeared to be good contact between the particle surfaces.

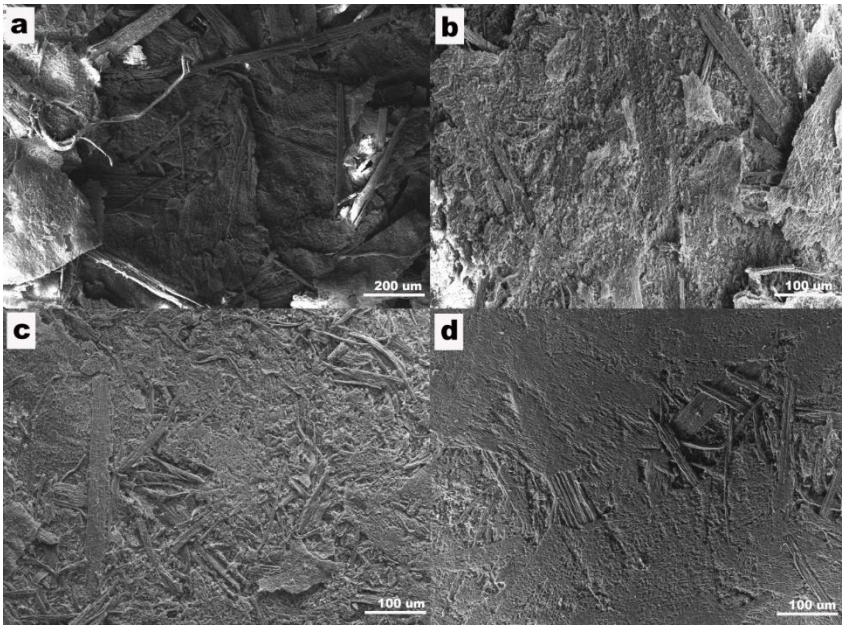

Fig. 5. The SEM micrographs of the BBPs surfaces pressed at different temperatures: (a) 140 °C; (b) 160 °C; (c) 180 °C; (d) 200 °C

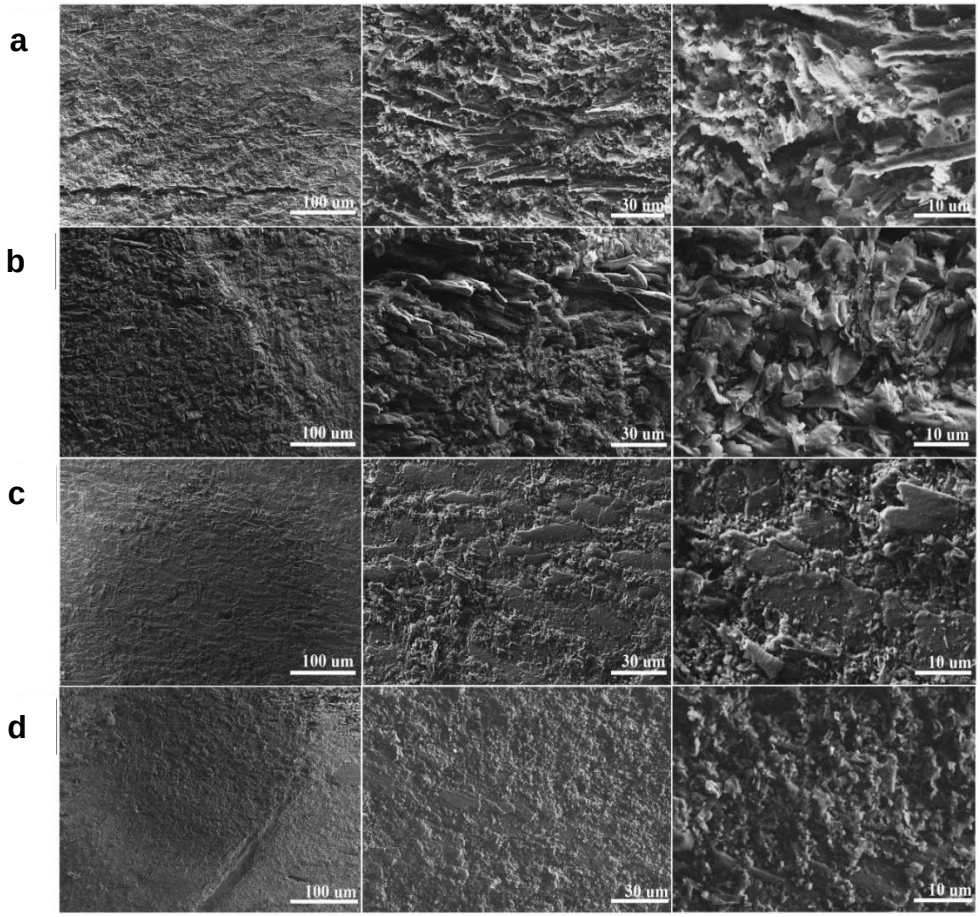

Fig. 6. The SEM micrographs of the cross-sections of BBPs pressed at different pressing temperatures: (a) 140 °C; (b) 160 °C; (c) 180 °C; (d) 200 °C (all four temperatures are shown at 60 x, 300 x, and 1000 x magnifications)

The EDX analysis revealed that all BBPs that were pressed at four different temperatures had two major elements, *i.e.*, carbon and oxygen, which occurred in a high percentage based on weight (Fig. 7). Significant differences were found in the inorganic elements when the BBP was pressed at a temperature of 140 °C. The material contained a small amount of these elements (in descending order): chlorine was greater than calcium, which was greater than potassium. The BBP pressed at a temperature of 160 °C only contained chlorine, while the BBP pressed at a temperature of 180 and 200 °C contained no major or minor minerals. The EDX analysis of wood fibers in a study by Dang *et al.* (2018) also detected the presence of carbon and oxygen as major elements. This shows that these major elements are related to lignocellulosic materials. Additionally, there were no heavy metal elements detected. All the chemical elements found in BBP pressed at 140 °C were the same as those found by Sutrisno *et al*. (2015) in bio-based nanomaterial from Jabon wood bark.

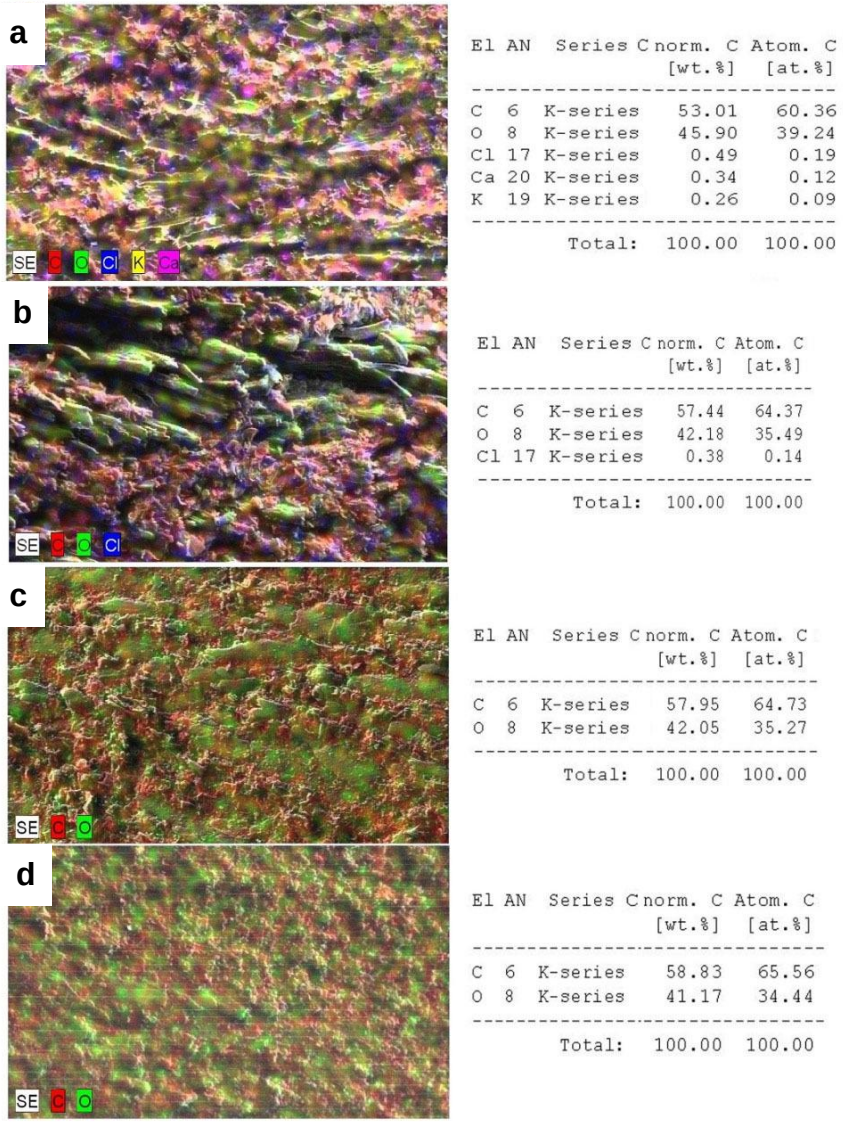

Fig. 7. The EDX mapping images of the cross-sections of BBPs pressed at different pressing temperatures: (a) 140 °C; (b) 160 °C; (c) 180 °C; (d) 200 °C (at a magnification of 300 x)

Mechanical Properties

Figure 8 shows the average values of the MoR, MoE, and TSPtPS of the BBPs made with different pressing temperatures. All the mechanical properties of the BBPs were significantly affected by the hot-pressing temperature treatments (ANOVA p-value was less than 0.01). In general, the MoR, MoE, and TSPtPS values tended to increase as the pressing temperature increased. The average MoR, MoE, and TSPtPS values ranged from 15.0 to 40.5 kg/cm^2, 2070 to 7730 kg/cm^2, and 0.08 to 0.63 kg/cm^2, respectively. Based on the Tukey's test, it was found that the highest MoR value (from the 200 °C treatment) was significantly different from the MoR values of the 140 and 160 °C treatments; however, it was not significantly different from the 180 °C treatment.

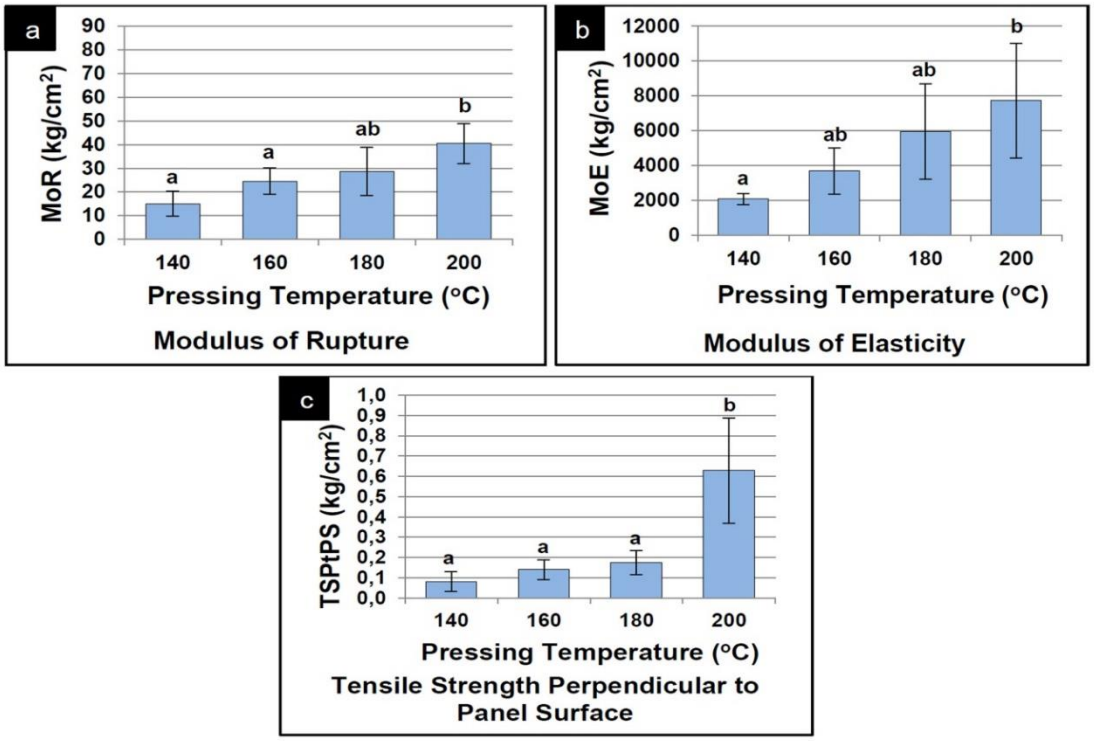

Fig. 8. The mechanical properties of BBP: (a) modulus of rupture; (b) modulus of elasticity; and (c) tensile strength perpendicular to the panel surface (means ± the error bar shows the standard deviation and means with different letters are significantly different at α = 0.05 (Tukey's test)

Meanwhile, the MoE values showed a significant difference only between the 200 and 140 °C treatments, whereas, the values between the 160, 180, and 200 °C treatments did not show significant differences. For the TSPtPS values, there was a significant difference between the 200 °C pressing treatment and the 140, 160, and 180 °C treatments. The results of the Tukey's test revealed that increasing the pressing treatment temperature to 200 from 180 °C when making a low-density BBP was not sufficient to significantly increase the MoR. This is probably because, at a pressing temperature of 200 °C for 20 min, only a portion of the bark extractives are polymerized (Chow 1972). Furthermore, according to Chow (1972), most of the bark extractives that polymerized during the manufacturing process of wood bark board occurred at 200 °C for 80 min, which resulted in the bending strength and IB values being similar to bark board with a 4.5% PF adhesive. However, the use of this longer pressing time is impractical. It seems to indicate that the

effect of plasticization still plays a prominent role in the formation of BBP at a pressing temperature of 200 °C, *i.e.*, it is possible the cure reaction is not yet working effectively. As pointed out by Araújo Junior *et al.* (2018), the cure reaction starts at a temperature of 210 °C, and an effective cure occurs at a temperature of 220 °C. These principles also apply to the results of the Tukey's test for the MoE. For the TSPtPS values, a 200 °C treatment temperature resulted in a significant increase of the TSPtPS value from the 180 °C treatment TSPtPS value, which indicated that at 200 °C, the polymerization of the phenolic materials had indeed occurred, even though only a small portion of the materials had polymerized. Figure 9b shows that the failure line in the middle of the sample after TSPtPS testing could be associated with the stronger adhesion among the particles in the board pressed at a temperature of 200 °C compared to those pressed at 180 °C. However, the results show that the TSPtPS value of BBP compressed at a temperature of 200 °C was still exceptionally low

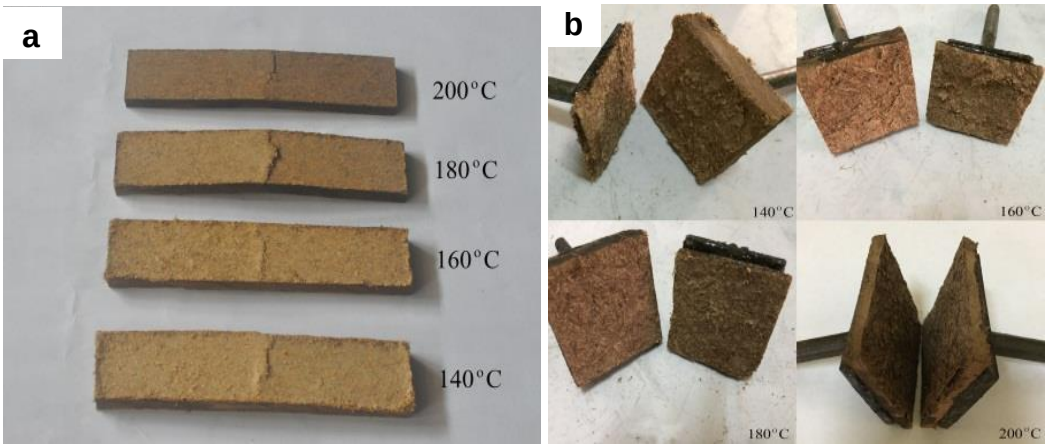

Fig. 9. Test samples after testing (a) the MoR and MoE; and (b) the TSPtPS of BBP pressed at a temperature of 140 °C, 160 °C, 180 °C, and 200 °C

Previous studies on manufacturing relatively high-density particleboards and fiberboards without adhesive *via* the hot-pressing method found that the mechanical properties of the board can be improved when the pressing temperature is increased to an optimum temperature of approximately 230 °C to 300 °C (Chow 1975; Gao *et al.* 2011; Gupta *et al.* 2011; Nonaka *et al.* 2013). However, it should be noted that these boards used different starting materials. As mentioned by Nonaka *et al.* (2013), the optimum conditions were achieved in the manufacture of bagasse binderless particleboard at a temperature of approximately 260 °C with a short pressing time of 10 min. These conditions result in an MoE equivalent to PMDI particleboard and a TS lower than PMDI particleboard. When manufacturing binderless fiberboard from refined bark, the best mechanical properties that also met the standard requirements were attained with a pressing temperature of 260 °C for 6 min (Gao *et al.* 2011). In another study, Araújo Junior *et al.* (2018) showed that the optimum pressing temperature was slightly higher than 200 °C (more precisely at 220 °C for 4 min), which resulted in high-density binderless fiberboard with good mechanical and physical properties being made from unripe coconut husks. Concerning the manufacturing of low-density BBP *via* the hot-pressing method, it is likely that temperatures higher than 200 °C are necessary. However, as mentioned previously at the beginning of this study, when the pressing temperature is raised above 200 °C for 20 min, the boards become

partially scorched. Nevertheless, if the pressing temperature is raised slightly higher than 200 °C for a shorter duration, this may result in a stronger bond between the bark particles, which in turn will improve the MoR, MoE, and TSPtPS of the board. Since there will be more phenolic polymerization, which becomes a dominant factor, this matter could be considering in future studies. Moreover, several methods have been proposed by other studies to improve the mechanical properties of binderless bark-based boards, *e.g.*, chemical pre-treatment of the bark particles with a 1% NaOH solution, pre-heating, and refining (Geng *et al.* 2006), as well as the addition of wood fibers (Gao *et al.* 2011).

Table 3. Comparison of the Mechanical and Physical Properties of the BBPs With Other Bark Boards Made *via* the Hot-Pressing Process With or Without the Addition of Adhesives

Reference	This Work		(Sato 2008)	(Purwanto 2015)	(Gupta *et al.* 2011)		
Material	GBW [1]		*Melaleuca* bark [2]	Galam tree bark (*Melaleuca leucadendra* L.) [3]	Beetle-infested lodgepole pine (*Pinus contorta*) bark [4]		
T (°C)	180	200	180	110 to 120	170	200	230
Pressure (kg/cm^2); Time (min)	30; 20	30; 20	40.79; 15	15; 15	28.1; 1 followed by 12.3; 19	28.1; 1 followed by 12.3; 19	28.1; 1 followed by 12.3; 19
MoR (kg/cm^2)	28.7	40.5	Approx. 28.55 to 45.89	104.2	20.5	32.8	73.2
MoE (kg/cm^2)	5947	7730	Approx 1019.72 to 1325.63	8191	4283	7383	17200
TSPtPS/ IB (kg/cm^2)	0.17	0.63	0.31−0.41	0.65	1.02	1.53	9.89
Density (g/cm^3)	0.52	0.55	0.80 (+)	0.77	0.80	0.86	0.92
TS24h (%)	12.93	4.94	Approx. 0.70 to 2	2	64.93	41.77	10.46
WA24h (%)	21.4	16.3	8 to 10	-	72.82	57.27	15.36

[1] Low-density BBP; single-layer; thickness of 10 mm; particles passed through 10 mesh size
[2] High-density bark binderless board; single-layer; target thickness of 14 mm; bark flakes (mesh size 50 mm x 100 mm)
[3] Medium-density particleboard with 15% UF resin; single-layer; thickness of 10 mm; Galam bark pieces 6 cm in length
[4] Bark board without synthetic adhesive; single-layer; thickness of 6.25 mm; particles passed through 4 mesh size
(+) Target density

Based on SNI standard 03-2105-2006 (2006), the MoR, MoE, and TSPtPS values of the BBP manufactured in this study did not meet the minimum requirements for Type-8 (a MoR of 82 kg/cm^2, a MoE of 20400 kg/cm^2, and a TSPtPS of 1.5 kg/cm^2). Nonetheless, it can be said that the low mechanical properties of the board panel made without adhesives are due to the low strength of the bark, *i.e.*, the fibers of the bark are shorter and weaker

than wood fibers, and the proportion of its fibers is lower than wood (Geng *et al.* 2006; Gao *et al.* 2011; Hosseinihashemi *et al.* 2017).

Table 3 compares the properties of the BBPs manufactured in this study with other bark boards made *via* the hot-pressing process, with or without the addition of adhesives. The MoR values of BBPs that have been pressed at a temperature of 180 and 200 °C were still within range of the MoR values of a high-density binderless board made from the bark of *Melaleuca* pressed at a temperature of 180 °C (Sato 2008). However, BBP pressed at a temperature of 200 °C had better mechanical properties (MoE and TSPtPS) than a high-density binderless bark board. The MoR and MoE of BBP pressed at a temperature of 200 °C had lower MoR and MoE values (61.13% and 5.63%, respectively) than medium-density particleboard made from Galam bark using a 15% urea formaldehyde (UF) adhesive, even though the TSPtPS values of the two boards were similar. After comparing the TSPtPS values listed in Table 3, it was found that the adhesive-free method for making particleboard from Gelam bark was more favorable than using UF adhesive; however, further studies are necessary to confirm this. In addition, a comparison of the MoR and MoE values of the BBP pressed at a temperature of 180 and 200 °C with bark board manufactured without synthetic adhesive pressed at a temperature of 170 and 200 °C revealed similar MoR and MoE values (Gupta *et al.* 2011). However, the TSPtPS values of the BBP samples were much lower. Raising the pressing temperature to 230 °C, as demonstrated in the study by Gupta *et al.* (2011), produced a board with higher mechanical properties than the BBP pressed at a temperature of 200 °C.

Physical Properties

Figure 10 shows the average values of the density, MC, TS24h, and WA24h of the BBP pressed at different pressing temperatures. Based on the analysis of variance, the pressing temperature had a significant influence on the physical properties of the BBPs (ANOVA *p*-value was less than 0.01).

The board density increased as the temperature was increased. On average, the density of the BBPs, based on the variations of the pressing temperatures, ranged from 0.44 to 0.55 g/cm^3, which met the requirement of SNI standard 03-2105-2006 (2006), *i.e.*, 0.40 g/cm^3 to 0.90 g/cm^3. These results categorize the manufactured BBPs as low-density particleboards (a density of less than or equal to 0.59 g/cm^3). The boards can be made with low-density because GBW has low-density. According to Roussan (1923), *Melaleuca* bark has a low specific gravity (0.18 to 0.20). Xu *et al.* (2004) asserted that low-density particleboards could only be made from low-density raw materials. There was a significant difference between the density value of the BBP pressed at a temperature of 140 °C with the BBPs pressed at the other tested temperatures; the BBP pressed at 140 °C had the lowest density value (0.44 g/cm^3). This is probably caused by the spring-back effect that occurs after the pressing process and the swelling that may occur during the conditioning (Iswanto *et al.* 2014, 2019), therefore decreasing its density. This aspect is also closely related to the TSPtPS value of the BBP (at a pressing temperature of 140 °C), which was poor and therefore not high enough to hold the particles in a compressed form when the pressure was released (Pintiaux *et al.* 2015). Furthermore, the density of the 160 °C treatment significantly differed from the density of the 200 °C treatment. However, there was no significant difference between density of the 160 °C treatment and the 180 °C treatment, nor was there a significant difference between the 180 °C treatment and the 200 °C treatment.

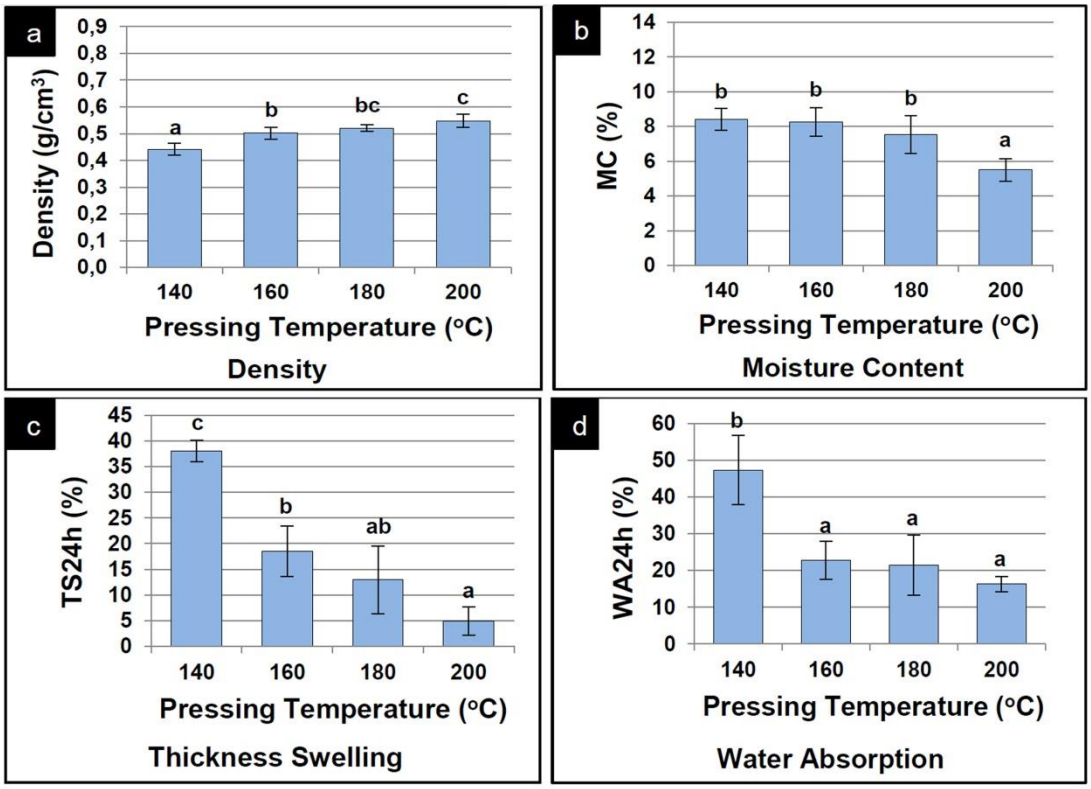

Fig. 10. The physical properties of the BBP: (a) density; (b) moisture content; (c) thickness swelling after 24 h of soaking; (d) water absorption after 24 h of soaking (means ± the error bar shows the standard deviation and means with different letters are significantly different at α = 0.05 (Tukey's test)

The average MCs of the manufactured boards ranged from 5.50% to 8.39%. The lowest MC was found in the board that was pressed at a temperature of 200 °C (5.50%), and it met the requirements of SNI standard 03-2105-2006 (2006), *i.e.*, less than or equal to 14%. The MC of the board manufactured at pressing temperature of 200 °C was significantly different from the MCs of the boards at pressing temperatures of 140, 160, and 180 °C. However, there was no significant difference between those three treatments.

The TS24h of the BBPs decreased from 38.06% to 4.94% as the pressing temperature increased from 140 to 200 °C. The treatment with a 200 °C pressing temperature significantly differed from the 140 and 160 °C treatments, in terms of the TS24h, but did not significantly different from the 180 °C treatment. The BBP made at a 200 °C pressing temperature had good dimensional stability since its TS24 h value met the requirements of the SNI standard 03-2105-2006 (2006) for the maximum thickness swelling (12%). Meanwhile, when the pressing temperature was increased from 140 to 200 °C, the WA24h value decreased from 47.35% to 16.3%. The WA24h value of the board pressed at a temperature of 200 °C was not significantly different from the board pressed at a temperature of 160 and 180 °C. However, the boards made at a pressing temperature of 160, 180, and 200 °C all significantly differed from the board pressed at a temperature of 140 °C.

A higher pressing temperature will lower the TS24h and WA24h values, since a higher pressing temperature will create a stronger bond between the board particles. This

phenomenon will make the board denser, *i.e.*, reduce or completely remove any void spaces between the particles, as shown by the SEM micrographs of the surfaces and the cross-sections (Figs. 5d and 6d); therefore, the water penetration of the board structure is reduced. Furthermore, there are also the lignins that flow onto the surfaces of the GBW particles (Fig. 5d). Since lignins are hydrophobic by nature, with non-polar hydrocarbon chains and aromatic rings that prevent water from entering (which can cause swelling in the cell wall), they cause an increased resistance to water penetration (Mancera *et al.* 2011; Nasir *et al.* 2019). Another aspect to consider is the reduction in the amount of hydroxyl groups that are easily accessible by water, due to hemicellulose degradation (Kurokochi and Sato 2020; Nitu *et al.* 2020; Song *et al.* 2020), which was also confirmed by the FTIR spectra of BBP in the present study. This view is also in line with the study by Gao *et al.* (2011), which asserted that a low TS value is associated with the polymerization, cross-linking, and/or other transformations of hydrophilic components of bark into a hydrophobic product during hot pressing under high temperature for a sufficient period.

Table 3 shows that the board made from GBW pressed at a temperature of 200 °C had a lower TS24h value than the board make by Gupta *et al.* (2011). However, the TS24h was still higher when compared to the medium-density particleboards made in Purwanto (2015) and the high-density bark binderless boards made by Sato (2008). The WA24h value of the BBP pressed at a temperature of 200 °C was similar to the WA24h value of the bark boards made by Gupta *et al.* (2011), *i.e.*, the board pressed at a temperature of 230 °C. The results of the TS24h and WA24h tests showed that boards made from *Melaleuca* bark had high dimensional stability and water resistance.

Figure 11 shows the TS24h and WA24h test samples (BBP pressed at 140, 160, 180, and 200 °C) after testing. It can be seen that they did not disintegrate.

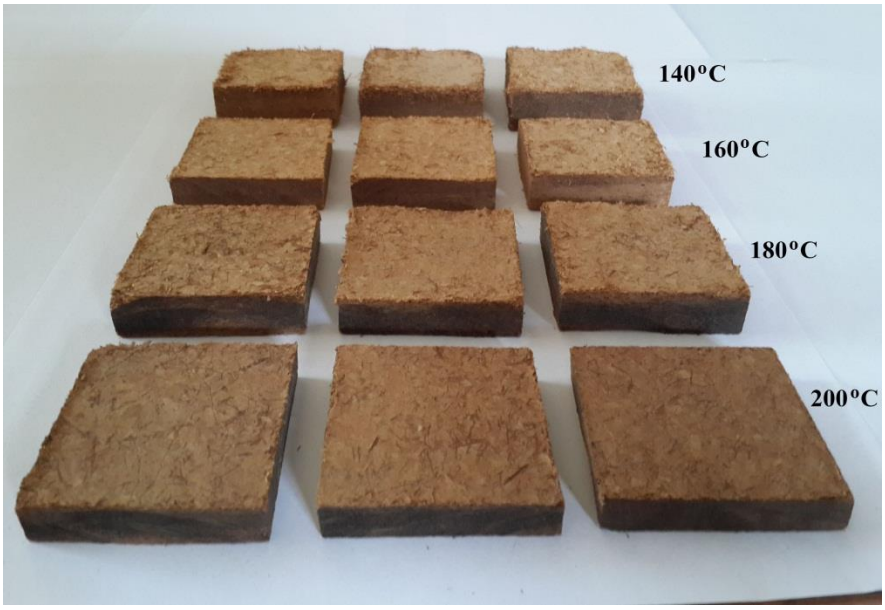

Fig. 11. The BBP test samples pressed at 140, 160, 180, and 200 °C after the TS24h and WA24h tests

Thermal Conductivity

A thermal conductivity test was performed, considering that BBP was a low-density board category. Since it was mentioned by Panyakaew and Fotios (2011) that a low-density

board tends to have a lower thermal conductivity than a high-density board, it is appropriate for usage as thermal insulation. Only the boards pressed at a temperature of 200 °C (density value 0.55 g/cm^3) were tested, since these boards had the best physical and mechanical properties among the four types of boards pressed at different temperatures. Kain *et al.* (2014) found that a certain level of compaction in the insulation board, *i.e.*, a density of greater than or equal to 400 kg/m^3, was required to meet the relevant mechanical property standards.

A comparison of thermal conductivity value of the BBP pressed at a temperature of 200 °C with conventional and natural insulation materials is shown in Table 4. The comparison showed that the thermal conductivity value of the BBP pressed at a temperature of 200 °C was not as low as the lightweight insulation materials (rock wool and expanded polystyrene). However, it was still higher than natural insulation materials, *e.g.*, kenaf, flax shives, sunflower bark, eucalyptus bark, poplar bark particles, larch bark particles, and coconut husk, but it is was comparable with others materials from *Quercus cerris* bark (particleboards with a density of 725 kg/m^3), wood particles, green coconut, and sugarcane bagasse fiber (multilayer particleboards with a density of 500 kg/m^3); it was also slightly lower than green coconut and sugarcane bagasse fiber (multilayers particleboards with a density of 700 kg/m^3). These results revealed that BBP pressed at a temperature of 200 °C had a high thermal conductivity value. This may be related to the fact that there were almost no voids of air pockets in the board, which can be confirmed by the results of the SEM micrographs showing the cross-section of the BBP (Fig. 6d), as it is known that air is a poor conductor of heat (Zhou *et al.* 2010; Liao *et al.* 2016; Fiorelli *et al.* 2019). However, the insulation boards from natural materials with low thermal conductivity values usually have densities less than or equal to 0.40 g/cm^3 since they have a large number of voids, which are filled with air. According to Asdrubali *et al.* (2015), the best material will have a thermal conductivity value of less than 0.05 W/m·K. However, Zhou *et al.* (2010) and Fiorelli *et al.* (2019) claimed that in general, any material with thermal conductivity of less than 0.25 W/m·K could be considering as thermal insulation material.

Relating to the usage of BBP pressed at 200 °C, its values of MoR (40.5 kg/cm^2), MoE (7730 kg/cm^2), and TSPtPS (0.63 kg/cm^2) were lower than the minimum required values SNI standard 03-2105-2006 for type 8; and hence they can be considered for thermal insulation materials. This consideration is taken by looking at the mechanical properties of BBP pressed at 200 °C compared with thermal insulators from natural/waste materials from other experimental studies. These mechanical properties (MoR and MoE values) of BBP were higher than *Quercus cerris* bark particleboards (density 550 to 725 kg/m^3, thermal conductivity 0.11 to 0.14 W/m·K, MoR 0.71 to 1.52 MPa, MoE 58.5 to 143.6 MPa, IB 0.18 to 0.28 MPa) (Lakreb *et al*. 2018). The TSPtPS/IB value of BBP pressed at 200 °C was lower than those particleboards. Further, they recommend *Quercus cerris* bark particleboards for exterior non-load bearing applications (shed roof insulation). Then, the MoR, MoE, and TSPtPS values of BBP slightly higher compared with thermal insulating particleboard reinforced with coconut leaf sheaths (density 410 kg/m^3, thermal conductivity 0.135 W/m·K, MoR 3.82 MPa, MoE 455 ± 94 MPa, IB 0.05 MPa), which stated to have the potential to be applied as a material building insulation (partition walls, ceiling coatings, and internal doors) (Vidil *et al*. 2016). Indeed in the building insulator sector, mechanical properties are not primary characterizations (Gupta and Maji 2020).

Table 4. Comparison of the Thermal Conductivity Value of the BBP Pressed at a Temperature of 200 °C with Conventional and Natural Insulation Materials

Material	Board Type	Density	Thickness (mm)	Resin Type	λ (W/m·K)	References
GBW	Binderless bark particleboard	0.55 g/cm^3	10	-	0.14	This work
Rock wool	-	40 kg/m^3 to 200 kg/m^3	-	-	0.033 to 0.040	(Asdrubali *et al.* 2015)
Expanded polystyrene (EPS)	-	15 kg/m^3 to 35 kg/m^3	-	-	0.031 to 0.038	(Asdrubali *et al.* 2015)
Kenaf	Binderless particleboard	0.15 g/cm^3* and 0.20 g/cm^3*	12	-	0.051 and 0.058	(Xu *et al.* 2004)
Flax shives	Binderless particleboard	500 kg/m^3*	15	-	0.077	(Mahieu *et al.* 2019)
Sunflower bark	Binderless particleboard	500 kg/m^3*	15	-	0.077	(Mahieu *et al.* 2019)
Eucalyptus bark fibers	Insulation panel	25 kg/m^3 to 100 kg/m^3	50	Synthetic fibers	0.045 to 0.049	(Casas-Ledón *et al*. 2020)
Poplar bark particles	Particleboard	250 kg/m^3* to 350 kg/m^3*	20	8% UF	0.059 to 0.079	(Pásztory *et al.* 2019)
Larch bark particles	Insulation board	500 kg/m^3*	20	Tannin hexamine	0.093	(Kain *et al.* 2014)
Quercus cerris bark	Particleboard	550 kg/m^3* to 725 kg/m^3*	10	10% PF	0.11 to 0.14	(Lakreb *et al.* 2018)
Wood particles	Particleboard	-			0.10 to 0.14	(Lakreb *et al.* 2018)
Coconut husk	Binderless insulation board	0.48 g/cm^3	25		0.115	(Panyakaew and Fotios 2011)
Green coconut and sugarcane bagasse fiber	Multilayer particleboards	500 kg/m^3 and 700 kg/m^3	15	Castor oil polyurethane resin	0.14 and 0.17	(Fiorelli *et al.* 2019)
Note: * denotes a target density						

However, if thermal insulation materials contributed to building structures, such as those applied to wall and roof surfaces, it requires at least adequate mechanical properties. Because according to Liu *et al*. (2017), several types of insulation are always directly installed on the surface of a wall or roof and facing the collision of hard objects. Also,

Wood-based panels, as thermal insulation panels, should withstand a minimum performance during handling, installation, and maintenance (Pásztory *et al*., 2019). The competitive advantage of BBP pressed at 200 °C is its high-water resistance compared to the aforementioned thermal insulators from natural/waste materials. Then BBP may be used for exterior purposes.

Based on the consideration of the thermal conductivity of BBP pressed at 200 °C combined with its mechanical and physical properties, so BBP pressed at 200 °C potentially uses for thermal insulation in buildings. Additionally, this thermal insulation material environmentally friendly since without formaldehyde adhesive.

CONCLUSIONS

1. The results showed that the pressing temperature affected the physical and mechanical properties of the manufactured boards. As the pressing temperature was increased from 140 °C to 200 °C, the average values of the mechanical properties also increased, even though the increase was not significant for the MoR and MoE values at pressing temperatures of 180 °C and 200 °C. However, the TSPtPS values significantly differed with different pressing temperatures. All the mechanical properties of the boards did not meet SNI standard 03-2105-2006 for Type-8 (2006). For the physical properties, the density increased as the pressing temperature increased, while the MC, TS24h, and WA24h decreased as the pressing temperature increased. The decreasing TS24h and WA24h values did not significantly differ for the 180 and 200 °C treatments. The BBPs pressed at a temperature of 140 to 200 °C had density and MC values that met the SNI standard 03-2105-2006 (2006). In addition, the TS24h values of the BBP pressed at a temperature of 200 °C was the only sample to meet SNI standard 03-2105-2006 (2006) requirements for the maximum thickness swelling (12%).
2. The best physical and mechanical properties were obtained from the BBP pressed at a temperature of 200 °C with a MoR value of 40.5 kg/cm^2, a MoE value of 7730 kg/cm^2, a TSPtPS value of 0.63 kg/cm^2, a TS24h value of 4.94%, and a WA24h value of 16.3%.
3. The thermal conductivity value of the BBP pressed at a temperature of 200 °C with a density of 0.55 g/cm^3 was 0.14 W/m·K. Therefore, it can still be taken into account as thermal insulation material for use in buildings. Besides, its low mechanical properties and also better thickness swelling value adequate for that usage.
4. The BBP pressed at a temperature of 200 °C had a smooth surface and had high-water resistance properties; therefore, it could potentially be used as an overlay material/surface layer in composite panels, such as a decorative insulation panel.

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